

Ecological Health of North Stradbroke Island's Sandy Beaches

Phase 1

Pilot studies on 4x4 vehicle effects
(Jan-June, 2006).

Final Report

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Assessment of Recreational Off-Road Vehicle (ORV) Impacts on North Stradbroke Island

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CONTENTS

LIST OF FIGURES	1
LIST OF TABLES	3
Executive Summary	4
Chapter 1: Literature Review.....	8
Introduction	8
Beach Morphology	10
Zonation on Sandy Beaches.....	11
Beach Classification.....	13
Quantitative Measures of Morphological Beach State.....	15
Physical Control of Beach Assemblages	16
Composition of Sandy Beach Macrobenthos	17
Environmental Drivers of Faunal Assemblages.....	17
Dominant Macrofaunal Species of Australian Beaches.....	19
Human Encroachment of the Coastal Zone	19
Recreational Impacts on Beaches	20
Pedestrian Impacts on Beaches	21
Off-Road Vehicle (ORV) Use on Sandy Beaches	22
History Of Research on Vehicle Impacts on Beaches.....	23
Vehicle Impacts on Sandy Beaches	28
Vehicle Impacts to Physical Beach Processes	28
Vehicle Impacts to Dune Vegetation.....	33
Vehicle Impacts to Beach Fauna	36
Invertebrates	36
Shorebirds and Turtles.....	45
Recreational ORV Management.....	47
Conclusion.....	48
Chapter 2: Physical Impact Caused by Off-road Vehicles (ORVs) to Sandy Beaches: Spatial Quantification of Vehicle Tracks on an Australian Barrier Island.....	51
Abstract.....	51
Introduction	52

Methods	53
Results	56
Magnitude of Damage by Vehicles	56
Across-shore Variation in Vehicle Impacts	58
Discussion	64
Potential Habitat Disturbance	65
Backshore Impacts and Driver Behaviour	67
ORVs and Recreational Demands.....	69
Implications for Management of Beach Traffic	69
Chapter 3: Exposure of Fauna to Off-Road Vehicle (ORV) Traffic on Sandy Beaches	72
Abstract	72
Introduction	73
Material & Methods	74
Results	78
Beach Traffic Patterns and Driver Behaviour	78
Overlaps between Traffic and Fauna Distributions.....	80
Discussion	84
Conclusion	88
Chapter 4: Estimating Direct Mortalities of Ghost Crabs by Off-Road Vehicle (ORV) Beach Traffic on North Stradbroke Island	90
Summary	90
Introduction	91
Methods	92
Difference in ghost crab population size between traffic areas	92
Direct impacts of ORVs on ghost crabs: experiments to quantify crushing rates.....	94
Experiment 1: crushing of ghost crabs by ORVs inside natural burrows	95
Experiment 2: crushing of ghost crabs by ORVs in simulated burrows: effects of depth and traffic intensity	96
Experiment 3: ghost crabs killed by night-time traffic while surface-active	97
Results	98
Ghost crab population size in relation to areas of different traffic intensity	98
Crushing of crabs by ORVs inside their burrows.....	104
Nocturnal Vehicle Impacts on Ghost Crabs.....	111
Pilot Assessment of Night Beach Traffic.....	112
Pilot Assessment of Night Beach Traffic.....	112
Discussion	114

Conclusion.....	116
Recommendations and Proposal	117
Recommendations:	117
PROPOSAL for Biological Effects Assessment of ORVs on North Stradbroke Island.....	119
Background.....	119
Aims and Objectives:	123
Literature Cited.....	124
Appendix 1.....	134
Appendix 2.....	135

LIST OF FIGURES

Fig 1. Indicates the annual (%) increase in Off-Road Vehicle sales of total vehicles sold in relation to passenger vehicles and other vehicles (Source ABS, 2005).....	9
Fig 2. The physical attributes of a typical sandy shore (Stephenson 1999).....	12
Fig 3. Countries that have produced the greatest percentage of published literature on the impacts of vehicles on sandy beaches.....	24
Fig 4. The percent of published literature available on the different response variables used to assess vehicle impacts on beaches.....	25
Fig 5. Flinders Beach, April 2005, indicating the physical disturbance to the foreshore caused by ORV traffic	29
Fig 6. The mean percent damage to intertidal organisms after 50 ORV passes, in 1 hour (van der Merwe & van der Merwe, 1991).....	41
Fig. 7 Map of North Stradbroke Island showing beach sites surveyed for physical damage caused by ORVs.	54
Fig. 8 Examples of the spatial distribution of vehicle impacts across the shore.....	60
Fig. 9 Distribution of vehicle ruts across the beach face on Flinders Beach	61
Fig. 10 Distribution of vehicle ruts across the beach face on Main Beach.....	62
Fig. 11 Comparison of sand displaced by vehicles in each beach zone versus beach width....	63
Fig. 12 Depth of ruts in relation to compactness of the sand in each of the two major beach zones.	63
Fig.13 Ordination (non-metric multidimensional scaling) of beach sites based on physical vehicle damage to the sand matrix.....	64
Fig. 14 Distribution of macrobenthic species across the beach face in relation to depth of vehicle ruts (a) and the density of tyre tracks per metre of rut (b).....	66
Fig. 15 Location of beaches surveyed for overlap between beach traffic and intertidal macrobenthos.....	75
Fig. 16 Temporal and spatial pattern of beach traffic in relation to tidal variation in water level on the five ORV-impacted beaches on North Stradbroke Island, Teewah Beach, and Noosa North Shore.....	79
Fig. 17 Position of vehicles across the beachface in relation to tidal height.....	81

Fig. 18 Cross-shore profiles of a) vehicle traffic, b) macrobenthic species distributions, c) density of total macrofauna, d) sand moisture, and e) beach elevation.....	83
Fig. 19 Location of sites for experimental and natural assessments of impacts to ghost crabs by 4WD vehicles on North Stradbroke Island.....	93
Fig. 20 Spatial layout of traffic zones for which the density of ghost crabs was compared at the Northern tip of Main Beach.....	94
Fig 21 Comparison of (a) sand moisture content and (b) sand grain size between sections of the beach with different traffic volumes in which ghost crab densities were assessed.....	98
Fig 22: Proportion of ghost crabs distributed below the drift line, which corresponds broadly to the area of heaviest traffic concentration across the beachface.	100
Fig. 23 Comparison of burrow openings between sections of the beach receiving different volumes of traffic (top panels) and size of burrow openings (bottom panel).....	101
Fig 24: Comparison of size frequencies of ghost crab burrow openings (\varnothing , mm) between traffic areas.....	103
Fig. 25: Size distribution of crushed and undamaged crabs following experimental application of ORV traffic to ghost crab populations under natural conditions.....	106
Fig 26: Mortality of ghost crabs through direct crushing by ORVs	108
Fig. 27 Ghost crab mortalities caused by simulated night-time traffic.....	112
Fig. 28 Nocturnal vehicle counts on Flinders Beach.....	113

LIST OF TABLES

Table 1: Percentage of beach sand volume disturbed by vehicle ruts.....	57
Table 2: Comparison of the severity of vehicle damage to beaches between the upper zone of the intertidal zone (drift-line to foredune) and the lower beach (swash to drift line).....	58
Table 3: Physical characterisation of the beaches sampled (values are means of three transects per beach).....	76
Table 4: Sediment moisture and grain size in three beach zones and the distribution of vehicle traffic across the beach face.....	80
Table 5: Overlap (%) in the distribution between beach traffic and macrobenthos species.....	82
Table 6: The physical variables tested for the sites where burrow counts were completed.....	99
Table 7: Comparison of ghost crab abundances between three sections of the beach receiving different amounts of beach traffic.....	99
Table 8: Comparison of the size of ghost crab surface burrow openings (mm) between three sections of the beach receiving different amounts of beach traffic, at varying distance downshore from the base of the foredunes.....	102
Table 9 Locality of experimental plots in which mortalities of ghost crabs inside their un-manipulated burrows were measured.....	104
Table 10: Changes in sediment compactness at varying intensities of ORV traffic applied to experimental plots that contained un-manipulated ghost crab burrows.....	105
Table 11: Summary of experimental results on mortality of ghost crabs impacted at intensities of ORV traffic.....	105
Table 12: Changes in sediment compaction following the application of vehicle treatments. The physical properties of the each site (% moisture, sand grain size μm) are also shown.....	107
Table 13: Percent crab mortalities observed at the different treatment intensities.....	109
Table 14: Crab activity when in relation to weather and moon cycles.....	111

Executive Summary

1. This report summarises the findings of three pilot studies on key aspects of the ecological condition of sandy beaches at North Stradbroke Island that may be affected by the use of 4x4 vehicles on beaches. The work was undertaken by the Marine Science Group of the University of the Sunshine Coast on behalf of Redland Shire Council from January to June 2006. It also contains a synopsis of the global literature on recreational impacts on sandy beaches, and several recommendations following these pilot studies.
2. Sandy beaches geographically dominate the open shoreline of South-East Queensland, including sand barrier islands such as North Stradbroke Island. The unique natural assets of sandy beaches underpin much of the regional economy, and beaches represent the prime coastal areas for human recreation. Beaches are particularly important as recreational areas on North Stradbroke Island.
3. A significant part of these recreational activities involves the use of Off-road vehicles (ORVs) on beaches, and recreational driving of ORVs is widely practiced on the eastern beaches of the island. This use may, however, be controversial, with one recent report suggesting that ORVs can cause significant environmental harm to organisms inhabiting the sandy shores. Neither are these concerns universally shared, nor are the mechanism of putative impacts known: a clear assessment of any ecological effects of ORVs seems thus premature given the lack of comprehensive local data.
4. The published literature on recreational effects on sandy beaches, in particular off-road vehicle (ORV) impacts, is mostly limited to overseas studies, particularly works from North America and South Africa. Except for a single study published early 2006, no ecological work has been conducted on beaches in SE Queensland. Thus, the ecological consequences of ORV traffic on beaches are essentially unknown for the regional and local situation. Also, most published work has concentrated on dune vegetation and shorebirds, while information about the effects on

invertebrates is scant. Consequently, current practices to manage the use of ORVs on sandy beaches in South East Queensland are not based on regionally-relevant, quantitative data on the ecological condition of beaches and human effects on these key habitats.

5. The published literature on ORV impacts indicates that: (a) public opinion on ORV use on beaches can be negative, with most recreational beach users perceiving four-wheel driving as harmful to the environment, (b) dune vegetation is readily destroyed by ORVs, (c) shorebirds are generally negatively impacted by ORVs, and closure of beaches to traffic results in significant recoveries of bird populations, and (d) invertebrates inhabiting the un-vegetated beach (e.g. pipis, ghost crabs) can be directly killed by ORVs travelling in the intertidal zone.
6. There exists a basic but fundamental data gap about the degree to which 4x4 traffic can modify the physical environment (and by implication habitat for the fauna) of sandy beaches. Physical habitat disruption caused by ORVs can be severe on North Stradbroke Island at times of high beach traffic. During the peak holiday period around the New Year 2005/06, much of the intertidal beach was deeply rutted by ORV tracks.
7. The density of tyre tracks per metre of beachface ranged from 2.69 to 6.35 on Flinders Beach, and from 2.38 to 8.06 on Main Beach. On Flinders Beach, 61% of the beach surface area was covered by vehicle tracks, and cars had rutted 54% of the sand surface on Main Beach. 4x4 vehicles caused corrugations of the beach down to 28 cm (mean depth: 5.86 ± 4.72 cm). On a volume basis, peak beach traffic can disrupt 5.8% (Main Beach) and 9.4% (Flinders Beach) of the available faunal habitat matrix (top 30cm of the sand) in a single day. About half of this sand displacement originates from the upper shore through very deep rutting, even though these sections cover a considerably smaller portion of the intertidal zone.
8. ORVs can only impact on organisms if the distribution of traffic overlaps with that of the fauna. This study found that the majority (65%) of burrowing invertebrate species of the intertidal zone are directly exposed to traffic, save for species inhabiting the swash zone. Larger species that are moderately to highly exposed to beach traffic on North Stradbroke

Island include ghost crabs (*Ocypode ceratophthalma* and *Ocypode cordimana*) and pipis (*Donax deltoides*) as well as several species of smaller crustaceans and worms buried in the sand.

9. Driver behaviour is directly related to the shape of the beach and sediment properties (e.g. sand moisture content), the position of the effluent line (ground water table outcrop), wave and swash regimes and tidal fluctuations. Despite driver education campaigns to the contrary, a considerable fraction of vehicles (23-67 %) traverses the soft, upper shore near the foredunes.
10. Population sizes of ghost crabs are significantly lower on beaches that receive high volumes of recreational ORV traffic. This spatial pattern suggests negative impacts of ghost crabs by ORVs, such as direct crushing of crabs by vehicles. Ghost crabs are buried inside the sand during the day, and this may afford them some protection against vehicles. However, this assumed protection is highly dependent on burial depths: if crabs are buried very shallow (5 cm), all crabs are killed by 10 vehicles passes. Mortality rates decline with depth into the sediment, but are still considerable (10-30 %) at 20 cm depth. Only crabs buried at least 30 cm or deeper seem to be largely immune to direct crushing by ORVs: these “deep-living” crabs represent about half of the population.
11. Crabs emerge at night to feed on the surface of the beach and thus become highly susceptible to crushing by nighttime traffic. Indeed, a single vehicle travelling at night on the beach can kill 13 - 26 crabs over a relatively short (200 - 700 m) distance: this represents 0.12 - 0.75 % of the resident crab population. Although this mortality figure may appear low, effects are likely to be cumulative. At the upper estimate of ORV mortality (e.g. 0.75 %) - representing a “worst-case scenario” - it would take fewer than 100 vehicle passes to reduce the population to half, and 300 vehicles to decimate the crab population to one-tenth: this equates to less than a single vehicle per night over the course of a year.

12. Recommendations

- a. Quantify direct mortalities of ORVs to key species of the intertidal beach, particularly the suite of invertebrate species buried in the sand.

- b. Comprehensively gauge the social acceptance of various types of recreational uses of sandy beaches, including ORV driving, the potential for social conflict between competing user groups, and related socio-cultural issues.
- c. Determine biological attributes and behaviour patterns of key species that influence their potential vulnerability to beach traffic, particularly patterns of activity and changes in distribution, to be used in the development of management practices aimed at minimizing overlap (both temporal and spatial) between fauna and beach traffic.
- d. Obtain defensible and robust quantitative information on whether ORVs can substantially change the composition and structure of ecological communities on sandy beaches to advance discussion about alleged or real “impacts”, including the identification of beach areas of high conservation significance.
- e. Quantify the economic costs and benefits of ORV use on the island’s beaches, including effects on local businesses and alternative income sources.
- f. Develop management practices for the use ORVs on sandy beaches based on ecological, socio-cultural and economic considerations.

Chapter 1: Literature Review

Introduction

Sandy beaches dominate the open shoreline of South East Queensland. The region's marine intertidal zone is almost entirely composed of sandy shores, punctuated by a few rocky headlands of minor geographical extent (Banks & Skilleter 2002). Beaches also underpin much of the regional economy, and are thus the single most important natural asset in supporting tourism, and ultimately the rapid population growth of the region (James 2000a, Jones et al. 2004, ABS 2005). Humans use a variety of coastal ecosystems in the region, but direct human interaction with coastal ecosystems is overwhelmingly concentrated on beaches. As it is sandy shores that have the closest link with most of the region's residents; it is predicted that a high concentration of human activities on the sandy beach ecosystem will cause considerable (but as yet unmeasured) pressures on beaches in South East Queensland (Banks & Skilleter 2002, Moss & McPhee 2006).

One of the most prevalent, widespread uses of sandy beaches is recreational four-wheel driving. Although evidence of negative environmental impacts of off-road vehicles (ORV) is scant compared with other human pressures, some information on ORV impacts is available from overseas (van der Merwe 1988, Stephenson 1999, Atkinson & Clark 2003). In some regions these studies, along with public pressure have led to a ban of non-essential vehicle use on beaches, which was the case in South Africa in 2002 (Atkinson & Clark 2003). By contrast, no published data on ORV effects are available for most of the Australian coastline with particular regard to beach organisms.

In terms of vulnerability to impacts, sandy shores are already physically and morphologically very variable and can be more readily disturbed by additional pressures (Brown & McLachlan 2002, Priskin 2003a-b). The lack of information

on vehicle impacts is remarkable considering sandy beaches are the dominant shore habitat in Australia and the increasing intensity of ORV use many beaches are receiving (Moss & McPhee 2006). Recent statistics on new vehicle purchases have indicated a substantial increase in the number of ORV's being purchased by consumers in relation to passenger vehicles and other vehicles (Fig. 1). Off-road vehicle sales to April 2005, currently make-up 19.3% of total new vehicles sold in this country. The percentage of the vehicles purchased, that are actually used on beaches is at yet unclear. In Australia, beach four-wheel driving and associated activities such as beach camping and fishing are immensely popular recreational pastimes (Hockings & Twyford 1997, Priskin 2003a-b). In South East Queensland, participation in recreational four-wheel drive use increased from 20% of residents in 1998 to 23% of residents in 2000, which represented approximately 430, 000 people (Moss & McPhee 2006).

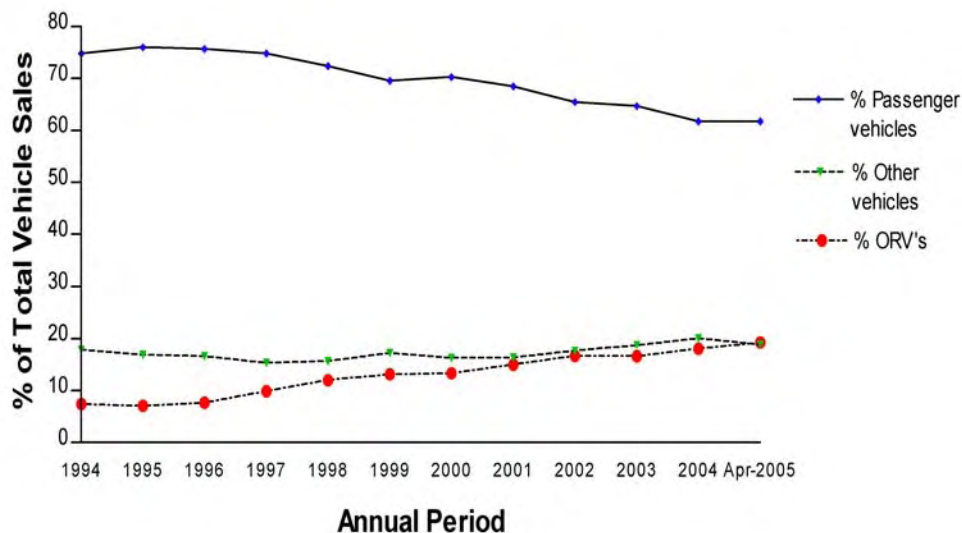


Fig. 1 Indicates the annual (%) increase in Off-Road Vehicle sales of total vehicles sold in relation to passenger vehicles and other vehicles (Source ABS, 2005).

The primary objective of this literature review is to summarise the available information on the ecological impacts of vehicle traffic on beaches. Because physical factors play a prominent role in shaping the faunal assemblages on

beaches (Defeo & McLachlan 2005), the main physical and morphological attributes of beaches are outlined. Similarly, the use of vehicles on beaches is embedded in a social and economic context, at times leading to conflicts between users, thus the social dimension of vehicle use on beaches will also be outlined.

Beach Morphology

Sandy beaches are unique and diverse environments that are constantly exposed to many physical elements such as tides, wind and waves (Short 1999). These elements are the dominant forces that shape and change beach morphology (Short 1999). In terms of the research on marine environments, sandy beaches have been relatively understudied compared to other environments such as rocky shores (Brown & McLachlan 1990, Brown 2001, Jones et al. 2004). This is due to the difficulty of sampling these areas in terms of labour and logistics, the behaviour of organisms (e.g. tidal migration, burrowing and nocturnal activity), as well as trying to incorporate physical factors such as waves, tides and weather conditions into sampling timeframes (Thompson 2005).

Beaches are a wave deposited accumulation of sediment (sand) that extends from the wave base to the upward limit of the resulting wave uprush or swash, which often coincides with the storm drift line and the base of the sand dunes (Short 2001). The sand of our beaches in South East Queensland is made of quartz grains eroded over millions of years from the granites of the highlands of New South Wales (Davie 1998). These grains have been transported northwards by wind and currents and deposited on our beaches as the result of wave and swash action (Davie 1998, Graham 2004). This deposition leads to the development of coastal dunes, which support vegetation that not only helps to protect their surface from erosion but also aids in sand accretion, thus

improving their role as the landward defence against the ocean (Ranwell & Boar 1986).

Zonation on Sandy Beaches

Beaches comprise about 75% of the world's shorelines (Bascom 1980), and these systems comprise 3 broad areas or zones.

- (1) The nearshore zone, which incorporates the area from where wave shoaling begins to the low water mark.
- (2) The beach, the area from the low water mark to the drift line, and
- (3) The dunes or the landward storm reach to stable dunes (Stephenson 1999).

These three major zones can then be subdivided into smaller zones and together these areas make up the littoral active zone, which is where the majority of physical change occurs and where new dunes are created (Fig. 2) (van der Merwe 1988, Stephenson 1999). The littoral zone is a complex interactive system in which the nearshore / foreshore areas are dominated by tides, wave climate, currents and swash energy, and the backshore and dunes are mainly influenced directly by wind energy and aeolian sediment transport mechanisms (Stephenson 1999).

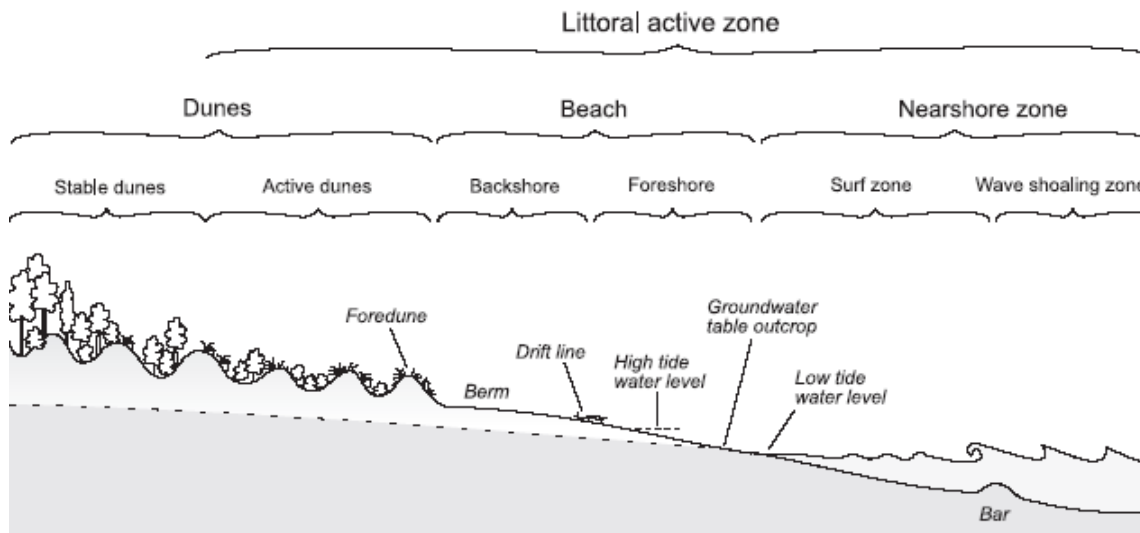


Fig. 2 The physical attributes of a typical sandy shore (Stephenson 1999).

The first seaward zone is called the wave shoaling zone and is where ocean swells start to shoal on outer banks, turning into waves that will influence the substrate of the shore (Short 1999, Stephenson 1999). The next zone is the surf zone where waves and swash dominate the geomorphic system and where the majority of sediment is transported by waves and currents. The foreshore zone is next and is dominated by swash uprush and backwash. This is the zone where the drift line, high water mark and groundwater table outcrop (effluent line) are located. The majority of burrowing organisms such as molluscs, polychaetes and intertidal crustaceans are commonly found in this zone (McLachlan & Dorvlo 2005).

The backshore zone occurs after the foreshore zone on the landward side of the drift line. This is where new dunes are created and the backshore zone extends to the foredune, which is the base of the active dune system and where the first terrestrial vegetation occurs (Stephenson 1999). In some circumstances, the drift line coincides with the foredunes resulting in a small or non-existent backshore zone. In these circumstances the beach or foreshore zone may extend from the dunes seawards to the low water mark. In this definition the beach is mostly intertidal with a small supralittoral fringe.

From here the active dune zone extends upwards to the more stable dune systems that dominate the landward edge of the coastal zone (Brown & McLachlan 1990, Stephenson 1999). From the foreshore to the landward edge of the stable dunes, terrestrial vegetation plays the most significant role as it helps stabilize new dune systems and prevent the erosion and loss of sediment from these habitats during storm events (Liddle & Greig-Smith 1975b, Stephenson 1999).

The nearshore and foreshore zones have distinctly different biota than the dune and backshore zones (Brown & McLachlan 1990, McLachlan & Jaramillo 1995). These zones are dominated by burrowing, swimming fauna and the backshore and dune zones are predominantly dominated by terrestrial plants, insects, birds and crawling animals (Brown & McLachlan 1990, McLachlan & Jaramillo 1995). In some cases different varieties of fauna, such as crabs and birds will be found to inhabit both areas. Ghost crabs are a prime example of this, inhabiting the active and stable dune zones as well as the frontal dune and backshore zones and are known to forage on the foreshore at night (Wolcott 1978, Barros 2001).

Beach Classification

Based on the three fundamental physical factors that shape beaches, including wave climate, sand grain size and tidal regime, beaches can be classed into six morphodynamic states, ranging from microtidal reflective beaches (narrow and steep) to macrotidal dissipative (wide and flat) (Short & Wright 1983, Short 1999, McLachlan & Dorvlo 2005). Based on these three fundamental factors, different beach classifications have been established that relate directly to these combined physical processes (Short 1999, Defeo & McLachlan 2005).

The surf and swash zones, where the effects of wave size and wave period on the beach face is determined, play the dominant role in determining the extent to which physical processes affect the shape of the beach (Stephenson 1999). For

example, in Australia, beaches that receive high wave exposure tend to be flatter, having wider surf zones where larger waves with longer wave periods can disperse energy over a greater area. These beaches that receive high wave exposure tend to have finer, well sorted sediments and are under constant change due to the physical dynamics of exposed swell coasts (Short & Wright 1984, McLachlan & Dorvlo 2005).

Reflective beaches generally have a steep beach face with coarse sands and small waves in a narrow or absent surf zone. The swash on these beaches is of short duration and usually only covers the lower shore due to the drainage of the steep beach face (Short 1999). Reflective beaches are formed under small tides where the lack of a distinct surf zone allows the wave energy to be reflected back to sea from waves breaking directly onto the steep beach face (Short 1999, Defeo & McLachlan 2005).

At the other end of the beach classification spectrum are dissipative beaches. This type of beach is flat with a wide surf zone where wave energy is dissipated over a larger area producing a more benign, dispersive swash climate, which results in sediment deposition and transport of finer particles (Short 1999, 2001, Defeo & McLachlan 2005). These beaches are formed in coastal areas that have large tides, high wave energy and fine sands (Defeo & McLachlan 2005).

Intermediate beaches lie between the reflective and dissipative extremes with respect to waves, beach slope, swash regimes, tides and sediment grain size (Short 1999, McLachlan & Dorvlo 2005). In Australia the majority of beach types are classed as intermediate with few extremely stable reflective or dissipative beach systems because of the dynamic nature of the coast, and a moderate to high exposure to waves and storm events (Short & Wright 1984, Short 1993).

Quantitative Measures of Morphological Beach State

One of the first quantitative measures of beach state to be widely used and accepted by sandy beach ecologists was Dean's dimensionless fall velocity or Dean's Parameter (Ω) (Short & Wright 1984, Short 1999, Defeo & McLachlan 2005, McLachlan & Dorvlo 2005). This method of classifying a beach can be determined by calculating (Ω).

$$\Omega = Hb / Ws \cdot T$$

Hb represents wave or breaker height (cm), Ws is sand fall velocity ($m s^{-1}$) and T represents the time between waves in seconds. Beaches with $\Omega < 2$ are classed as reflective, $\Omega > 5$ denotes dissipative and, Ω values falling between 2 and 5 indicate intermediate beach states (Short 1999, Defeo & McLachlan 2005). There are also extreme examples of dissipative beaches classified as ultra dissipative before reaching the state of tidal flat (intertidal gradient flatter than 1/100), these areas usually have extremely fine sediments and tend to have a higher moisture content at low tides than higher energy beaches (McLachlan & Dorvlo 2005).

Dean's Parameter is a general model and does not take into account tidal range. It has been argued that spot measurements of wave height and wave period may be too variable to allow for accurate beach classification using Ω (McLachlan et al. 1993, Hacking 1998). Therefore, alternative, compound parameters of beach classification have been developed. Two of these aggregate measures, the Beach State Index (BSI) (a modification of Ω) and Beach Index (BI) include tide range. In addition BI also incorporates the beach slope (Defeo & McLachlan 2005). The formula for BSI is expressed as:

$$BSI = \log ([\Omega M / E] + 1)$$

where M is the maximum tide range (m) and E is a constant representing the maximum theoretical equilibrium tide for the earth covered in water ($E=0.8$).

BI is defined as:

$$BI = \log_{10} ([Mz \cdot TR] / S)$$

where Mz is the mean grain size (in phi units + 1, to avoid negative values), TR is the maximum spring tide range (m) and S is beach face slope (McLachlan & Dorvlo 2005). The BI has been found to be the most robust measurement in terms of beach morphodynamic classification (Rodil & Lastra 2004, Thompson 2005). Classification boundaries for each of the compound indices are shown in Appendix 1.

Physical Control of Beach Assemblages

Beach environments are extremely dynamic in space and time and also lack biological structures, thus their intertidal macrofauna assemblages have been considered physically controlled in terms of the Autecological Hypothesis (McLachlan & Dorvlo 2005). Essentially, this hypothesis reasons that, in physically controlled environments, communities are structured by the independent responses of individual species to the physical environment with biological interactions playing at best a secondary role (Noy-Meir 1979, McLachlan & Dorvlo 2005). This hypothesis has been extensively tested and it has shown that community attributes should correlate directly with physical environmental parameters on sandy beaches (McLachlan & Dorvlo 2005).

Since beaches are highly active physical environments, especially on the wave exposed coasts of eastern Australia, they undergo changes from one beach state to another in response to climatic conditions and seasonal variation (Short & Wright 1984, Hacking 1998). Thus, because macrofauna assemblages are considered to be primarily controlled by the physical habitat properties, assessments of any human impacts on beach biota must implicitly incorporate physical factors in design, analysis and interpretation (McLachlan & Dorvlo 2005).

Composition of Sandy Beach Macrofauna

The benthic macrofauna of beaches includes representatives of many phyla, but is usually dominated by crustaceans (mostly isopods, amphipods and decapods), polychaetes, and molluscs (Brown & McLachlan 1990, Defeo & McLachlan 2005). In a study of beaches on the New South Wales (NSW) coast, Dexter (1983) recorded 118 species of macrofauna. Of these, 65 species (55%) were crustaceans, 30 (25%) were polychaetes, 16 (14%) were molluscs and 7 (6%) comprised other taxonomic groups. Hacking (1998) also recorded 38 macrofaunal species from 10 NSW beaches. Sandy beaches are also important as nesting sites for turtles and birds, and foraging areas for both resident and migratory avifauna (Summers & Hockey 1980, Hosier et al. 1981, Rickard et al. 1994, Walsby 1996, Stephenson 1999, Colwell & Sundeen 2000, Lafferty 2001, Ruhlen et al. 2003, Burger et al. 2004).

Environmental Drivers of Faunal Assemblages

As the physical morphodynamic state of the beach is determined by tides, wave climate and sediment type, these forces are also the dominant drivers that control the dynamic habitat of the organisms that live on the backshore and foreshore (Brown 2001, Defeo & McLachlan 2005). On exposed beaches macrofauna communities have shown unique adaptations to deal with the prevailing physical disturbance by waves and storms. The ability to burrow within the sediment is an essential behavioural trait that helps these organisms to survive in extreme conditions (Brown 2001).

Macrofaunal assemblages have been well correlated with physical factors such as grain size, beach slope and wave/swash processes (Hacking 1998, Defeo et al. 2001, McLachlan & Dorvlo 2005). In relation to beach classification it has been shown that species richness and overall biomass of a beach increases from reflective to dissipative, with ultra dissipative beaches and tidal flats having high species richness and biomass (Defeo & McLachlan 2005).

Reflective beaches, because of their steepness, coarse sands, harsh swash climate and well-drained physical characteristics limit the availability of food and nutrients to interstitial fauna and macrofauna. These factors also affect the ability of organisms such as crustaceans, polychaetes and molluscs to burrow into the substrate and maintain their positions on the beach. Essentially, the low tidal variation of reflective beaches does not allow a vertical exposure gradient along which intertidal species can establish themselves (McLachlan & Dorvlo 2005). An analysis of the worldwide data by McLachlan & Dorvlo (2005) on macrobenthic communities indicated that steeper beaches with coarser sands and a low tidal range generally, have a lower incidence of species richness and abundance. This has also been linked to the Swash Exclusion Hypothesis (SEH), which states that species of macro invertebrates may be excluded from inhabiting beaches with harsh swash regimes (Defeo et al. 2001, Defeo & McLachlan 2005).

Dissipative beaches on the other hand, have high abundances of macrofauna and interstitial forms because of the benign nature of the swash climate (laminar flow), finer sediments, which retain food and nutrients, and because wave and swash action are distributed over a much broader surf zone. An increase in tidal range also tends to make beaches more dissipative allowing organisms a greater vertical exposure gradient so that species can establish themselves (Defeo & McLachlan 2005, McLachlan & Dorvlo 2005). The flatter more gentle gradient of the beach and benign swash climate allow filter feeding organisms, such as bivalves, to maintain their position on the beach and allows time for burrowing and feeding. The difference in tidal variation also allows other macrofauna, which occur on the upper backshore and foredune zones (e.g. ghost crabs) to forage on the upper intertidal areas of the foreshore during nocturnal low tides (Wolcott 1978, Barros 2001). Other authors have also suggested that macrofauna assemblages in surf zones tend to increase with depth across different types of beaches (Barros et al. 2002, Lastra et al. 2006).

Dominant Macrofaunal Species of Australian Beaches

Bivalve molluscs representing members of the Genus *Donax* such as *Donax deltoides* (Pipi or Eugarie), ocypodid brachyurans such as *Ocypode cordimanus* (ghost crab), naticid gastropods including *Polinices incei* (Moon Snail) and large polychaete worms such as *Australonuphis teres* (Giant Beach Worm or Kingworm), frequently dominate the beach benthos, in terms of biomass, in South East Queensland (Davie 1998, Hacking 1998). These common species of macrofauna are also found on the beaches of New South Wales and are often used for bait and food by recreational beach users (Dexter 1983, McLachlan et al. 1993, Davie 1998, Hacking 1998).

Human Encroachment of the Coastal Zone

Large-scale and extensive urbanisation of the coastal strip in many areas of Australia, especially in South East Queensland has substantially increased the intensity of recreational beach use (James 2000a, Jones et al. 2004, Moss & McPhee 2006). Many of Australia's beaches, particularly those on barrier islands such as Fraser Island and North Stradbroke Island, are highly sought after tourism destinations, leading to further increases in beach use (Hockings & Twyford 1997, Moss & McPhee 2006). Tourism and recreation frequently alter both the abiotic and biotic structures and processes of coastal environments even at low use intensities (Priskin 2003a-a, Jones et al. 2004).

Impacts by humans on coastal environments arise indirectly from development (mostly linked to tourism and urbanisation) and from direct interactions between nature and people (Priskin 2003a-b). Negative changes to coasts through hard engineering activities, including the development of seawalls, groins, marinas, and sand dredging are well documented (Fairweather 1990, Pigram & Ding 1999, Peterson et al. 2000, Brown & McLachlan 2002, Priskin 2003a-a, b). By contrast, the effects of direct interactions of humans with beaches are comparatively less well known (Priskin 2003a-b). Direct activities by humans

that interact with beach environments include swimming, walking, sunbathing, surfing, fishing, camping and four-wheel driving (Priskin 2003a-b).

Recreational Impacts on Beaches

The growth of populations in coastal areas, particularly in South East Queensland has increased dramatically over the last 10 years (ABS 2005). In the period from 2003-2004 South East Queensland coastal regions and city fringes recorded the highest growth rate in Australia. Brisbane and the Gold Coast's populations increased by 17, 600 and 13, 200 people respectively, the largest increases in population of all Local Government Areas (LGA's) in Australia (ABS 2005). Rapid population growth in these areas is expected to continue and with this growth, it is assumed that increasing pressures will be placed on the adjacent coastal strip. Many recreational activities are concentrated on the beach more so than any other coastal environment (Priskin 2003a-b).

Beach tourism and recreation, are generally considered to have moderate to severe impacts on the biota of beaches and dunes (Hosier & Eaton 1980, Brown & McLachlan 2002). In addition to ecological effects, recreational activities may alter physical characteristics of the beach such as sand stability (Anders & Leatherman 1987a, Arthukhin 1990, Brown & McLachlan 2002, Schlacher & Thompson 2006b). Activities such as swimming, walking, sunbathing, fishing and surfing are intensified as a result of continuing coastal development caused by the large internal migration of Australians to the coast (Priskin 2003a-b, Jones et al. 2004). A summary of the literature regarding recreational impacts such as pedestrian trampling and beach camping is essential when considering the overall view of impacts on beaches as some of these activities, either interact with, clash or compound vehicle impacts.

Pedestrian Impacts on Beaches

In terms of ecological impacts, recreational pursuits are frequently associated with trampling effects, that can often be concentrated in small pockets of intense use close to population centres (Liddle & Greig-Smith 1975a, 1975b, Hosier & Eaton 1980, Brown & McLachlan 2002). Trampling can significantly change soil properties and cause negative impacts to the vegetation and fauna of dune areas (Liddle & Greig-Smith 1975a, 1975b, Steiner & Leatherman 1981, Moffet et al. 1998a).

Beach users deem four-wheel driving to be extremely harmful to coastal ecosystems while pedestrian activities such as walking were considered to be mostly harmless (Priskin 2003a-b). Other studies conducted, have indicated that pedestrian traffic, in the form of walking or trampling, can have negative effects on dunes, beaches and soft sediment environments (Liddle & Greig-Smith 1975b, Hosier & Eaton 1980, Hosier et al. 1981, Carlson & Godfrey 1989, Hockings & Twyford 1997, Moffet et al. 1998a, Bernd-Cohen & Gordon 1999, Kutiel et al. 1999, Barros 2001, Milazzo et al. 2003).

The major focus of these studies has been on trampling effects associated with vegetation and soil compaction with the exception of Hosier et al (1981), Jaramillo et al (1996), Watson et al (1996), Moffet et al (1998), Lesesberg et al (2000), Lafferty (2001), Rumbold et al (2001), Thomas et al (2003), Zharikov and Skilleter (2004) and Burger et al (1994) who designed studies focusing on human disturbance and trampling effects to marine organisms including loggerhead turtles, delicate macrofauna crustaceans, juvenile bivalves and birds. These studies have indicated that intense pedestrian activity can crush crustaceans and juvenile bivalves, disturb the nesting and rearing behaviour of birds, and also affect turtle nesting behaviour. In their study on the effects of human activity on loggerhead turtles, Rumbold et al (2001) indicated that the turtles would completely avoid nesting on beaches that received high human activity, even though these beaches may have once been their native nesting sites.

It has also been stated in the literature that pedestrian impacts may be detrimental in terms of disturbing bird behaviour, but that other recreational impacts such as four-wheel driving may disturb the habitat and crush nests (Buick & Paton 1989, Burger 1994, Lord et al. 2001, Ruhlen et al. 2003, Thomas et al. 2003, Burger et al. 2004, Zharikov & Skilleter 2004). Other authors suggest that for certain species of shorebirds, such as the Pied Oyster Catcher (*Haematopus longirostris*), that disturbance from ORV traffic has no significant influence on their distribution (Owner & Rohweder 2003). However, as no baseline data exists (apart from anecdotal evidence) on the population dynamics of shorebirds on ORV impacted beaches in Australia, it is still uncertain whether which type of recreational use has the most detrimental affect on bird behaviour and distribution.

Other studies have identified human impacts that are associated with pedestrian traffic such as litter. Litter has become a major issue in many countries around the world (Brown & McLachlan 2002). Studies in the 1970's, (Ranwell 1972, Liddle & Greig-Smith 1975a), have already highlighted that litter was accumulating on dunes and beaches. Litter negatively affects surf-zone animals as well as fauna located further up the beach towards the backshore and dunes (Ranwell 1972).

The majority of the literature indicates that indirect hard engineering methods have detrimental effects on beach fauna, while direct interactions between humans and beaches through recreational activities have mild to severe impacts, with four-wheel driving rating as one of the most severe activities (Brown & McLachlan 2002, Priskin 2003a-b)

Off-Road Vehicle (ORV) Use on Sandy Beaches

Recreational activities such as four-wheel driving, beach camping and fishing impact on the biota of beaches and dunes, but generally are not concentrated

on urban beaches (Hosier & Eaton 1980, Steiner & Leatherman 1981, Wolcott & Wolcott 1984, van der Merwe 1988, van der Merwe & van der Merwe 1991, Kutiel et al. 1999, Stephenson 1999, Brown & McLachlan 2002, Thompson 2005). The impacts associated with these activities are being felt more on beach systems that are not localised to population centres. The impacts now extend to more previously isolated areas that were largely inaccessible fifty years ago (Hockings & Twyford 1997). These areas have now become more accessible to humans, mainly through the use of off-road vehicles (ORV's).

Since the advent of the four-wheel drive Jeep in World War II, use of dunes and beaches for recreational activities has become more widespread (van der Merwe 1988). The increase in economic development in the last century and increased technical innovation has led to more people being able to afford ORV's. The vehicles themselves have become easier to drive, and people now have more recreation time to use them (van der Merwe 1988, Fairweather 1990).

With the expansion of human development in coastal zones, humans are now broadening their recreational horizons directly related to ORV use. The "escape off the beaten track" mentality has firmly established itself in Australian recreational pursuits in the last thirty years (Priskin 2003b). Humans from a variety of backgrounds and professions are taking to the great outdoors with unprecedented enthusiasm. Many previously, relatively untouched coastal areas and beaches are one of the most highly sought after destinations. These areas are also extremely "ORV friendly", being close to urban areas and offering easy access to beaches and coastal dunes.

History Of Research on Vehicle Impacts on Beaches

A brief outline of the history of research on vehicle impacts on sandy beaches is represented in Appendix 2. A summary of the percent of published literature on vehicle impacts from a worldwide perspective is represented in Figure 3. This indicates that the majority of studies on ORV impacts on sandy beaches has

been conducted in the USA. Within these studies the greatest response variable assessed for impacts is vegetation (Fig. 4). Until recently little research has been completed in Australia. Of the available published literature on vehicle impacts to beaches in Australia before 2005, published studies completed only covered impacts to vegetation and birds (Appendix 2). Of the recent published literature (Moss & McPhee 2006, Schlacher & Thompson 2006b, a), two studies focused on macrofauna and one on physical disturbance to the foreshore by ORVs.

The first significant study into the impacts of vehicles in the coastal zone was conducted by Liddle & Moore (1974), which identified impacts associated with the creation of tracks through sand dune vegetation (Stephenson 1999). Earlier literature associated with vehicle use has been documented (American Association for the Advancement of Science, 1973), although this was in relation to desert environments in California (Steiner & Leatherman 1979). Liddle (1974) followed up his examination of impacts to dunes with two more experimental studies on the nature of impacts to vegetation (Liddle & Greig-Smith 1975b) and soil (Liddle & Greig-Smith 1975a).

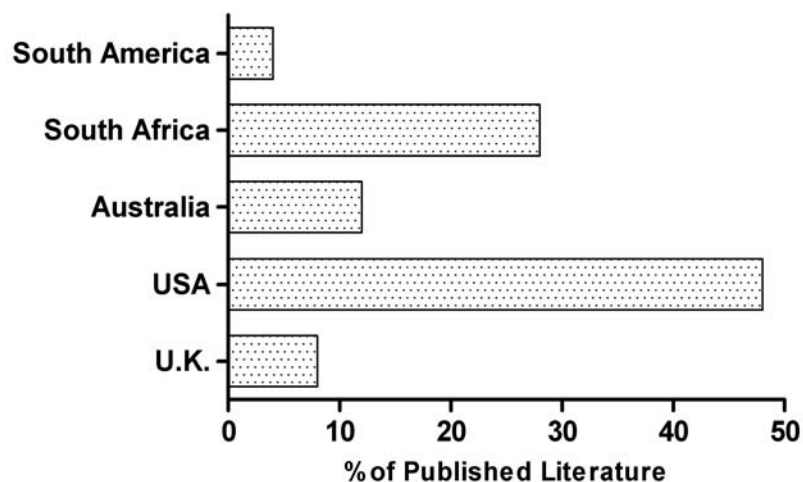


Fig. 3 Countries that have produced the greatest percentage of published literature on the impacts of vehicles on sandy beaches (n=28).

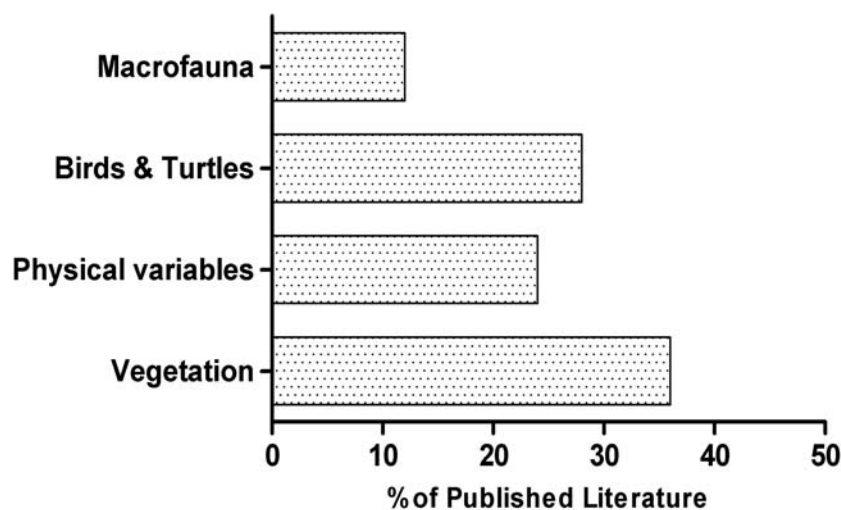


Fig. 4 Flinders Beach, April 2005, indicating the physical disturbance to the foreshore caused by ORV traffic. In some places especially in the softer sand, track depths were up to 25 (cm) deep.

In America from 1973 to 1979 numerous experimental studies were undertaken by the University of Massachusetts / Amherst, National Parks Service Cooperative Research Unit to identify impacts to the Cape Cod National Seashore in relation to off-road vehicles and pedestrian traffic (Stephenson 1999). The studies were designed to assess impacts on beach, salt marsh and tidal flat ecosystems (Stephenson 1999). Research findings were summarised later in an annotated bibliography by Steiner & Leatherman (1979) and by Godfrey et al. (1980) and Godfrey (1981).

In the 1980's further research was undertaken in America, South Africa and Australia. In America research was undertaken in relation to off-road vehicle effects on the beaches and dunes of barrier islands (Stephenson 1999). Principle experimental analysis of vehicle impacts to vegetation (Hosier & Eaton 1980, Godfrey 1981, Anders & Leatherman 1987b), beach macrofauna including crustaceans and surf clams (Steiner & Leatherman 1981, Wolcott & Wolcott 1984), turtles (Hosier et al. 1981), physical characteristics of sediment structure (Anders & Leatherman 1987a) and other abiotic and biotic characteristics of beaches and dunes (Abele et al. 1984, Anders & Leatherman 1987a, Carlson &

Godfrey 1989) have provided a general insight into what impacts can occur, how they occur, and which zones of the beach are most sensitive to vehicle impacts.

In South Africa, the concern of uncontrolled and unrestricted vehicle access to pristine beach ecosystems and continued coastal development prompted research initiatives to quantify environmental impacts (van der Merwe 1988). A review of impacts to the coastal zone was undertaken by van der Merwe (1988), which established what potential and actual impacts may or have occurred to these environments. This led to further studies in South Africa with regards to the impacts of trampling and recreation in the littoral active zone (Heath 1987, Moffet et al. 1998b), the quantitative examination of vehicle impacts to fauna in the intertidal zone (van der Merwe & van der Merwe 1991), a survey of off-road vehicle use on the Eastern Cape of South Africa (Els & McLachlan 1990), impacts on dune vegetation by vehicular and pedestrian traffic (Rickard et al. 1994) and other (e.g. impacts to birds and turtles) simulated anthropogenic disturbances (Rickard et al. 1994).

In Australia, until recently there has been limited research conducted on vehicle impacts to beaches but also very little published research on other recreational disturbances such as trampling, beach camping and fishing. Although a number of published studies have been conducted on beach ecology in Australia (Dexter 1983, 1984, 1985, Fairweather 1990, Murray-Jones & Ayre 1997, Davie 1998, Hacking 1998, Barros et al. 2002), up until 2005, only four have measured the impacts of ORV's, and these are limited to birds and dune vegetation (Gilberstson & Foale 1977, Buick & Paton 1989, Hockings & Twyford 1997, Priskin 2003b). Two other studies have observed the increase in physical and vegetative disturbance caused by ORV activity by analysing aerial photographs over given time frames, but they did not quantitatively measure the extent of impacts (Hockings & Twyford 1997, Priskin 2003b).

Of information available concerning ORV impacts on intertidal organisms of Australian beaches, there are two Honours theses (Bell 2002, Hastie 2002), which provided inconclusive results due to design problems (e.g. spatial replication, amount and duration of simulated vehicle impacts). Also, a recent study by Moss and McPhee (2006) provided data on the impacts of ORVs to the ghost crab *Ocypode cordimana*. In this study the authors used ghost crab burrow counts as a tool to assess ORV impacts on crab populations between beaches with and without ORV traffic. More recent studies undertaken by researchers from the University of the Sunshine Coast have also provided much needed information regarding ORV impacts to intertidal organisms and beach habitat disturbance (Thompson 2005, Schlacher & Thompson 2006b, a).

The first major study, which incorporated observations of recreational impacts to beaches, dunes and other coastal habitats was published by the Nature Conservation Society of South Australia in 1977. This study into four-wheel drive vehicle impacts examined beaches in the Coorong area of South Australia. The study analysed the impacts of four-wheel drive vehicles on Hooded Plovers (*Charadrius rubricollis*) and assessed whether these impacts affected their ability to nest (Buick & Paton 1989). Public perceptions of nature-based tourism, including four-wheel drive use, were investigated by Priskin (2003a), which also assessed the physical impacts of four-wheel drive related tourism.

Apart from other recommendations in legislative guidelines there is still relatively little published scientific literature available on the impacts of four-wheel drive vehicle use especially in the South East Queensland region. Although this is the case, some Shire Councils have endeavoured to establish management strategies to help curb perceived impacts. Noosa Shire Council under a recommendation in the *Noosa North Shore Management Strategy (2003)* have taken steps to prepare and implement a programme to assess the long-term impacts of vehicle activity on the beach and associated foredune areas on the Noosa North Shore (Summers 2005). Redlands Shire Council have also made

recommendations to assess four-wheel drive impacts on the beaches of North Stradbroke Island (Carter 2005). This highlights the need for the collection of comprehensive quantitative data so that management options may be implemented appropriately. Basing management options on factual data is of great importance as long term data collection will help establish present and future trends in fauna and flora distribution patterns on impacted and non-impacted beaches.

Vehicle Impacts on Sandy Beaches

As has been outlined above, the literature on ORV impacts on beaches stems back to the mid 1970's. The vast majority of studies were conducted overseas with little published literature relating to vehicle impacts in Australia, and none for Queensland beaches, with the exception of three recent papers by Moss & McPhee (2006) and Schlacher & Thompson (2006) on ORV impacts on the abundance of ghost crab burrows on North Stradbroke Island. Of the early studies undertaken by researchers the majority of research that actually focused on vehicle impacts to the intertidal ocean beach stemmed from the Cape Cod area in the USA and later in South Africa (Steiner & Leatherman 1979, van der Merwe 1988, van der Merwe & van der Merwe 1991).

Vehicle Impacts to Physical Beach Processes

Although there is a widespread perception and a wealth of anecdotal observations that vehicle traffic degrades the physical morphology of the beach (Fig. 5), there are few scientific studies available that actually quantify damage due vehicle use (Atkinson & Clark 2003). One of the main reasons for this lack of quantitative evidence is because almost no baseline data exists about the condition of beaches before vehicle use has occurred (Atkinson & Clark 2003).



Fig. 5 Flinders Beach, April 2005, indicating the physical disturbance to the foreshore caused by ORV traffic. In some places especially in the softer sand, track depths were up to 25 (cm) deep.

Initial investigations into the effects of vehicle traffic on the physical characteristics of the foreshore and backshore zones by Leatherman & Long (1978) indicated that vehicle tracks increased the surface roughness of impacted beaches in relation to beaches, which did not receive any vehicle traffic. This increase in surface roughness resulted in larger and higher velocity turbulent eddies near the surface of the foreshore, thus increasing sand transport. The impacted site thus had more mobile sediment available for natural erosion and accretion mechanisms. The authors indicated that vehicle traffic, especially on the higher shore increased the instability of embryo and active dune systems making impacted areas more prone to heavy storm erosion.

By contrast, subsequent research showed that on backshore areas that may be affected by aeolian transport mechanisms, the tracks can act as sediment traps resulting in accretion (Anders & Leatherman 1981). The study did not specify whether these erosion and accretion effects caused by off-road vehicles offset or enhanced natural geomorphologic rhythms.

Early studies of sand transport on beaches have indicated that sand exchange between offshore and onshore deposits are about 150 m³ per annual cycle of sediment exchange (Niedoroda 1975). In terms of the geomorphic state of beaches, van de Merwe (1988) concluded that the annual cycle of onshore and offshore sediment exchange is compounded by vehicle activity and increases the availability of sediment to natural erosion and accretion mechanisms. Essentially, this means that incremental increases in the availability of sand to existing physical transport processes could greatly influence the natural dynamics of sand transport over an annual period. However, Smith and Guastella (2002) state that any additional change induced by vehicle traffic to beach morphology must be analysed with caution if a lack of baseline data on the pre-existing natural changes of the beach in question is unavailable.

A later study on sediment transport undertaken by Anders & Leatherman (1987) indicated that vehicle use of the beach at Fire Island, New York could be contributing to overall erosion rates of the beach by delivering large quantities of sand to the swash zone (max. of 119,300m³/yr). The authors found that the key factors influencing the seaward transport of sand include beach slope, sand compaction, the number of vehicles passes over a given time period, tyre pressure and the size and weight of the vehicle. They suggest that increased amounts of sediment may be transported by aeolian and hydraulic processes due to incremental disturbance by vehicles. Thompson (2005) and Schlacher & Thompson (2006) also found that sand displacement was a key function of beach slope, number of vehicle passes and sand moisture content as well as where on the beach the traffic is concentrated. Both the amount of sediment transported to the swash zone and the amount removed by aeolian and hydraulic processes in relation to vehicle activity would have to be measured to get an overall indication as to the extent of sand movement caused by vehicle activity (Anders & Leatherman 1987a).

Schlacher & Thompson (2006) also found that intense ORV traffic can cause significant amounts of sediment to be disturbed and displaced. The authors found that on North Stradbroke Island, Australia, during a heavy traffic period, up to 50, 591m³ of sand could be displaced of which 49-55% originates from the middle to upper shore. Of the beaches sampled the majority of sand displacement occurred in a narrow band on the middle to upper shore, which only equated to 13-36% of the beach width.

The type and size of sand particles, and whether they are saturated or not, also play significant roles in determining whether the sediment is likely to be eroded or not (Smith & Guatella 2002, Thompson 2005, Schlacher & Thompson 2006b). Fine, wet sand in the intertidal zone is less likely to be displaced than drier, soft sand further up the beach (Smith & Guatella 2002, Schlacher & Thompson 2006b). But there is evidence to suggest that continual traffic over the wet sand may increase the rate at which the sand dries out (Smith & Guatella 2002, Thompson 2005, Schlacher & Thompson 2006b). This combined with fine weather and moderate to strong winds may increase the availability of sand for aeolian transport.

It is widely accepted that lower tyre pressure reduces the amount of sand displaced during vehicle passes and lessens sand compaction as the vehicle weight is distributed over a wider surface area (Smith & Guatella 2002). The amount of compaction that occurs as a result of vehicle passes in the intertidal zone is thought to be minimal in relation to the natural physical wave and swash processes, which act to flatten and compact the sand (Atkinson & Clark 2003). However, Thompson (2005) found that moisture content and the path the vehicle takes can also influence sand compactness. In sand with a moisture content below 18% vehicles tend to decrease compactness, while under more saturated conditions ORV traffic tends to harden the sand (Thompson 2005). Vehicles that are consistently turning on the beach will in almost all cases displace and soften the sand and as straight vehicle passes increase (>75

passes) the sand will predominantly soften regardless of moisture content (Thompson 2005).

Conversely, on the drier, softer sand of the upper beach, tyres can penetrate up to 20cm into the sand, depending on tyre width, vehicle weight and driver behaviour, displacing sand and increasing the rate of beach erosion by as much as 25% (Leatherman & Godfrey 1979, Atkinson & Clark 2003, Schlacher & Thompson 2006b). The first initial passes along the beach tend to displace the most sand with each successive pass resulting in less sand removal (van der Merwe 1988). However, continued heavy traffic will compound initial sand displacement (Schlacher & Thompson 2006b).

The negative effects of driving on the foredune and active dune areas is well documented, and on most beaches with vehicle access, driving on these areas is prohibited (Atkinson & Clark 2003). The main concerns in regards to driving on the backshore and foredune areas are that they will become destabilised through vegetation removal and the subsequent supply of sand for aeolian transport, thus making them more susceptible to storm erosion (van der Merwe 1988, Atkinson & Clark 2003).

The shear force between the vehicle tyres and the beach surface acts to push the sand in the opposite direction to which the vehicle is travelling creating sand displacement (Atkinson & Clark 2003). This shear stress does not only impact the surface layers but can be transmitted to depths of up to 30 (cm) into the substrate (van der Merwe 1988, Atkinson & Clark 2003). This is an important point as macrofauna and other interstitial forms are commonly found in the upper 30 (cm) layers of the substrate and this added stress may affect their behaviour or directly crush and kill them (van der Merwe 1988, van der Merwe & van der Merwe 1991, McLachlan et al. 1993).

Vehicle Impacts to Dune Vegetation

The negative impacts of ORV traffic on dune vegetation is well documented (Brown & McLachlan 2002). As yet few data exist for Australian beaches. Vehicle traffic across the stable and active dune zones to access the beach causes major changes to dune vegetation (Liddle & Greig-Smith 1975b, Broadhead & Godfrey 1977, Godfrey 1981, Abele et al. 1984, Anders & Leatherman 1987b, Bernd-Cohen & Gordon 1999, Brown & McLachlan 2002). Removal of this vegetation increases erosion of dune sediments (Liddle & Greig-Smith 1975b, Broadhead & Godfrey 1977, Anders & Leatherman 1987b).

Early studies on vehicle impacts to dune vegetation by Liddle (1975) and Broadhead & Godfrey (1977) have shown that it is the first few vehicle passes that cause most of the damage. After a summer season of vehicle traffic that consisted of approximately 600-700 vehicle passes over vegetated dune areas, the above-ground vegetation was completely destroyed (Broadhead & Godfrey 1977). Enough underground roots and rhizomes were, however, still in existence at the end of the season, so that small amounts of vegetative re-growth could occur through the late summer and autumn (Broadhead & Godfrey 1977).

Later studies undertaken in Australia by Hockings & Twyford (1997) and Priskin (2003) have used aerial photography to assess the extent of impacts of vehicle use and dune camping. Hockings & Twyford (1997) conducted their experimental study on Fraser Island analysing camping and vehicle impacts, spatial and temporal patterns of camping and vehicle use, and the associated environmental impacts. Aerial photographs from 1974, 1982 and 1994 were the primary tools used for assessment combined with ground surveys. The results indicated an increase in areas classed as moderate to high impact from 34% in 1974 to 64% in 1994. Also the number of low impact areas increased from 1982 to 1994.

Priskin (2003) provided a more robust examination of the expansion and use of vehicles on beaches in the Central Coast region of Western Australia. Aerial photographs from 1965 and 1998 were compared and the length and amount of tracks were examined as well as the number of access points. The results indicated a 57.3% increase in vehicle tracks as well as a 115.7% increase in the number of access points to the beach. The highest mean track density in 1965 was concentrated around rocky promontories in sheltered areas whereas in 1998 the highest mean track density was concentrated on the cusped forelands of exposed beaches. From 1965 to 1998 exposed beach usage increased by 137.8% and exposed beaches were receiving a significantly higher rate of use than sheltered beaches.

The results indicate that in this region off-road vehicle use has become an uncontrolled activity and the overall impact on the environment will increase with increased use (Priskin 2003b). It was found that approximately 2500 km² need rehabilitation due to damage caused by off-road vehicle use. The author also states that biotic indicators may have given a more comprehensive view of the levels of degradation.

The drift line is another important component of the backshore and foredune areas that is prone to impacts from vehicle traffic especially during high tide. The wrack deposited at the drift line is habitat to a range of organisms (Dugan et al. 2003). ORV damage to the deposited wrack can have negative effects on these wrack associated assemblages (van der Merwe & van der Merwe 1991). The drift line, which is the position of the swash uprush during high tide, is often the area where deposits of seeds, organic matter and plant fragments are found (Dugan et al. 2003). The organic matter is rapidly broken down by bacteria and fungi and nutrients are thus released back into the sand providing food for macrofauna, meiofauna and shorebird communities (Dugan et al. 2003).

The literature also indicates that the drift line is where new dune systems are created and the vegetation in these areas tends to recover faster than that of established dunes (Rickard et al. 1994, Dugan et al. 2003, Olivier & Garland 2003). Rickard et al (1994) found that vegetation assemblages in pioneer dune systems recover faster after vehicle impacts than established dune shrub assemblages. This is due to the pioneer species fast growth rate, while established dune shrubs exhibit signs of damage for longer periods. The authors also found that a single application of high intensity impact resulted in an initial decline in vegetation height and cover immediately after the impact, which was followed by further decline over the next three months.

Washed up seeds grow into plants, trapping sand and slowly creating embryo dunes (Atkinson & Clark 2003, Dugan et al. 2003). The impact of vehicle traffic across the drift line acts to disperse organic matter and destroy seedlings, thus interfering with natural dune creation (Leatherman & Long 1978, Leatherman & Godfrey 1979). Also the sand around the drift line is often soft allowing vehicle tracks to penetrate deep into the substrate influencing the feeding behaviour of organisms such as isopods, terrestrial amphipods, crabs and birds (Leatherman & Long 1978, Leatherman & Godfrey 1979, Dugan et al. 2003).

Vehicle Impacts to Beach Fauna

Invertebrates

Although the focus of this study is on the impacts to the beach macrobenthos, studies on the impacts to other beach fauna will also be briefly reviewed in an attempt to gain an overall understanding of the influence of vehicle activity on the beach biota. Studies on vehicle impacts to beach organisms originated in the Cape Cod area of the USA with early studies investigating meiofauna populations and other interstitial forms such as micro algae and bacteria (Steiner & Leatherman 1979, van der Merwe 1988, Stephenson 1999). These early studies found that due to the high variability amongst samples, effects of vehicle damage were often indistinguishable from natural variation (Leatherman & Long 1978, Godfrey 1981). This does not imply that no traffic impacts actually occurred, but rather highlight inadequate design protocol (e.g. spatial and temporal replication) as limitations to show such effects. Nevertheless, bacteria communities associated with the drift line were found to be impacted quite severely by vehicle activity, which dispersed and obliterated the organic material that these organisms feed on (Leatherman & Godfrey 1979, Godfrey 1981).

Wolcott & Wolcott (1984) assessed vehicle damage to *Emerita talpoida* (mole crab), *Donax variabilis* (surf clam) and *Ocypode quadrata* (ghost crab) on Cape Lookout National Seashore, North Carolina. Vehicle damage to ghost crabs was found to be a function of the crab's activity rhythms between day and night. During daylight hours the crabs are inactive inside burrows, which appears to buffer any impact of vehicles passing overhead. In stark contrast, during the night ghost crabs emerge from their burrows to forage and feed on the foreshore (Wolcott 1978), where they suffer heavy mortalities from ORV's travelling at night (Wolcott & Wolcott 1984). Over four nights of sampling, where the authors completed single passes along a 5 km stretch of beach they observed an average of 77 crab mortalities per linear kilometre. In one instance ghost crab

activity was high and over 500 crab mortalities were observed after a single vehicle pass.

The ghost crabs tended to be disorientated by the headlights of the vehicles and instead of fleeing the approaching light, seemed to become deranged, actually running towards the source of the light and were crushed under the oncoming tyres. Although nocturnal mortalities were quite significant, minimal vehicle activity was observed during night hours. However, the authors suggest that even low traffic intensities during the nocturnal hours would greatly reduce ghost crab populations.

Although there were no significant mortalities shown for the surf clams, 1.4% of mole crabs mortalities were crushed by vehicles. This did not differ significantly from the control sites and could have been due to handling error. The authors imply that the protection offered by the sand combined with behavioural traits and the physiology of the mole crabs and surf clams (e.g. burrowing ability) meant that direct impacts (mortality) caused by vehicles was minimal.

The overall conclusions of the research indicated that surf clams show no vulnerability and mole crabs only show vulnerability when directly crushed. The ghost crabs show no vulnerability during the day when they retreat to their burrows, but that they are quite susceptible to impacts at night when they come out to forage. Predicted mortalities calculated from observed kills of ghost crabs per vehicle-kilometre ranged from 14-98% for 100 vehicle passes (Wolcott & Wolcott 1984). The authors recommended that recreational vehicle use is restricted to daylight hours.

Other studies conducted using ghost crabs as the response variable found up to four-fold and ten-fold differences between ghost crab populations in areas that were open and closed to beach driving in North Carolina, USA (Steiner & Leatherman 1981). Steiner and Leatherman (1981) found that beaches

receiving vehicle traffic had significantly lower densities of ghost crabs than beaches that received no use or light pedestrian traffic. The mean densities of crabs per 0.1ha plot was 10 on the undisturbed site, 19 on the site that received pedestrian use only, 1 on the pedestrian and vehicle impacted site and 0.3 on the site that received heavy use of vehicles. They also found that the size of crab burrows were significantly smaller on the vehicle sites compared to those found on the undisturbed and pedestrian beaches.

Both direct and indirect impacts of vehicles on crabs must be taken into consideration. Steiner and Leatherman (1981) emphasize that direct impacts of vehicles such as crushing, damage and burying are major concerns, but that the indirect disturbance caused to their habitat may be more damaging in the long term affecting reproductive cycles and crab behaviour. The major focus of the study by Steiner & Leatherman (1981) was to determine whether beaches that were subject to different recreational uses (vehicles, pedestrian) influenced the number of ghost crabs (*Ocypode quadrata*) that occupied these beaches. The major conclusions were that vehicle disturbance probably results in fewer crabs with no reproduction and new inhabitants migrating from undisturbed areas. The authors also concluded that pedestrian traffic has no harmful effects on crabs and they suggest that the crabs may even capitalise on food scraps left by pedestrians.

Barros (2002) in his study comparing ghost crab (*Ocypode cordimana*) densities between urban and non-urban beaches found that the number of ghost crab burrows was greater on non-urban beaches than on urban beaches. The author therefore concluded that human activity on beaches appears to affect ghost crabs in some way, but emphasizes that how this occurs is not clearly understood. Barros (2002) also suggests that the results of the research conducted by Steiner and Leatherman (1981) must be considered with caution, as spatial replication was minimal. Barros (2002) suggests that, as a result of his research, the worldwide genus of *Ocypode* could be used as a tool for rapid

ecological assessment between beaches that receive different types of human use. This assessment involves using burrow numbers and size as the response variable, which would determine actual densities as well as providing insight into whether the crabs are reaching sexual maturity.

Moss & McPhee (2006) used Barros (2002) study methods to assess impacts of ORVs on the ghost crab *Ocypode cordimana* on four beach sites on North Stradbroke Island. Two sites were classed as control sites and two were classed as impact sites. The results of their study indicated that the number of ghost crab burrows were significantly less on impacted beaches than on non-impacted beaches. However, there are certain factors in relation to this study, which make the results inconclusive. Firstly, at least two species of ghost crabs exist on the beaches studied including *O. cordimana* and *O. ceratophthalma* (Davie 1998). Secondly, one of the control sites does receive ORV traffic although only in restricted amounts. Thirdly, the authors do not make it clear, whether they counted active or emergent burrows or both as only active burrows tend to have crabs residing in them (Barrass 1963).

Of the three (50m long, parallel to the water line x 1m wide) sampling lines used, one was located on the high water mark and the other two were located within four metres of the first sampling line. Thus, the authors did not cover a great deal of the upper shore area on the beaches studied. Other studies (Thompson 2005, Schlacher & Thompson 2006b) have shown that the upper shore can extend up to 40m above the high water mark to the foredunes. Thus, the study does not give a comprehensive analysis of actual *O. cordimana* populations between beaches. This species of crab has also been observed to inhabit upper shore areas, with *O. ceratophthalma* inhabiting the shore lower down the beachface (Schlacher & Thompson unpubl. data). The authors also state that night-time traffic on Flinders Beach could be the dominant factor influencing differences in population sizes between control and impact sites. However, during a heavy recreational traffic period (Christmas Holidays 2005) night traffic

appeared to be relatively low or non-existent on Flinders Beach (Schlacher & Thompson, unpubl. data). Therefore, the results of the study must be interpreted with caution in terms of assigning ORVs as the dominant function influencing the differences in ghost crab populations between beaches.

Van der Merwe & van der Merwe (1991) quantified the mortalities caused by vehicles on intertidal and supratidal macrofauna by experimenting at Sundays River Beach, South Africa. The species investigated included the bivalves *Donax serra* and *Donax sordius*, the gastropod *Bullia rhodostoma*, the mysid *Gastrosaccus psammodytes* and the air breathing isopod *Tylos capensis*. Damage inflicted to small and large individuals of the gastropod *Bullia*

rhodostoma was the same at low intensity impacting (5 vehicle passes) (van der Merwe & van der Merwe 1991). High intensity impacts of 50 vehicle passes did result in direct mortalities although the percent of mortalities out of the sample population was relatively small (Fig. 6). 8.6 % mortalities were observed for 50 vehicle passes in 1 hour and 0.6 % for 50 vehicle passes in 24 hours. This shows that higher intensity impacts cause greater mortalities if the intensity of impacts is concentrated within shorter periods (van der Merwe & van der Merwe 1991).

High intensity treatments of 50 vehicle passes in 1 hour on both large and small *Donax serra* damaged 7.4% of large individuals and 6.3% of small individuals. The same mean % of damage was recorded for 50 passes in both 1 and 24 hours (van der Merwe & van der Merwe 1991). For *Donax sordidus* of unspecified sizes the mean % damage was 2.9 for 50 passes in 1 and 24 hours (van der Merwe & van der Merwe 1991). After the original design used to test the response of the mysid *Gastrosaccus psammodytes* to vehicle impacts resulted unnatural mortalities a second more natural sampling method was employed. This involved sampling in vehicle tracks (treatment) and sampling beside the tracks (control) after 50 passes (van der Merwe & van der Merwe

1991, Stephenson 1999). No significant differences were found between the control and treatment samples and no animals were damaged using this sampling method.

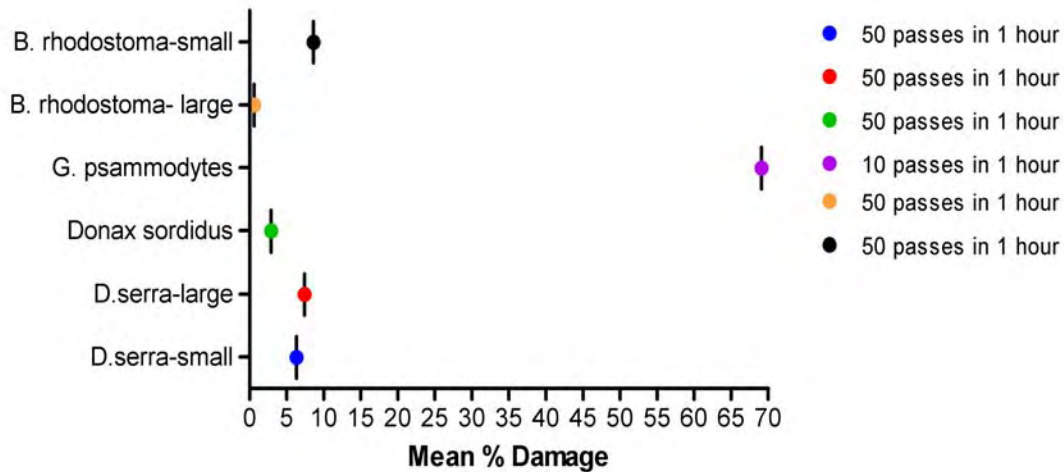


Fig. 6 The mean percent damage to intertidal organisms after 50 ORV passes, in 1 hour (van der Merwe & van der Merwe, 1991).

The supratidal species *Tylos capensis* received low (10 passes), medium (25 passes) and high (50 passes) intensity treatments (van der Merwe & van der Merwe 1991). The number of *Tylos capensis* that were completely crushed or that had cracked exoskeletons increased linearly with the increase in impact intensity. Ten percent of individuals sustained damage at 17 passes with over 30% sustaining damage at 50 passes (van der Merwe & van der Merwe 1991).

The main conclusions of the study appear to indicate that the damage inflicted on the intertidal forms considered was negligible (0-5%). What the authors do not mention is the cumulative impacts to populations or exponential decline of species due to ORV impacts. This would suggest that if 5% mortalities of intertidal forms were observed in a single day than 100% may be observed in 90 days.

The amount of damage inflicted on the isopod *Tylos capensis* on the upper beach was considerable and the authors suggest that the tendency for drivers using this area to follow in the same tracks accentuates this. The study indicated that the intertidal macrofauna are relatively immune to impacts even at relatively high intensities provided that they are buried and the sand was reasonably compact (van der Merwe & van der Merwe 1991, Stephenson 1999). Direct mortalities to these individuals occur if they are exposed on the surface of the sand except for the gastropod *Bullia rhodostoma*, which proved to be relatively robust enough to withstand direct impacts when exposed on the surface of the beach (van der Merwe & van der Merwe 1991, Stephenson 1999). The authors concur with Wolcott & Wolcott (1984) and recommended that vehicles be restricted to the area below the high water mark and that driving only be permitted at low tide during daylight hours.

In Australia, an Honours thesis completed by Hastie (2002) through the University of New England, looked at the impacts of vehicles on beach macrofauna. The experiment was conducted on Arrawarra Beach on the northern coast of NSW. The experiment was based on a Before After Control Impact (BACI) design and the 5 response variables examined included the total number of individuals, species richness and the abundances of the three most common species, the isopod *Pseudolana concinna*, the Ghost Crab *Ocypode cordimana* and the polychaete blood worm *Lobochesis longiseta*.

The study examined the response of the above five variables to three intensities of vehicle impact. Low intensity impact was 10 passes, medium intensity impact was 20 passes and a high intensity impact of 40 passes. Each of the different vehicle intensities were replicated twice, spatially and two control sites were also observed. Two pre-impact samples were taken as well as five post impact samples ranging from 1 day, 1 week, 1 month, 2 months and 4 months after the impact experiment was conducted.

The results of the experiment indicated that no statistically significant impact was observed in regards to any of the five response variables between the different impact treatments and the control sites. The author concluded that any observed variations between the samples was due to the natural physical processes that govern the abundance and diversity of organisms on sandy shores. It was concluded that although the study did not find any evidence of vehicle impacts on Arrawarra Beach this is not to say that greater intensities of vehicle traffic over a longer period of time will not cause impacts on beach macrofauna (Hastie 2002).

Another Honours thesis conducted by Thompson (2005) from the University of the Sunshine Coast tended to add further weight to the results of van der Merwe and van der Merwe's (1991) paper. The thesis identified 3 important aspects of the interaction between ORV use and beach macrofauna, including:

- 1) The spatial and temporal patterns of traffic on beaches ('driver behaviour') and the extent to which this traffic overlaps with that of the macroinfauna,
- 2) The degree that ORVs cause direct mortality to invertebrates of the intertidal zone, and
- 3) Shifts in assemblage structure (species composition and abundance) between beaches with and without ORV traffic.

Driver behaviour and the spatial and temporal position of vehicles driving on the shore were quantified on 5 beaches in South East Queensland (3 on North Stradbroke Island and 2 on Noosa North Shore and Teewah Beach). Comparisons were then made with the occurrence of invertebrates across the beach face.

Mortalities of invertebrates were experimentally assessed for a key member of the intertidal community-the beach clam *Donax deltoides* (Pipi or eugarie)-by subjecting clam populations in the field to traffic intensities ranging from 5 to 100

vehicle passes. Finally, faunal community structure was quantitatively compared between two beaches from which ORV traffic is excluded (Peregian and Sunrise), and two morphologically similar beaches (Noosa North Shore and Teewah) on which traffic occurs year round.

The results of the study indicated that despite claims that ORVs use the compact lower shore (and most drivers do indeed migrate down-shore with falling tides), a considerable fraction of beach traffic (23-67%) traversed the softer sections of the upper beach near the foredunes. This traffic considerably altered the physical beach environment, at times causing deep-rutting and substantial sand displacement. These findings were further supported by a later study by Schlacher & Thompson (2006) on North Stradbroke Island, which also found that ORVs cause severe disruptions to the sediment matrix on the mid to upper shore.

Thompson (2005) and later Schlacher & Thompson (2006) found that species, which predominantly inhabit the swash zone, appear to be less affected by traffic as few (if any vehicles) drive on this area of the beach. By contrast, it was found that species that occur mostly in the middle and upper section of the beach are heavily impacted by ORVs. This was found to be because their distributional ranges overlap with that of the traffic and the invertebrates mostly affected included, isopods, ghost crabs and (to a variable degree) beach clams. Schlacher & Thompson (2006) later extrapolated these results for publication and found that up to 65% of burrowing invertebrate species of the intertidal zone are directly exposed to traffic, save for species inhabiting the swash zone.

Thompson (2005) found that direct crushing of beach clams can be substantial and the results were found to be in line with van der Merwe & van der Merwe's (1991) study, which used similar methods to quantify ORV impacts to beach clams. Thompson (2005) found that the proportion of clams crushed by ORVs was found to be a direct function of traffic intensity and sand compactness. The

author found that negligible numbers of clams are crushed by low traffic intensities (5 passes or less), but rises to ~10-30% at 100 vehicle passes. Clam mortality is greatly increased by turning vehicles with up to 50% of clams being crushed at medium traffic intensities of 40 to 75 passes, particularly in soft sand. The results of the study also showed that shifts in faunal assemblages are clearly detectable in the upper section of the beach face near the foredunes on beaches that are subjected to intense ORV traffic.

Shorebirds and Turtles

Other fauna that are prone to vehicle impacts on the backshore and foreshore areas are species of birds and turtles that use these areas for nesting and feeding. Several species of birds and turtles nest on the backshore of the beach above the high water mark (Stephenson 1999, Cornelius et al. 2001). In Australia, the impact of ORVs on the nesting success of hooded plovers was examined in the Coorong region of South Australia. Buick & Patten (1989) used artificial nests to observe how many nests may be impacted on a daily basis. The authors found that on average 6% of nests were run over per day and concluded that over the incubation period that 81% of nests may be run over on the beaches studied. The authors also observed a low rate of fledgling success and this suggested that the use of vehicles potentially reduced the reproductive output of hooded plovers in the region (Buick & Paton 1989, Stephenson 1999).

Birds can often acclimate to vehicle traffic passing close to their nests, but are more prone to become agitated when dogs or people come close to nesting areas (Godfrey & Godfrey 1980, van der Merwe 1988, Watson et al. 1996, Cornelius et al. 2001, Atkinson & Clark 2003). In many instances though, if the birds are forced to vacate nesting sites and the eggs left exposed they can overheat and developing chicks can perish (Brokensha 1984, van der Merwe 1988). Shore-nesting birds are more prone to impacts from ORVs on narrow beaches and traffic becomes concentrated towards nesting areas, when vehicle

activity is pushed upshore during high tides (Brokensha 1984, van der Merwe 1988, Atkinson & Clark 2003).

In South Africa, off-road vehicles have been found to have negative effects on the feeding and breeding habits of Oystercatchers (*Haematopus moquini*), Whitefronted plovers (*Charadrius marginatus*) and the rare Damara tern (*Sterna balanaerum*) (van der Merwe 1988, Watson et al. 1996, Leseberg et al. 2000). Also juvenile Sandpipers suffer high mortalities because they tend to hide in vehicle tracks on the high shore. Drivers will often use the same tracks as previous drivers and the birds are consequently run over by the successive passes (van der Merwe 1988).

Turtle species such as the leatherback (*Dermochelys coriacea*) and loggerhead (*Caretta caretta*) may avoid nesting on beaches adjacent to human settlements (Hosier et al. 1981, Kikukawa & Kamezaki 1999, Atkinson & Clark 2003). Females and their hatchlings are most exposed to vehicle impacts during nesting and hatching periods (Hosier et al. 1981). Effects on turtles may include:

- Hatchlings may become entrapped in their nests if numerous vehicle passes occur over them
- Churning of the sand on the high shore adjacent to the high water mark may cause the nests to become exposed thus resulting in a failure of juveniles to hatch
- Once hatched, the juveniles trying to make their way to the ocean may crawl into a deep tyre track and continue along the track, which runs adjacent to the shoreline. This may result in direct mortality in the form of crushing by another vehicle pass or exhaustion from exposure.
- Physical impediments to hatchlings may reduce their ability to reach the shelter of the ocean thus making them more vulnerable to predators such as ghost crabs and birds. This in turn can lead to increased mortalities of ghost crabs from direct crushing of subsequent vehicle passes.

Recreational ORV Management

The concern over the unrestricted access and potential environmental degradation caused by ORV's on the beaches of South Africa led to the release of a report by the Council for the Environment in 1986 (Atkinson & Clark 2003). The report entitled "*A Policy for Controlling Off-Road Vehicles in the Coastal Zone of the Republic of South Africa*" made two significant recommendations prohibiting:

- non-essential vehicle use unless such use could be regulated in terms of a permit system; and
- all vehicle use on bathing beaches and in ecologically sensitive areas (Atkinson & Clark 2003)

Local authorities that regulated the use of ORVs on beaches in South Africa took various actions according to their local jurisdictions. Some authorities enforced the recommendations while others did not. This variation in management led to the development of the *General Policy for the Control of Vehicles in the Coastal Zone (1994)*. This in turn led to regulations being put in place in 2001 that imposed a general ban on non-essential vehicle use on beaches. By 2002 these regulations were enforced and consequently the use of vehicles was banned on the majority of South African beaches except in designated Recreational Use Areas (RUA's) (Atkinson & Clark 2003, Celliers et al. 2004).

Celliers et al (2004) developed seven principles that enabled management authorities to select RUA's with confidence. The seven attributes or characteristics of the coastal zone of KwaZulu-Natal that would immediately disqualify such an area from being considered as a potential RUA include:

- any area outside the hard sand of the intertidal zone
- fragile, rare, relict or vanishing vegetation
- wildlife sanctuaries and reserves

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- unsuitable physical attributes of beaches or natural barriers
 - areas of fragile natural features or scientific interest
 - areas of potential beach user conflict
 - unidentified or unexplored key ecological processes (Celliers et al. 2004).

This type of management outcome was achieved after the comprehensive temporal and spatial collation of data on the impacts of ORVs was established. Although this type of management outcome may not be feasible for beaches in South East Queensland it provides a framework from which to base practical management initiatives. Before this type of management practice can be applied to beaches in South East Queensland a complete temporal and spatial profile of ORV use on the regions beaches including socio-cultural, economic and environmental aspects needs to be accomplished.

Conclusion

The significance of vehicle related impacts to beaches is becoming increasingly important especially in areas that receive widespread recreational vehicle use. The consequent disturbance to natural physical processes by vehicle use is insignificant on a daily or even weekly basis when compared to storm-generated beach erosion (van der Merwe 1988). However, as the literature has stated, the significance of small modifications to the physical environment can be significant on an incremental basis, which in turn could render the beach more susceptible to erosion from storm events in the future. The general consensus of the literature indicates that vehicle impacts to dunes and backshore areas are of a greater concern to environmental management than the intertidal foreshore. What the literature hasn't confirmed is whether the organisms of the foreshore, and the associated biotic interactions with higher trophic levels, are under threat from long-term high intensity vehicle activity.

The response of macrofauna communities to vehicle activity has been highlighted, with some organisms showing a high tolerance to vehicle activity and others being more susceptible to impacts. What has not been examined is if these macrofauna assemblages also change on an incremental basis with the associated changes in their physical habitat. Because there is limited regionally relevant data on beaches available, environmental management of beaches is either restricted to physical and geo-morphological aspects (excluding all ecological properties), consists of poorly informed ad-hoc measures, or simply does not exist at all.

In Australia, especially in South East Queensland, beaches receive high vehicle use (Thompson 2005, Moss & McPhee 2006, Schlacher & Thompson 2006b). Some of these beaches are located in areas that were once mostly inaccessible to humans. Driving of ORV's is particularly popular on the beaches of Noosa's North Shore, North Stradbroke Island, Moreton Island and Fraser Island. Traffic densities can be high, especially during holiday periods and weekends. It is not currently known whether this heavy use of vehicles on beaches has long term impacts on the biota inhabiting the intertidal zone. This information gap currently impedes the development of effective and informed management policies regarding the recreational use of off-road vehicles on beaches.



Chapter 2: Physical Impact Caused by Off-road Vehicles (ORVs) to Sandy Beaches: Spatial Quantification of Vehicle Tracks on an Australian Barrier Island.

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Abstract

Beach traffic has the potential to substantially modify the physical environment and habitat quality on sandy beaches. This study quantified the magnitude and extent of physical impacts to the sand matrix of beaches caused by off-road vehicles (ORVs). Vehicles impacts were quantified on North Stradbroke Island, a barrier island on the East Coast of Australia that receives large volumes of recreational ORV traffic. Beach traffic is concentrated on two beaches (Flinders and Main Beach) that comprise 89% of the exposed coastline of the island. Beaches were surveyed for the distribution, density and depth of vehicle ruts during the peak holiday period around late December and early January 2005/06. The density of tyre tracks per meter of beachface ranged from 2.69 to 6.35 on Flinders Beach, and from 2.38 to 8.06 on Main Beach. The area of the beach surface covered by tyre tracks was 61% and 54 % on Flinders and Main Beach respectively, but vehicle track coverage could be as high as 90 % at some sampling sites. ORVs left corrugations as deep as 28 cm (mean depth: 5.86 ± 4.72 cm). On a volume basis, beach traffic disrupted 5.8% (Main Beach) and 9.4% (Flinders Beach) of the available faunal habitat matrix (top 30 cm of the sand) in a single day. The deepest rutting occurred between the foredunes and the drift line, or just down-shore of the drift line. Traffic density was higher on the lower shore, but ruts were significantly deeper in the soft sand of the upper shore. Half of the sand displaced by vehicles on Flinders Beach originated from the upper shore, although this section represents only 36% of beach width. Similarly, the narrow (13% of beach width) upper shore on Main Beach

contributed 55% of the total volume of sand dislodged by ORVs. Beach traffic overlapped to a large extent with the distribution of the invertebrate in-fauna, and despite driver education, vehicles routinely disturbed the drift line and the base of the foredunes. This study emphasizes the need to develop multi-faceted management strategies for recreational ORV use on beaches. Such strategies will need to embrace physical data such as those presented here, and balance ecological requirements with socio-cultural and economic demands.

Introduction

Sandy beaches are prime sites for human recreation. Arguably, it is the strong attraction to of beaches that underpins many coastal economies, and which continues to fuel commercial developments, tourism, and population shifts to coastal areas. Such pre-eminence of sandy beaches in many modern societies is manifested by the emergence of distinct 'beach cultures', and beaches have acquired icon status in Australia and elsewhere (James 2000b, Jones et al. 2004). Recreational beach use encompasses a wide spectrum of pursuits including walking, swimming, surfing, beach-camping, fishing, sun-bathing, nature-based tourism, and adventure activities (Priskin 2003a-b).

Driving of off-road vehicles (ORVs) on beaches is mostly done in the context of leisure activities, but this specific beach use is not without controversy. While most tourism has some undesirable environmental consequences, it is environmental degradation attributed to beach traffic – whether putative or real – that is more readily perceived by the public due to the visually and audibly highly prominent nature of ORV vehicles on beaches (Priskin 2003b). There is a growing body of evidence on the nature and extent of environmental degradation caused by ORVs on beaches including: geomorphological changes (Anders & Leatherman 1987a, b, Priskin 2003b), destruction of dune vegetation (Hosier & Eaton 1980, Rickard et al. 1994), impacts on wildlife such as turtles (Hosier et al. 1981), birds (Watson & Kerley 1995, Watson et al. 1996, Williams

et al. 2004), and invertebrates (Wolcott & Wolcott 1984, van der Merwe & van der Merwe 1991, Moss & McPhee 2006).

Beach traffic can cause ecological degradation via direct impacts on plants and animals (e.g. crushing of organisms under vehicles) or indirect effects such as behavioural changes and habitat destruction (Stephenson 1999). One mechanism that may alter the habitat suitability for beach organisms is physical disturbance to the sand matrix that serves as habitat for a diversity of invertebrate infauna. Often, such physical disturbance is clearly manifested by vehicles tracks cut into the beach-face. Thus, a basic and fundamental step in gauging the effects that ORVs may have on beach biota is to document the extent to which beach traffic modifies habitat properties. Thus, the primary objective of this study was to quantify the magnitude of physical beach impacts by ORVs. We focused on the unvegetated beach between the dunes and the swash, as this is the zone that carries almost all beach traffic. Specifically, we quantified vehicle disturbance of beaches in terms of: i) the distribution of vehicles tracks across the beach face (dune to swash), ii) the area of beach visibly corrugated by vehicle tracks, iii) the depth to which the sand matrix is disrupted, and iv) the volume of sand displaced by vehicles.

Methods

North Stradbroke Island is a sand barrier island forming the south-eastern rim of Moreton Bay off the coast of Brisbane, Queensland, Australia (Fig. 7). The island is a popular tourist destination and receives large amounts of ORV beach traffic, especially during peak holiday periods (Carter 2005). In fact, of the 46 km of open, oceanic beaches on the eastern and northern side of the island, 40 km (89 %) currently receive ORV traffic. This traffic is concentrated on Flinders Beach (8.4 km) and Main Beach (34.5 km); only small sections (< 1.2 km) on the northern end of these two beaches are currently closed to vehicular traffic.

Flinders and Main Beach both have camping sites in the dunes, but there are no backroads to reach the camp grounds. Thus, campers must travel in ORVs along the beach. Access points for ORVs are located on the northern and southern end of Flinders Beach, and at the northern end and central part of Main Beach (Fig. 7). The locations of ORV access points necessitates extensive travel along the beach to reach the majority of campsites that are located in the central sector of Flinders Beach and the southern part of Main Beach. Fishermen also rely on ORVs to reach 'optimum' fishing spots along the beach. Another component of beach traffic is by 'day-trippers' who travel on the beach to reach preferred wimming spots or simply for 'scenic drives' on the shore. Traffic volumes can reach up to 500 cars per day during the peak tourism season (Schlacher & Thompson, unpubl. data).

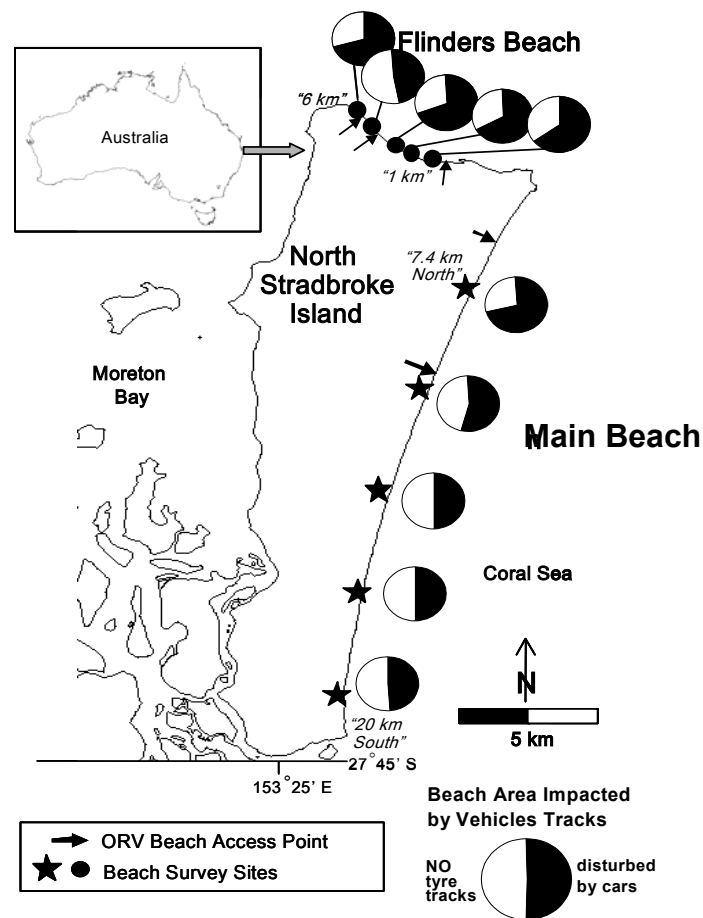


Fig. 7 Map of North Stradbroke Island showing beach sites surveyed for physical damage caused by ORVs. Pie-charts show the percentage of the surface area on the beach that was impacted by vehicle tracks (blank segments).

We surveyed five sites on each of the two beaches for morphological parameters and vehicle impacts (Fig. 7). Beach profiles were measured using standard theodolite surveying techniques. These profiles included the first two to three ridges of the foredunes only; at several sites the dunes are wider, extending up to 300 m inland. It was, however, logistically not possible to extend the surveys into these regions. Sediment compactness was measured at 2 m intervals from the foredunes to the swash limit with a pocket penetrometer (Geotester). For the determination of sediment granulometry and moisture, sand samples (5 replicate cores of 2 cm diameter and 10 cm depth) were collected from three positions at each site: i) at the drift line (DL), ii) half-way between the DL and the base of the foredunes (FD), and iii) in the centre of the lower beach between the DL and the swash limit. All surveys were undertaken over a 3 day period from 30-Dec-2005 to 01-Jan-2006, coinciding with a peak holiday period on the island.

In terms of morphodynamics, the main difference between Flinders and Main Beach is the degree of exposure to the dominant SE-swell: Flinders Beach is more protected with generally smaller waves < 1 m, while Main Beach is more exposed with larger waves usually > 1.5 m. Flinders Beach has a more variable slope (1.82° - 5.36°), while Main Beach has a more uniform slope (2.04° - 3.60°). Both beaches can be broadly categorised as intermediate with Beach Index values (McLachlan & Dorvlo 2005) of 1.78 - 2.40 for Flinders Beach and 1.90 - 2.18 for Main Beach. Flinders Beach is more tide-modified (Relative Tide Range, RTR: 5.05 - 6.73) compared with higher wave-dominance on Main Beach (RTR: 2.02 - 4.04). Beach sediments consist of medium sand (mean grain size: 0.283 - 0.343 mm at Flinders; 0.315 - 0.362 at Main Beach) that is generally moderately well sorted.

Physical disturbance by ORVs was quantified at each site by mapping the position, width, and depth of every vehicle rut found between the base of the dunes and the upper swash (Fig. 7). A 'rut' is defined as a distinct furrow in the sand made by one or more ORVs. A rut can contain either a single or several to numerous tyre tracks. The number of tyre tracks in each rut was estimated by visual identification of the different tyre tread patterns. The number of tyre tracks could be readily enumerated for narrow ruts that contained few distinct tread patterns, particularly on medium-compacted sand. In soft sand, the tread patterns of individual vehicles were sometimes not clearly distinguishable, and the number of vehicle tracks may have been underestimated. Similarly, for wide ruts in the lower intertidal that contained many overlapping or superimposed tyre treads, the reported number of recorded tracks is also a conservative value. All rut measurements were made ± 2 hrs either side of the predicted time of low water.

Results

Magnitude of Damage by Vehicles

A total of 398 vehicle ruts (197 and 201 on Flinders and Main Beach respectively) were mapped, comprising a minimum of 2 078 individual tyre tracks. The number of tyre tracks per linear meter of beachface ranged from 2.69 to 6.35 on Flinders Beach, and 2.38 to 8.06 on Main Beach. This considerable number of vehicle ruts and tracks is reflected in the extensive area of the beachface that is visibly disturbed by beach traffic. On Flinders Beach, 61% of the beach surface was impacted by vehicle tracks. Similarly, cars had rutted 54% of the sand surface on Main Beach (Fig. 7). Mean surface area disturbance was similar for the two beaches (ANOVA, $F(1,16) = 2.99$, $P(2) = 0.103$).

Surface damage was significantly greater on narrower sections of the beaches where traffic was more concentrated compared with wider sections (Spearman rank correlation between beach width and area rutted: $r_s = -0.87$, $P(2) = 0.001$).

Vehicles caused deep corrugations of the beach surface. The mean depth of ruts was 5.86 (\pm 4.72) cm, but many ruts were considerably deeper: 57% of vehicle ruts were deeper than 5 cm, 21% were deeper than 10 cm, and the maximum recorded rut depth was 28 cm. The large area of impact combined with the depth to which ORVs furrow the sand resulted in large volumes of sand being compacted and displaced. It was estimated that beach traffic disrupted 38 018 m³ of sand in a single day on Main Beach, and 12 573 m³ on Flinders Beach. These volumes of displaced sand represented 1.3 – 2% of the total sand wedge of the unvegetated beach from the base of the foredunes to LWST (Table 1).

Table 1: Percentage of beach sand volume disturbed by vehicle ruts. Impact is calculated as the volume of sand displaced by vehicles in relation to a) the top 30cm of the sand that is the primary habitat for most of the benthic infauna, and b) the total volume of sand encompassed between the LWST and the base of the foredune (subaerial sand wedge).

Section/Zone	Site:	Flinders Beach		Site:	Main Beach	
		Sand volume disturbed			Sand volume disturbed	
		A -Top 30 cm	B - (Total Sand Wedge)		A -Top 30 cm	B - (Total Sand Wedge)
Upper	6 km N	24.5%	(2.8%)	20 km S	10.6%	(1.4%)
Middle/Lower		4.6%	(0.9%)		3.3%	(0.9%)
Beachface		5.8%	(1.1%)		6.5%	(1.2%)
Upper	5 km N	9.0%	(1.4%)	13 km S	8.9%	(1.1%)
Middle/Lower		4.7%	(1.6%)		3.4%	(1.3%)
Beachface		6.9%	(1.4%)		4.1%	(1.2%)
Upper	3 km N	10.9%	(1.7%)	6 km S	12.7%	(2.0%)
Middle/Lower		8.0%	(2.2%)		0.9%	(0.3%)
Beachface		9.3%	(1.9%)		3.3%	(0.9%)
Upper	2 km N	9.1%	(1.8%)	0.2 km S	37.4%	(4.2%)
Middle/Lower		14.2%	(6.0%)		2.3%	(0.4%)
Beachface		11.9%	(3.4%)		6.3%	(1.1%)
Upper	1 km N	29.1%	(4.8%)	7.4 km N	16.9%	(2.0%)
Middle/Lower		16.4%	(4.2%)		8.7%	(2.1%)
Beachface		20.9%	(4.5%)		10.7%	(2.1%)
Upper	BEACH	11.3%	(1.8%)	BEACH	14.2%	(1.9%)
Middle/Lower		8.1%	(2.3%)		3.3%	(0.9%)
Beachface		9.4%	(2.0%)		5.8%	(1.3%)

From an ecological and conservation perspective it may, however, be more meaningful to consider the actual habitat usable by the benthic infauna; this generally comprises the top 30 cm of the sand matrix, with few animals living deeper. When assessed in this manner, ORVs were estimated to have disrupted 5.8% (Main Beach) and 9.4% (Flinders Beach) of the faunal habitat matrix in a single day (Table 1).

Across-shore Variation in Vehicle Impacts

The extent of the physical damage caused by ORVs varied significantly between the upper (foredunes to drift-line) and lower beach (drift-line to swash; Table 2, Figs. 8-10). Vehicle ruts were wider on the lower shore (Table 2). Vehicle ruts on the lower shore also contained more individual tracks, and traffic density integrated over the whole section was similarly higher (Table 2). At several survey sites, long (~25 m) stretches of the lower beach were solidly covered by tyre tracks, many of which overlapped, or numerous tyre tracks were superimposed on each other in these wide ruts (Figs. 9 & 10): at two survey sites of Flinders Beach, cars had rutted 91 % of the lower shore (Fig. 9). The average area corrugated by vehicles was generally lower on the upper shore (Table 2). Substantial disturbance (80 %) was, however, recorded on the upper beach at narrow sections where the drift line was close to the base of the foredunes (Figs. 8-10).

Table 2: Comparison of the severity of vehicle damage to beaches between the upper zone of the intertidal zone (drift-line to foredune) and the lower beach (swash to drift line). Contrasts are calculated for a) properties of individual vehicle ruts recorded in each zone, and b) damage integrated over each beach zone.

	Upper Beach (n=148)		Middle-Lower Beach (n=245)		F-value	P ₍₂₎
	mean n	(s)	mean	(s)		
a) Rut width (m)	0.48 7	± (0.253)	1.063	± (2.146)	11.26	0.001
Rut depth (cm)	9.10 3	± (3.950)	3.922	± (4.086)	145.17	<0.001

No. of tracks per vehicle rut	2.05 ± (1.287) 4	7.220 ± (16.216)	15.08 <0.001
Track density per metre of vehicle rut	4.33 ± (2.031) 4	6.972 ± (4.395)	48.52 <0.001
	Upper Beach (n=10)	Middle-Lower Beach (n=10)	F-value P ₍₂₎
b) Percentage of surface area disturbed	46% ± (17%)	67% ± (15%)	9.76 0.007
No. of tyre tracks per metre of beachface	1.77 ± (1.033) 3	4.606 ± (1.141)	34.13 <0.001
Sand volume displaced per metre of beachface (m ³)	0.05 ± (0.016) 1	0.020 ± (0.029)	8.46 0.010

At several sites, the ruts became markedly deeper around the drift line, and these deep corrugations continued up-shore towards the base of the foredunes (Fig. 8). Vehicles cut significantly deeper into the sand on the upper shore (Table 2, Fig. 8), resulting in much higher rates of sand displacement above the drift line (Fig. 11). ORVs corrugated the beach to a greater depth on the upper shore, principally because of the softer sand in this zone (Fig. 12).

Vehicles that traversed the upper shore disrupted up to 37% of the top 30 cm of the sand matrix in a single day (Table 1). Of the 12 573 m³ of sand displaced by vehicles on Flinders Beach, 6 161 m³ (49%) originates from the upper shore, although this section represented only 36% of the beach width. Similarly, on Main Beach the upper shore was narrow, comprising only 13% of the beachface, but 55% (21 139 m³) of the 38 018 m³ of sand dislodged by cars came from this zone (Table 1). Overall, the upper and lower shore were clearly delineated in terms of the intensity and nature of physical impacts caused by beach traffic (Fig. 13). It is truly remarkable that such a distinct “zonation” of the beach is evident solely as a result of human disturbance.

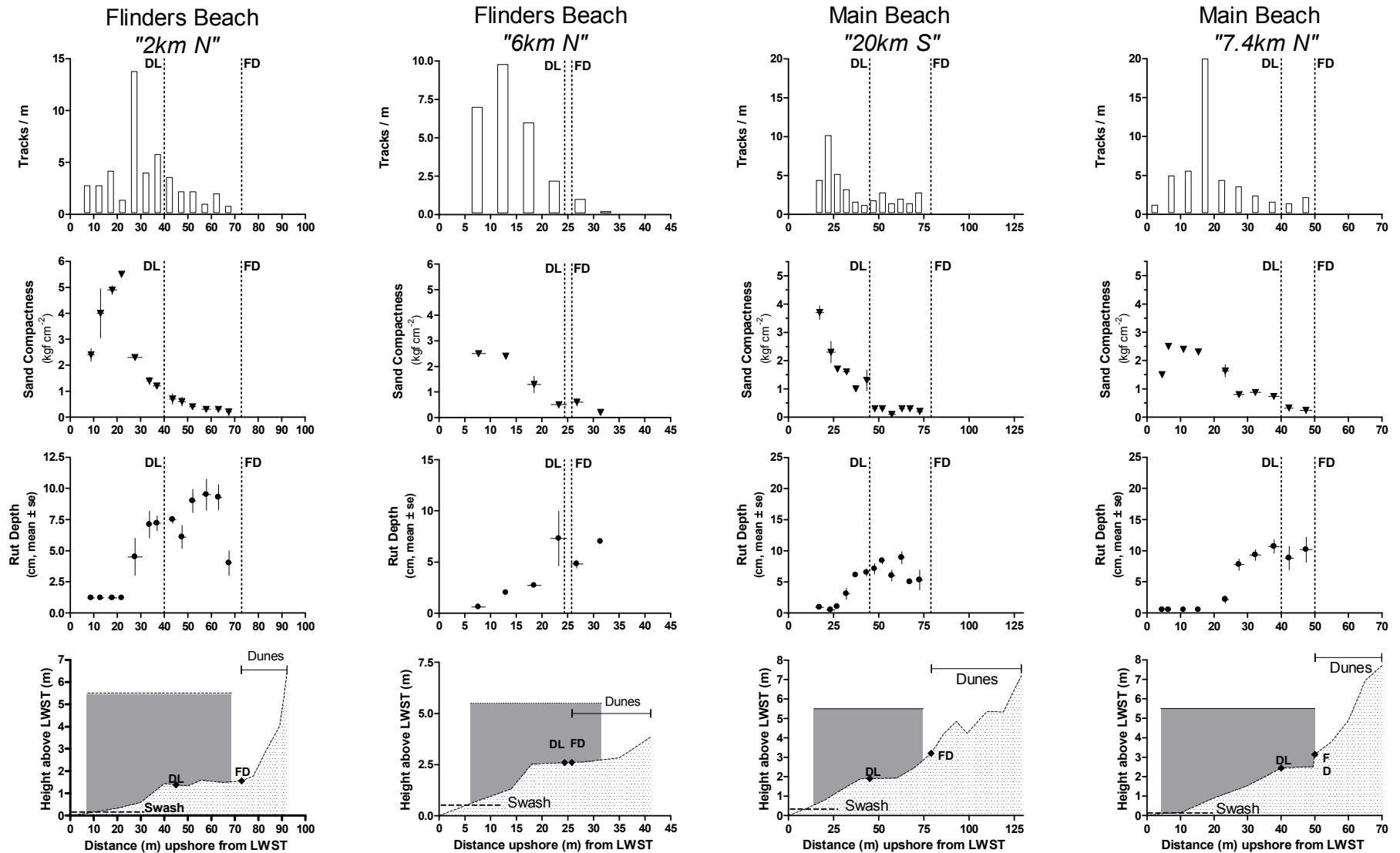


Fig. 8 Examples of the spatial distribution of vehicle impacts across the shore in terms of the number of vehicle tracks (top row) and the depth of vehicle ruts (third row from top) compared with compactness (second row from top) and the beach profiles for each site (bottom row). The shaded area in the bottom-row panels shows the zone over which vehicle ruts were observed (DL = drift line, FD = base of foredune).

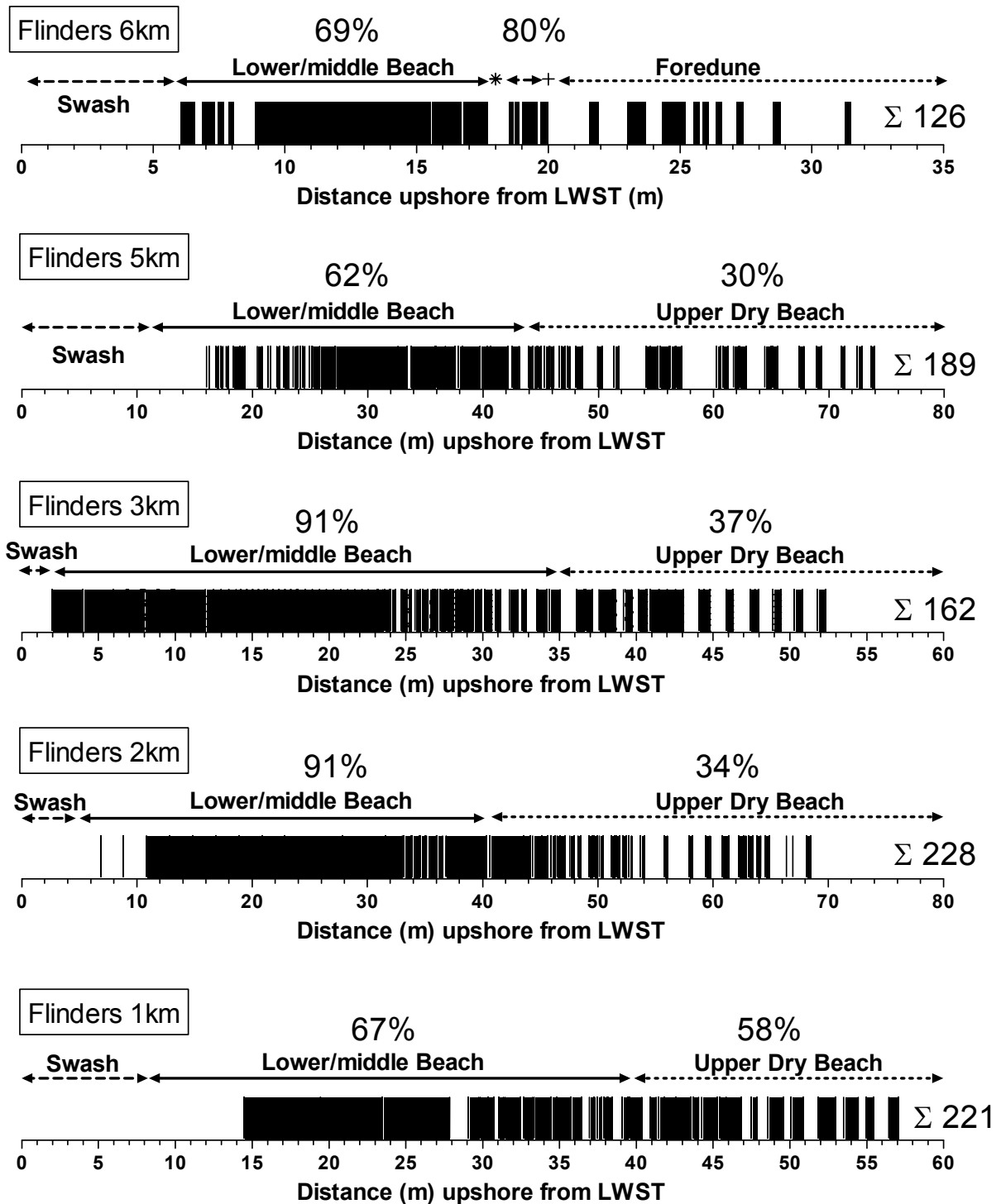


Fig. 9 Distribution of vehicle ruts across the beach face on Flinders Beach. Solid, black bars denote vehicle ruts and open bars areas without visible tyre tracks. Percentage values denote the surface area of each zone that was visibly rutted with vehicle tracks (total number of tracks observed is denoted by Σ).

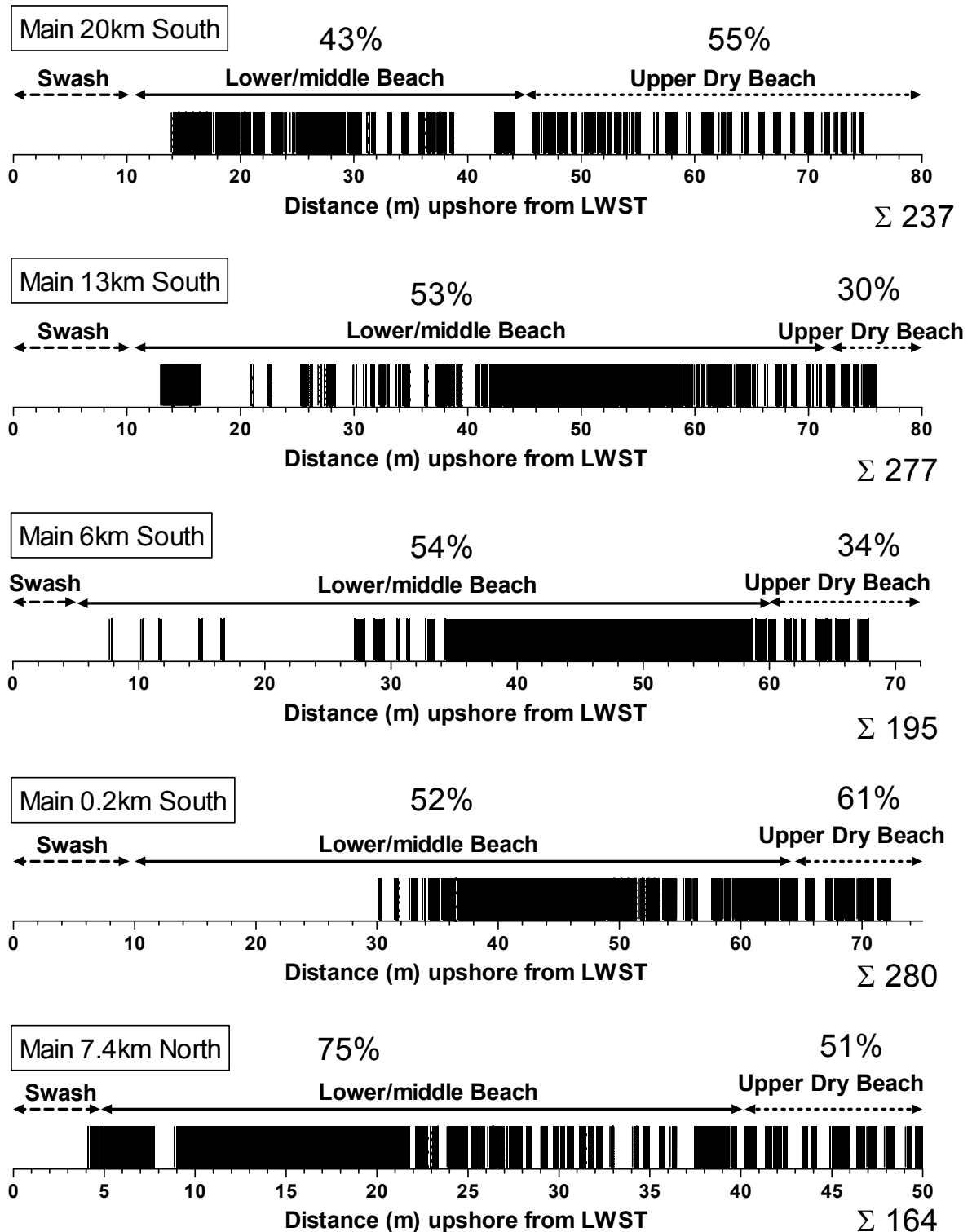


Fig. 10 Distribution of vehicle ruts across the beach face on Main Beach. Solid, black bars denote vehicle ruts and open bars areas without visible tyre tracks. Percentage values denote the surface area of each zone that was visibly ruted with vehicle tracks (total number of tracks observed is denoted by Σ).

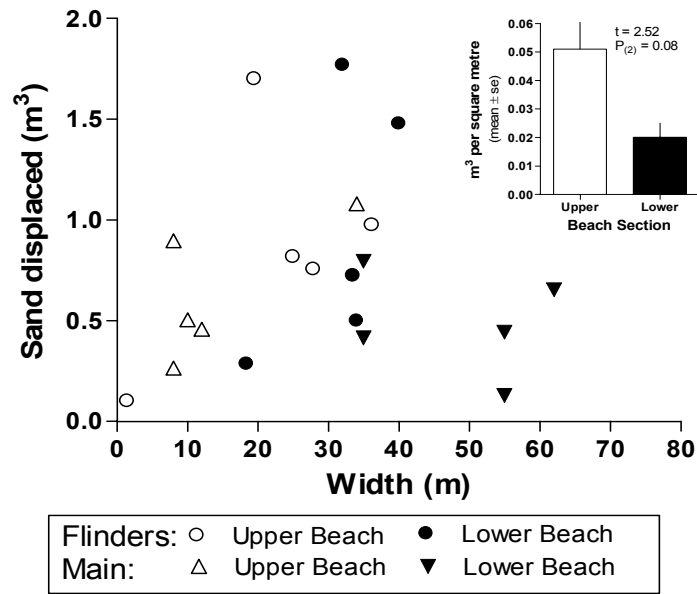


Fig. 11 Comparison of sand displaced by vehicles in each beach zone versus beach width. Main graph shows total volume of sand displaced summed over each section. Insert shows the mean volume of sand (m³) displaced per square metre of beach.

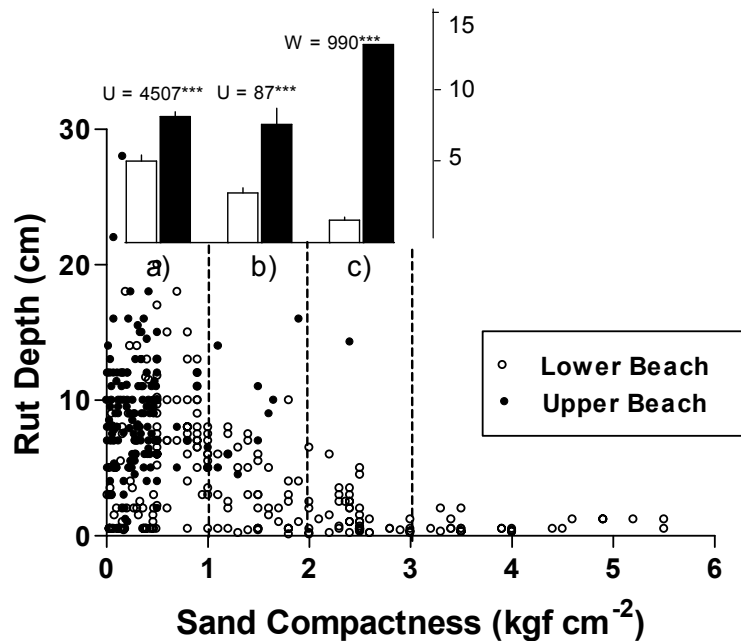


Fig. 12 Depth of ruts in relation to compactness of the sand in each of the two major beach zones. Insert (bar graphs) compares mean rut depth between upper-(solid, black bars) and lower (open bars) sections of the beach pooled over three compactness classes: a) < 1 kgf cm⁻² b) 1-2 kgf cm⁻² and c) 2-3 kgf cm⁻²

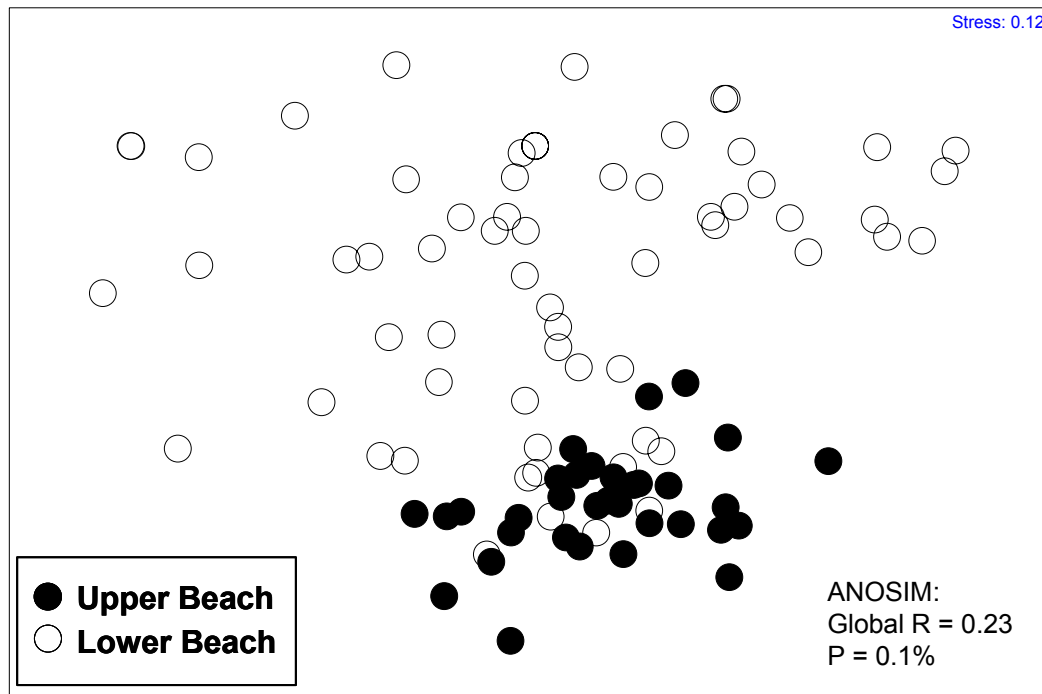


Fig.13 Ordination (non-metric multidimensional scaling) of beach sites based on physical vehicle damage to the sand matrix. Analysis based on normalised Euclidean distance matrix including the following 10 variables: A) 'Traffic Intensity': 1) Total No. of vehicle ruts, 2) Total No. of tyre tracks, 3) No. of tyre tracks per rut, 4) No. of tyre tracks per metre of rut, and B) 'Impact Intensity': 5 & 6) Mean and maximum width of ruts, 6) Max. rut width, 7 & 8) Mean and maximum depth of ruts, 8) Max. rut depth, 9 & 10) Mean and maximum volume of sand displaced per vehicle rut.

Discussion

Beach traffic caused widespread and substantial physical disturbance to sandy beaches, including: a) large areas (up to 90%) of the beachface being rutted by vehicle tracks (Figs. 8-10), b) compaction and displacement of significant volumes of sand by ORVs (Fig. 11, Table 1), and c) considerable disturbance of the backshore, the drift-line and the base of the foredunes (Figs. 9 & 10). Remarkably, a clear "zonation" of the beachface into upper and lower sections was evident based solely on differences in the intensity and nature of vehicle disturbance (Fig.13).

Vehicles can cause a net displacement of sand downshore and enhance sand mobility through increased bottom turbulence caused by ruts, both processes

possibly enhancing erosion (Anders & Leatherman 1987a). Our estimates of sand displacement and compaction do indicate that vehicles can disturb considerable volumes of beach sand in a single day (Table 1), but it does not necessarily follow that ORVs contribute to increased shoreline erosion in this particular situation - this would clearly be speculative. Published evidence on vehicle effects on beaches does, however, clearly show that physical disturbance of the beach environment is a form of environmental degradation (Hosier 1980, Priskin 2003b), which has ramifications for the biota (Stephenson 1999), the economic values of beaches linked to tourism and other uses (Priskin 2003a-b), and environmental management (James 2000a, Brown & McLachlan 2002, Jones et al. 2004).

Potential Habitat Disturbance

Vehicle ruts overlapped to a large extent with the distribution of the invertebrate in-fauna (Fig. 14). Species that inhabit mainly the upper shore (e.g. ghost crabs, isopods, some polychaetes) are predicted to experience considerable habitat modification from deep corrugations. On the lower shore, vehicle ruts are shallower but this area tends to receive high volumes of traffic (Table 2), coinciding with the distribution of majority of species (Fig. 14). By contrast, few vehicles drive in the swash and species concentrated in the swash (e.g. mysids) should be less impacted by beach traffic. Simple overlap in the distribution of fauna and traffic does not automatically imply direct mortality (e.g. crushing) of the animals. However, some beach invertebrates of the lower shore have been shown to be sensitive to crushing by vehicles (van der Merwe & van der Merwe 1991).

Ghost crabs whose centre of distribution is on the upper shore are apparently protected from vehicle damage when inside their burrows during the day (Wolcott & Wolcott 1984). Adult ghost crabs construct relatively deep burrows (> 30 cm) on the local beaches, which is generally below the rut depths measured in this study. At beach access points, ruts can, however, be much

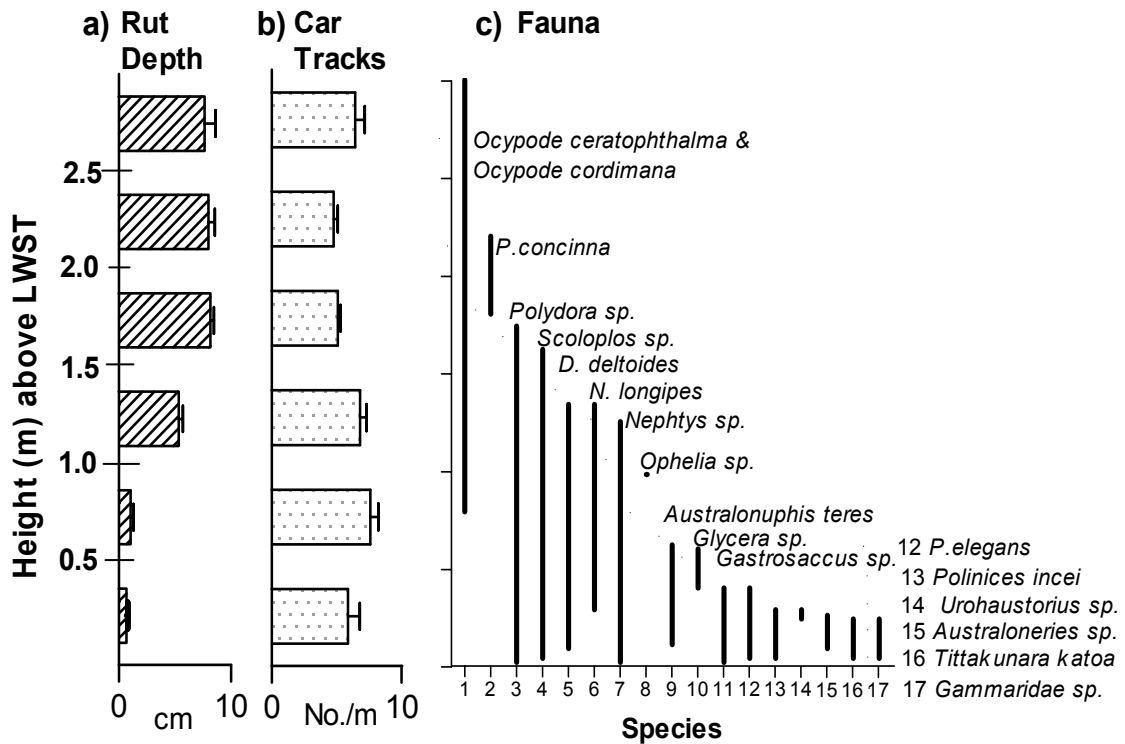


Fig. 14 Distribution of macrobenthic species across the beach face in relation to depth of vehicle ruts (a) and the density of tyre tracks per metre of rut (b).

deeper (> 0.5 m from visual estimates as the high traffic intensity made it unsafe to survey these areas), which may possibly kill ghost crabs directly. Access points cover only a small percentage of the beach though. New recruits and juvenile ghost crabs burrow only a few centimetres into the sediment (Schlacher, pers. obs.) and direct crushing cannot be excluded, given the rut depths measured in this study. Whether vehicles cause direct crushing of beach invertebrates in the present situation certainly warrants detailed quantification to unambiguously determine effects of ORVs on beach invertebrates.

The actual consequences of beach traffic will depend both on the nature and intensity of the impacts (e.g. traffic volumes, distribution across the beach-face,

rut depth, etc.) and the sensitivity of each species to disturbance. A particularly poignant illustration of the negative impact of beach traffic on wildlife is the significantly lower rate of newly hatched turtles that reach the surf; also, their slower rate of movement when travelling over beach sections rutted by cars makes them more vulnerable to predation (Hosier et al. 1981). On Stradbroke Island densities of ghost crabs are lower on beaches with ORVs compared with beaches that are closed to traffic (Moss & McPhee 2006). The actual mechanisms for this spatial difference are unknown, but it has been suggested that nocturnal ORV traffic may be responsible for killing large numbers of surface-active crabs (Moss & McPhee 2006).

An alternative hypothesis for such spatial contrasts in ghost crab numbers is that habitat suitability is lowered by ORVs. Vehicles break the thin, hard surface crust of the upper beach, causing drying and loosening of the sediment (Schlacher, pers. obs.). This less cohesive sand may be less suitable for burrow construction and crabs may exert extra metabolic energy in constructing burrows, particularly when burrow openings tend to collapse during hot weather. We have observed ghost crabs tunnelling to the surface inside vehicle ruts. This indicates survival following disturbance by cars when crabs are inside their burrows, but it must also place extra metabolic demands on the organisms to repeatedly repair their burrows. Thus, a 'habitat effect' caused by ORVs cannot be excluded to affect ghost crab numbers on beaches, but the extent of any impact on ghost crab populations via habitat modification remains to be quantified.

Backshore Impacts and Driver Behaviour

Although traffic density was generally lower above the drift line (i.e. most cars did drive on the harder, lower beach), the deeper vehicle rutting on the upper shore resulted in a 155% increase in the amount of sand being displaced per linear metre of beach compared to the lower shore (Table 1, Fig. 14). Thus, on

both beaches, the deepest rutting occurred between the foredunes and the drift line or just down-shore of the drift line (Fig. 8).

Conventional wisdom holds that the foredune and backshore areas of beaches are much more sensitive to environmental impacts by humans compared to the more resilient foreshore (Anders & Leatherman 1987b, Rickard et al. 1994, Brown & McLachlan 2002). This dichotomy in the sensitivity to human impacts is universally applied in beach driver education. ORV users are generally advised to stay below the high water mark, travel during low tide, and avoid driving on the drift line and in the dunes. The physical damage to the upper shore recorded by us does, however, show that such advice is not heeded by all beach drivers. Cars had heavily rutted the upper sections of the beaches, many vehicle tracks ran over the wrack deposits at the drift line, and a few vehicle ruts extended into the foredunes (Figs. 8-10).

Such physical disturbance of the upper beach is widespread during peak holiday periods. In a subsequent study during the Easter weekend of 2006, only one undisturbed area of the upper beach could be found along 16 km of Main Beach; this single small patch was small (ca. 3m wide x 100 m long). We have also observed occasional vehicle ruts in the dunes and in soft sand areas where renegade drivers have apparently used the backshore to test the capabilities of their vehicles. Beach traffic can also be forced above the drift line when people park their cars on the lower shore. Traffic can also be “channelled” to the upper shore when inexperienced drivers stay in existing tracks (many of which are deeply incised and thus clearly visible) created during preceding high tides. It should be emphasized that ORV user groups actively promote codes of conduct for responsible beach driving, and the bulk of vehicles do not traverse the backshore. Yet, the magnitude of physical rutting on the backshore and the drift line clearly indicates a need for more comprehensive driver education and, possibly, active visitor management.

ORVs and Recreational Demands

While the ecological impacts caused by beach traffic would tend to argue against ORVs, such arguments might be parried by socio-cultural and economic considerations (Celliers et al. 2004). For example, people have an inalienable right to outdoor leisure activities and some beaches are only accessible by ORVs (Celliers et al. 2004). In the present situation, North Stradbroke Island is one of the closest ocean beaches for the people of the large Brisbane Metropolitan area. Both fishing and camping are highly popular activities on the Island, but both require beach driving because no alternative access exists. By contrast, the opportunity to escape from motor vehicles is an equally important fundamental of human recreation and beach traffic severely impairs these opportunities (Wilkinson 2001). In fact, most coastal tourists perceive four-wheel driving to be highly- to extremely harmful to the environment (Priskin 2003a-b). ORVs also tarnish the wilderness character of beaches and reduce their attractiveness for people to engage in 'nature experiences' (Wilkinson 2001). Local communities may derive tangible benefits from ORV-based tourism, but these could potentially be off-set when other visitor groups stay away from ORV beaches. Because data regarding both the social acceptance of beach traffic and the economic costs and benefits of this activity are generally lacking for most beaches, management responses of beach traffic are not well-grounded or inclusive of social and economic dimensions.

Implications for Management of Beach Traffic

Management of beach traffic is challenging and multi-dimensional (James 2000b). To minimize conflicts between user groups, it has to embrace the multi-faceted nature of ORV uses on beaches that includes ecological, social, historical, cultural, and economic dimensions (Celliers et al. 2004). In the present situation – and much of Australia – local authorities have the prime responsibility for regulation of beach traffic (James 2000a). State-wide legislative controls on beach traffic are limited to traffic regulations that apply on conventional roads (e.g. speed limits, blood alcohol levels of drivers, etc.).

These are enforced by Police patrols on beaches, and some beaches in Queensland are designated as roads (including beaches in national parks). Active beach traffic management such as placing limits on traffic volumes, or restrictions on seasons and tides when beach driving is allowed is currently not practiced on beaches open to ORVs. From an environmental conservation perspective it seems reasonable to introduce measures which may: a) limit access to beaches to times of low water to reduce impacts to the backshore caused by driving during high tides (THIS STUDY), b) prohibit night traffic to reduce mortalities of beach fauna that is surface-active at night (Wolcott & Wolcott 1984), and c) enforce no-go areas above the high water mark on beaches to protect the environmentally sensitive backshore areas and dunes (Anders & Leatherman 1987a, b).

While such management actions – taken on environmental grounds - have been suggested (Moss & McPhee 2006), there are several caveats to be considered: (1) A variety of people use beaches for different purposes, spanning a broad spectrum from ORV enthusiasts to the enjoyment of pure wilderness experiences that excludes motor vehicles. Thus, for management to be inclusive, social and cultural factors need to be quantified; (2) Beach traffic may have both economic costs and benefits. Neither the net balance of these nor the scales over which they may operate are presently known; (3) The compatibility of beach traffic with significant cultural and historical connections by traditional owners of the land, including beach areas of archaeological and spiritual significance, needs to form part of a comprehensive management approach; (4) Although several detrimental effects of ORVs on beach biota have been documented (Stephenson 1999), knowledge gaps make unambiguous assessments about the severity of putative impacts difficult. For example, the present data clearly show that beach traffic causes substantial and widespread physical disruption of the habitat. It is, however, unknown, whether this level of habitat disruption translates into measurable effects on local species or ecological assemblages. In summary, we argue that any approach to ORV

management on beaches must be broadly encompassing, but that management actions are currently impeded by a lack of information regarding the responses of local beach species and communities to ORV disturbance (including any mechanism of change), and the socio-economic corollaries of vehicle traffic on sandy shores.

Chapter 3: Exposure of Fauna to Off-Road Vehicle (ORV) Traffic on Sandy Beaches

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Abstract

Driving of off-road vehicles (ORVs) on sandy beaches is common and widespread, but is not universally embraced due to putative environmental impacts on beach biota. For ORVs to impact the beach fauna, traffic areas must overlap with faunal habitat: a fundamental pre-requisite for impact assessments but as yet un-quantified for sandy beaches. Thus, this study quantified the spatial and temporal patterns of ORV traffic on five Australian beaches, and measured the degree to which the distribution of intertidal macro-invertebrates overlaps with traffic zones. Traffic volumes on beaches can be considerable (up to 500 vehicles per day). The position of beach traffic across the beach-face is principally governed by tides and driver behaviour. Despite driver education campaigns to the contrary, a considerable fraction of vehicles (23-67 %) traverses the soft, upper shore near the foredunes. The majority (65 %) of burrowing invertebrate species of the intertidal zone is directly exposed to traffic, save for species inhabiting the swash zone. Because beach traffic presents a formidable management challenge, a fundamental first step in identifying whether ecological impacts are indeed likely, is to assess the potential for spatial and temporal conflict between human pressures (e.g. ORVs) and biological resources (e.g. beach fauna). While this potential is certainly substantial for sandy shores used by ORVs, the actual ecological impacts on the intertidal fauna can only be predicted in situations where the responses (e.g. direct mortality, behavioural changes) of individual species to beach traffic are known.

Introduction

Sandy beaches geographically dominate the world's shores, and rank amongst the most intensively used coastal habitat types by humans (Bascom 1980, Brown & McLachlan 1990, Banks & Skilleter 2002, Jones et al. 2004). The human use of beaches is intensifying globally, mainly as a consequence of the disproportional strong growth of coastal populations, causing a wide range of physical changes to sandy shore systems (Brown & McLachlan 2002). Ecological impacts on sandy shores may be equally diverse and several anthropogenic pressures on sandy beach biota are directly linked to human recreational pursuits (Brown & McLachlan 2002, Priskin 2003a-b).

Beaches are used for a variety of recreational pursuits including, walking, swimming, surfing, beach-camping, sun-bathing, fishing and four-wheel driving (Priskin 2003a-b). Driving of off-road-vehicles (ORVs) on beaches is a highly prominent, and arguably environmentally damaging, human activity on sandy shores (Moss & McPhee 2006). This beach traffic is mostly of a recreational nature and common in several regions of Australia (Priskin 2003b). It is not uncommon to report on the putative negative ecological consequences of beach traffic (Priskin 2003a-b), but the body evidence to support such inferences can be fragmentary if the actual mechanism is not quantified.

Although there are data available on the impacts of ORVs on beach habitats and their biota (reviewed by (Stephenson 1999), the measured biological response variables include mostly vertebrates and vegetation (Rickard et al. 1994, Watson et al. 1996). By contrast, the effects of vehicles on beach invertebrates, particularly those of the intertidal zone, are largely unknown (van der Merwe & van der Merwe 1991). Invertebrate species may differ considerably in their sensitivity to beach traffic, and thus any ecological responses may be primarily related to the fauna's tolerance to traffic (Steiner & Leatherman 1981, Wolcott & Wolcott 1984, van der Merwe & van der Merwe 1991), preventing general predictions about vehicle impacts at present.

The most basic property that determines whether beach traffic has the potential to damage the intertidal fauna on beaches is the intensity and distribution of vehicles in relation to the distribution of the fauna across the beachface. Fundamentally, if beach traffic does not overlap with the distribution of the fauna, vehicle impacts are predicted to be negligible.

Conversely, in situations where traffic and fauna are concentrated in the same sections of the beach, ecological consequences may be more severe. Thus, it is the degree of overlap between vehicles and species that lies at the core when assessing what effect ORVs may have on beach invertebrates. It is thus surprising that neither traffic patterns nor driver behaviour have been quantified to date. Therefore the main thrusts of this study were to: a) determine traffic patterns on beaches in terms of vehicle positions and traffic volume across the beachface, and b) quantify to which degree the distribution of macrobenthic species overlaps with beach traffic.

Material & Methods

Five beaches, located in southern Queensland on the Australian East Coast were sampled (Fig. 15, Table 3). Two beaches (Teewah Beach and Noosa North Shore) were located on the Sunshine Coast north of the town of Noosa. These beaches are designated as official roads, carrying both recreational traffic and acting as a thoroughfare for vehicles travelling north to Rainbow Beach and Fraser Island. A further three beaches were sampled on North Stradbroke Island (Flinders Beach, Adder Rock, and Main Beach).

North Stradbroke Island is a large barrier island, located on the eastern side of Moreton Bay (Fig. 15). The island is a popular tourist destination and used for a variety of recreational pursuits, including four-wheel driving on beaches, beach fishing, and beach camping (all requiring the use of ORVs). All of the island's

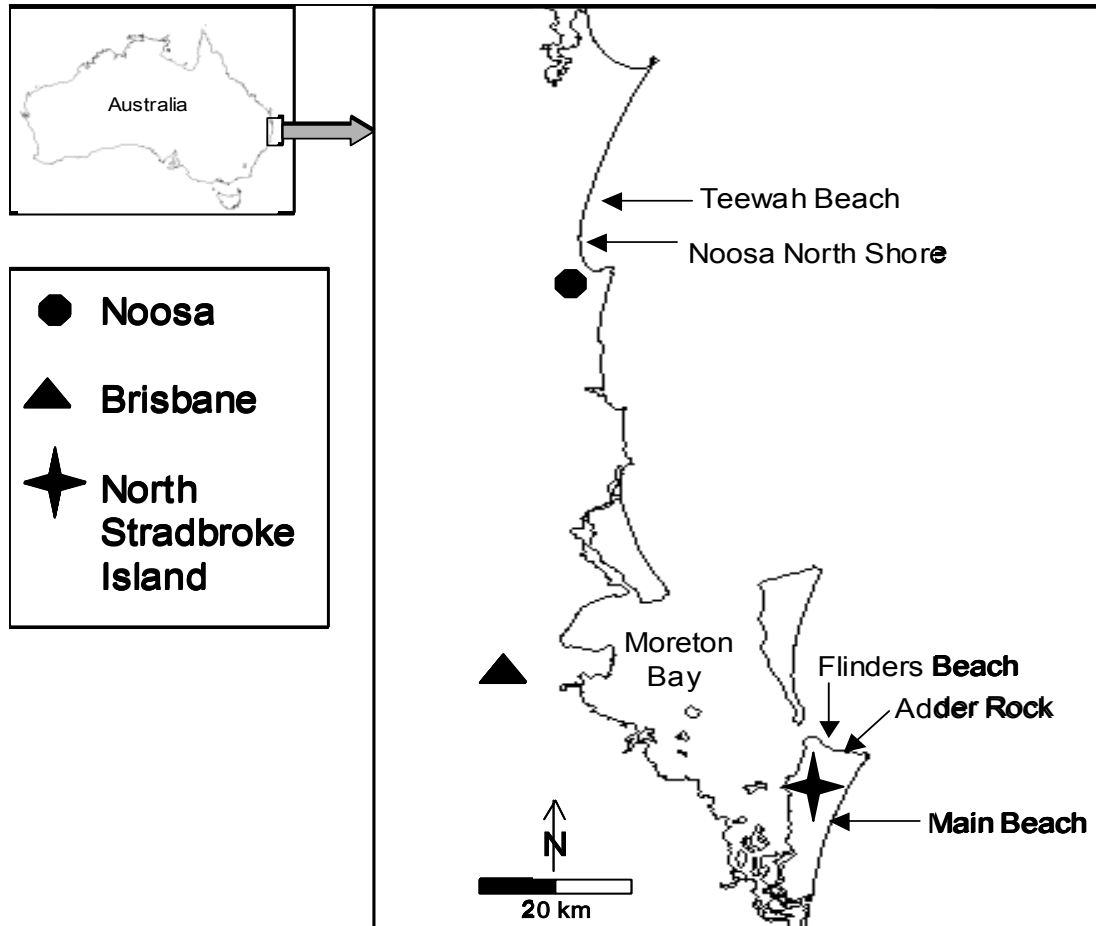


Fig. 15 Location of beaches surveyed for overlap between beach traffic and intertidal macrobenthos.

eastern beaches have ORV access, except for three small pocket beaches (Frenchman's, Deadman's, and Cylinder) and the northern end of Main Beach. All beaches open to ORVs receive moderate to heavy amounts of vehicle traffic, especially during peak holiday periods (Thompson 2005). Flinders Beach and Adder Rock on North Stradbroke Island are more sheltered from the dominant south-east swell and tend towards a reflective morphodynamic state, while the other beaches are slightly more exposed (Fig. 15, Table 3). Traffic and faunal counts were made on North Stradbroke Island over the Easter weekend from the 25th to the 28th of April 2005, and on the two northern beaches on the 30th and the 6th of August 2005.

Table 3: Physical characterisation of the beaches sampled (values are means of three transects per beach).

	Beach				
	Flinders	Adder Rock	Main Beach	Teewah	North Shore
Month sampled	April	April	April	August	August
Lat. South	27° 24'	27° 25'	27° 31'	26° 16'	26° 20'
Long. East	153° 28'	153° 30'	153° 30'	153° 04'	153° 03'
Orientation	NE	NE	SE	SE	SE
Width (m)	48	74	66	72	70
Beach Face Slope β (°)	2.83	1.55	2.14	2.45	2.18
Mean Grain Size (mm)	0.35	0.26	0.27	0.29	0.29
Compound Indices and Morphodynamic Classification (R = reflective, I – intermediate, D = dissipative / T = tide-modified, W = wave-dominated)					
Ω - Deans ^(Short 2001)	1.34 (R)	2.27 (I)	3.53 (I)	4.43 (I)	3.79 (I)
BSI – Beach State Index ^(Hacking 1998)	0.63 (I)	0.83 (I)	0.99 (I)	1.08 (I)	1.03 (I)
BI – Beach Index ^(McLachlan & Dorvlo 2005)	2.01 (I)	2.34 (I)	2.19 (I)	2.12 (I)	2.17 (I)
RTR - Relative Tide Range ^(Short 2001)	4.04 (T)	5.05 (T)	1.68 (W)	1.35 (W)	1.35 (W)

At each beach we measured a range of physical descriptors for each of three transects (spaced 30 m apart along the shore) that included: a) beach profiles (theodolite surveys from the base of the foredunes to the low-water, spring tide mark - LWST), b) swash zone width (calculated from the maximum up-rush and down-rush position of 10 consecutive swashes), c) wave height and period, and d) sediment properties (triplicate cores of 30 mm diameter, 100 mm deep at each of 12 levels; Table 3). All physical measurements were made around the time of low water. Sediment parameters (mean grain size, sorting, skewness, kurtosis) were calculated with the GRADISTAT software, using the Folk and Ward method (Blott & Pye 2001).

The chief purpose of the vehicle survey was to determine both the spatial (i.e. position across the beach-face) and temporal patterns at which ORVs drive on the beach. To this end, the beach was divided into 10 m wide bands that ran for 100 m parallel to the shoreline. The upshore boundary of the most landward band was located at the base of the foredunes, and the most seaward in the swash zone below the effluent line. The boundaries of these 'vehicle count bands' were marked with small pieces of flagging tape inserted into the sand. The zone markers were small enough not to be noticed by drivers (avoiding possible bias), but easily visible to observers. Observers (posing inconspicuously as tourists or sunbathers near the foredune) recorded the position and time of each passing vehicle. Traffic was generally recorded from sunrise to sunset, save for the northern beaches where rising tides necessitated an earlier cut-off to return safely.

The distribution of macrobenthic species was determined from sampling 12 levels along of each of three replicate transects (spaced 30 m apart) per beach. Transects extended from the base of the foredune (level 12) to the low water spring tide (LWST; level 1). Levels were spaced equidistant along each transect. At each level, five replicate cores (inner diameter 154 mm, 200 mm deep) were taken ca. 1 m apart, and pooled into a composite sample. The fauna was washed from the sediment through a 1 mm mesh sieve in the swash and preserved in 75 % ethanol.

Zones of the beachface (i.e. lower-, middle-, and upper beach) were determined from similarities in environmental attributes of each beach level sampled, using group-average clustering based on normalised Euclidean distance (Clarke & Warwick 2001). The five environmental variables included in the cluster analysis were: (1) percent sand moisture content, 2) elevation above low water, 3) slope, 4) sediment grain size (ϕ), and 5) the position of each sample relative to the effluent line (dichotomous). We quantified the degree of overlap between

vehicles and the fauna using Bray-Curtis resemblance functions on standardized data of macrobenthos abundance and vehicle passes. Essentially, this is akin to a conventional, multivariate analysis of species distributions, except that vehicles are taken as an 'extra' species (Clarke & Warwick 2001).

Results

Beach Traffic Patterns and Driver Behaviour

The vehicle surveys quantified three main attributes of beach traffic: (1) the position of passing cars across the beach face in relation to the primary physical boundaries of the habitat such as the effluent line (water table outcrop on the lower beach), the swash zone, and the storm drift line (maximum reach of waves during rough seas marked by a line of deposited wrack on the upper shore), (2) temporal patterns in traffic intensity during daylight hours, and (3) changes in the position of vehicles over time in relation to tides.

On North Stradbroke Island, traffic counts were done during a peak holiday period (Easter weekend), recording a total of 495 vehicle passes at Flinders Beach, 335 at Adder Rock, and 471 vehicles at Main Beach during a single day. Traffic counts on the northern beaches (Noosa North Shore and Teewah Beach) were conducted during weekends outside any holiday period in the middle of winter. Still, substantial amounts of vehicle passes were recorded in 9 hours: 431 vehicles at Teewah Beach, and 372 at the Noosa North Shore. Peak traffic occurred on all beaches from late-morning to mid-afternoon. On the beaches of North Stradbroke Island, this concentration of traffic coincided with falling tides and the time of low water (Fig. 16). Thus, substantially more vehicles used the beach during falling tides. By contrast, on the northern beaches, a substantial amount of traffic was observed while the tide was high or rising (Fig. 16).

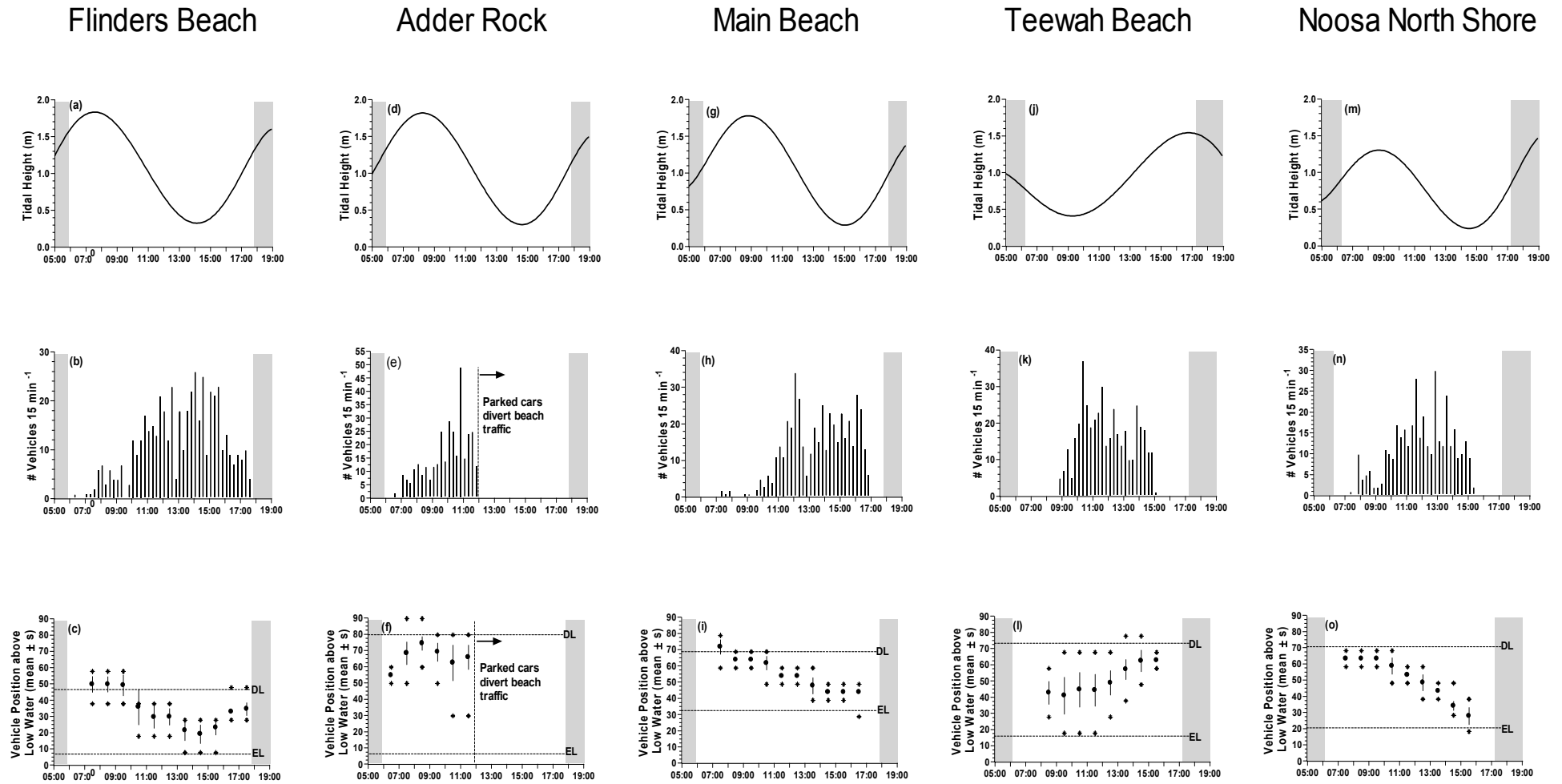


Fig. 16 Temporal and spatial pattern of beach traffic in relation to tidal variation in water level on the five ORV-impacted beaches on North Stradbroke Island, Teewah Beach, and Noosa North Shore. Position of the effluent line (EL) and the drift line (DL) is indicated by dashed lines; maximum up-shore and down-shore position of cars is denoted by star symbols.

Although few cars drove on the extreme landward limits of the beach and in the foredunes, a substantial fraction of beach traffic did occur on the dry, upper beach (Table 4, Fig. 16). On average, 67% of traffic was concentrated on the upper shore at Teewah Beach, and 23-27 % on the other three beaches (Table 4). Drivers of ORVs migrated with the tide: during high water, vehicles traversed the upper beach, followed by a progressive down-shore shift as the tide receded (Fig. 17).

Table 4: Sediment moisture and grain size in three beach zones and the distribution of vehicle traffic across the beach face.

		Lower Shore & Swash	Middle Shore	Upper Shore
Sand Moisture	Flinders Beach	19.8%	12.2%	1.6%
	Main Beach	19.7%	16.6%	3.0%
	North Shore	20.4%	18.7%	2.6%
	Teewah Beach	20.1%	15.8%	2.0%
Sediment Grain Size	Flinders Beach	444µm	395µm	275µm
	Main Beach	330µm	271µm	257µm
	North Shore	332µm	292µm	237µm
	Teewah Beach	355µm	300µm	221µm
ORV Traffic	Flinders Beach	0%	80%	27%
	Main Beach	0%	74%	26%
	North Shore	0%	77%	23%
	Teewah Beach	0%	33%	67%

Overlaps between Traffic and Fauna Distributions

The majority (65 % or 15 spp.) of recorded taxa occurred in the same zone in which vehicles drive along the beach; only eight species (35 %) were distributed below the main area of vehicle traffic (Table 5, Fig. 18). Although there was spatial variation between beaches in the degree to which traffic and fauna

overlapped, three broad clusters could be identified: (1) species whose range overlaps considerably with that of beach traffic, (2) species which show low to moderate degrees of overlap with traffic depending on site-specific patterns, and (3) species whose distribution is completely disjunct from that of the traffic (no overlap).

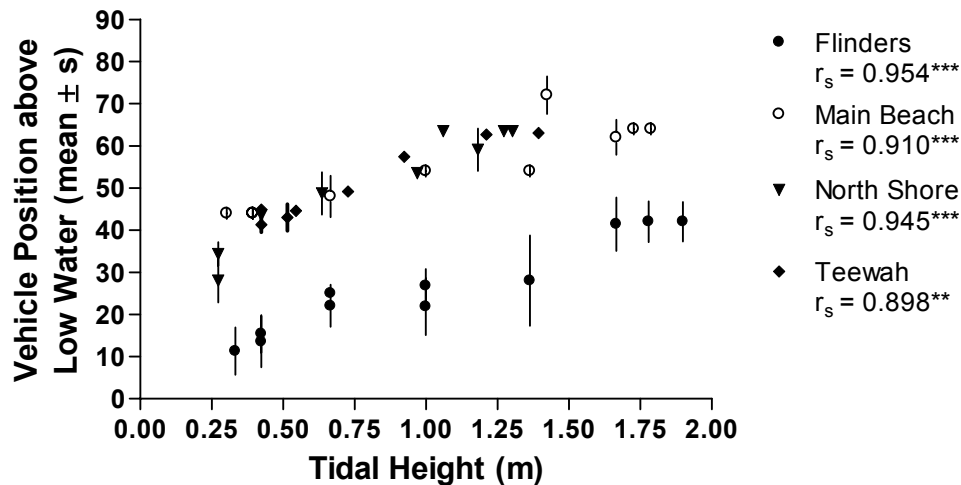


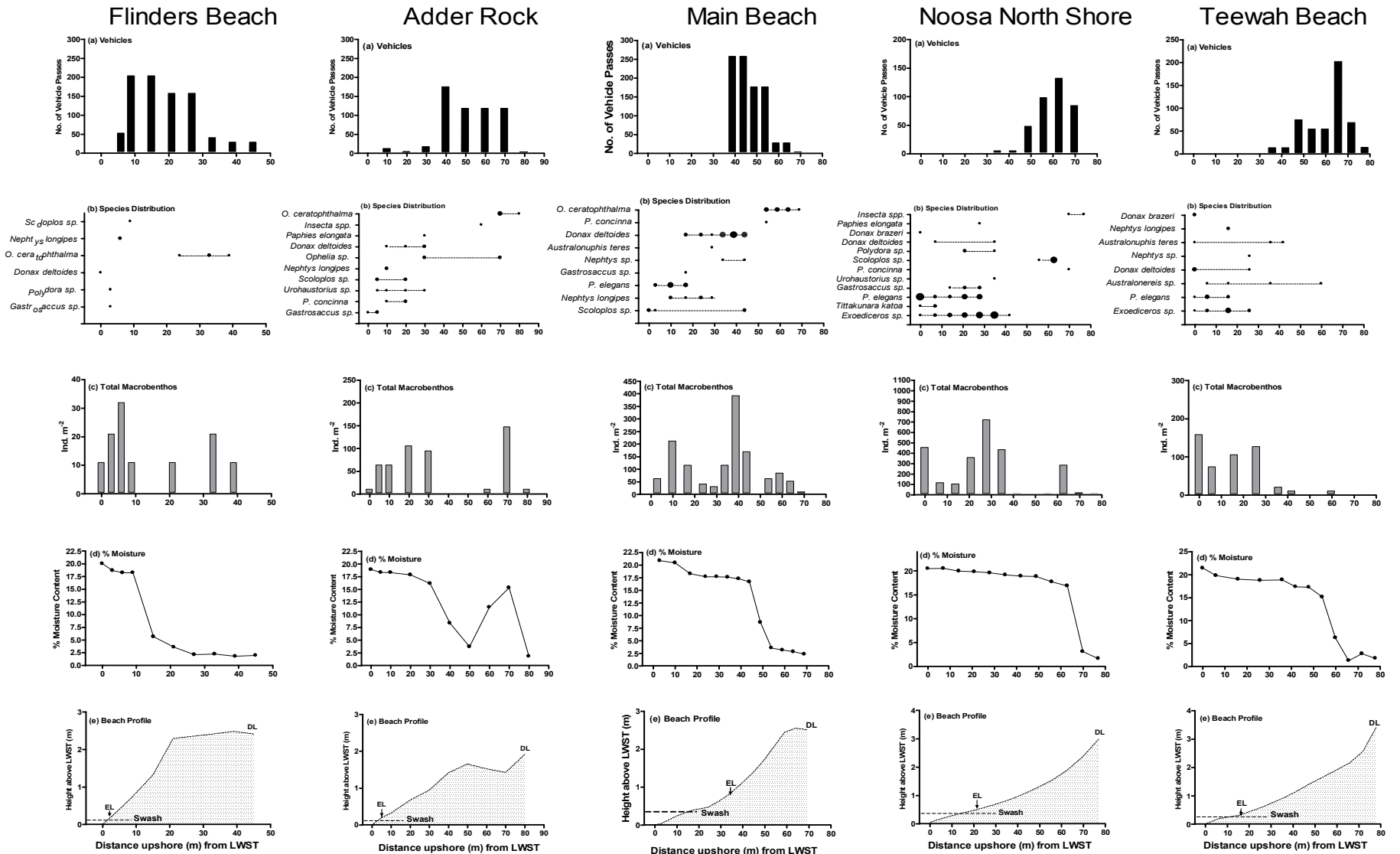
Fig. 17 Position of vehicles across the beachface in relation to tidal height.

At least five species occurred close to, or directly under the zone of heaviest traffic (Table 5, Fig. 18). The overlap between the distribution of these species and traffic could be as high as 69 %, indicating that the majority of individuals live in heavy traffic areas (Table 5). This group, which is potentially most heavily impacted upon by ORVs, comprised mostly species of the upper, dry shore (the ghost crab *Ocypode ceratophthalma* and the isopod *Pseudolanna concinna*), as well as species that straddle the upper- and middle zone of the beach (the polychaetes *Scoloplos sp.* and *Nephtys longipes*, and the surf clam *Donax deltoides*; Table 5, Fig. 18).

Table 5: Overlap* (%) in the distribution between beach traffic and macrobenthos species. Tabulated values are means across three transects per beach with ranges in parentheses. Zero values indicate that a species was present on the beach, but its distribution did not overlap with that of traffic, while hyphens (-) denote that a species was not recorded on a particular beach.

	Flinders Beach		Adder Rock		Main Beach		Teewah Beach		North Shore	
<i>Austrolepidopa schmitti</i>	-	-	-	-	-	-	0	(0-0)	-	-
<i>Matuta planipes</i>	-	-	-	-	-	-	-	-	0	(0-1)
<i>Glycera sp.</i>	-	-	-	-	0	(0-0)	-	-	-	-
<i>Lumbrinereis sp.</i>	-	-	-	-	-	-	-	-	0	(0-0)
<i>Tittakunara katoa</i>	-	-	-	-	0	(0-0)	-	-	0	(0-0)
<i>Polinices incei</i>	-	-	0	(0-0)	0	(0-0)	-	-	-	-
<i>Donax brazeri</i>	-	-	-	-	-	-	0	(0-0)	0	(0-0)
<i>Pseudolana elegans</i>	-	-	0	(0-0)	0	(0-0)	0	(0-0)	0	(0-0)
<i>Exoediceros sp.</i>	-	-	-	-	0	(0-0)	0	(0-0)	1	(1-2)
<i>Gastrosaccus sp.</i>	0	(0-0)	1	(0-4)	0	(0-0)	0	(0-0)	0	(0-1)
<i>Paphies elongata</i>	-	-	2	(0-5)	-	-	-	-	0	(0-0)
<i>Australonuphis teres</i>	-	-	-	-	0	(0-0)	3	(3-3)	0	(0-0)
<i>Urohaustorius sp.</i>	-	-	11	(5-25)	0	(0-0)	-	-	0	(0-0)
<i>Australonereis sp.</i>	-	-	-	-	0	(0-0)	16	(0-47)	-	-
<i>Insecta</i>	-	-	4	(0-4)	0	(0-0)	-	-	15	(0-23)
<i>Nephtys sp.</i>	-	-	2	(0-5)	15	(0-28)	3	(0-9)	0	(0-0)
<i>Polydora sp.</i>	0	(0-0)	0	(0-0)	19	(0-50)	0	(0-0)	1	(1-2)
<i>Ophelia sp.</i>	-	-	16	(12-18)	6	(0-18)	-	-	-	-
<i>Pseudolana concinna</i>	-	-	7	(5-12)	13	(11-19)	1	(0-3)	9	(3-24)
<i>Nephtys longipes</i>	28	(11-52)	3	(0-4)	6	(0-19)	1	(0-3)	0	(0-0)
<i>Donax deltooides</i> (juveniles)	4	(0-11)	16	(3-29)	18	(0-36)	1	(0-3)	0	(0-1)
<i>Donax deltooides</i> (adults)	0	(0-0)	0	(0-0)	36	(37-50)	0	(0-0)	0	(0-0)
<i>Donax deltooides</i> (all)	4	(0-11)	16	(3-27)	36	(32-47)	1	(0-3)	0	(0-1)
<i>Ocypode ceratophthalma</i>	12	(9-28)	19	(13-30)	27	(26-29)	-	-	-	-
<i>Scoloplos sp.</i>	7	(0-21)	1	(1-1)	30	(27-69)	12	(0-23)	41	(36-50)
Total Fauna	38	(29-41)	28	(17-33)	48	(43-52)	13	(5-17)	7	(3-14)

* Measure of overlap is Bray-Curtis resemblance function on standardized data of macrobenthos abundance and vehicle passes. This is conceptually akin to a conventional analysis of species distributions (Clarke 1993), only that vehicles are taken as an 'extra' species.



Legend

- 0-11 Ind. m⁻²
- 50-100 Ind. m⁻²
- 200-400 Ind. m⁻²

Fig. 18 Cross-shore profiles of a) vehicle traffic, b) macrobenthic species distributions, c) density of total macrofauna, d) sand moisture, and e) beach elevation.

Ten species showed varying degrees of overlap with ORVs, and this depended to a large extent on their specific distributions on a particular beach (Table 5, Fig. 18). For example, the polychaete *Polydora* sp. occurred outside the traffic zone on three beaches, but on Main Beach up to 50 % of the population overlapped with beach traffic. Similarly, the bivalve *Paphies elongata* was found on two beaches only, and overlap could reach 5 % on one beach but was zero on another beach (Table 5).

The third group of eight species had distributions that did not overlap with that of vehicles on any of the beaches surveyed. These were mainly species occurring below the effluent line and in the swash zone (Fig. 18, Table 5), including two species of decapods (*Austrolepidopa schmitti*, *Matuta planipes*), the amphipod *Tittakunara katoa*, the isopod *Pseudolanna elegans*, two species of polychaetes (*Glycera* sp. and *Lumbrinereis* sp.) the gastropod *Polinices incei*, and the bivalve *Donax brazeri*. Since few if any vehicles drive below the effluent line and in the swash, this section of the beach may provide a spatial refuge for certain taxa from vehicle impacts.

Discussion

Impacts to the backshore area and dunes are generally regarded as more severe compared to the foreshore (Broadhead & Godfrey 1977, Leatherman & Godfrey 1979, Godfrey & Godfrey 1980, Anders & Leatherman 1987a, Buick & Paton 1989, van der Merwe & van der Merwe 1991, Rickard et al. 1994, Hockings & Twyford 1997, Stephenson 1999, Brown & McLachlan 2002, Atkinson & Clark 2003, Priskin 2003b). Consequently, a frequent recommendation to ORV users on beaches is to drive on the hard, compacted sand low on the beach-face. Yet, this study has shown that a considerable fraction of beach traffic does occur on the upper beach near the foredunes. It also demonstrates that shifting traffic to the lower shore would result in a direct overlap with the benthic invertebrates inhabiting this zone of the beach.

Advisory signs on beaches and driver education campaigns urge drivers to drive on the mid- to lower beach during low tides, and to avoid driving on the beach when the tide is high (2003, Carter 2005, Summers 2005). This does, however, only partly tally with the real-world traffic patterns observed by us. Driver behaviour was strongly influenced by tides and the morphological properties of the beachface, such as the position of the swash, sand moisture, and the position of the effluent line. Human behaviour also plays a role in determining traffic patterns: during the survey at Adder Rock, several cars parked on the mid- to lower shore and this forced all other traffic further up the beach towards the dunes (Fig. 18).

Also, we observed that drivers tend to follow previous drivers and tracks. Because some drivers seem reluctant to stray from the “beaten track”, traffic can concentrate on the upper shore even though the mid- to lower zones (above the effluent line and swash zone) may be more suitable for driving in terms of sediment compactness. Such “channelling” of traffic into pre-existing tracks made during previous high tides on the upper shore can lead to severe and deep rutting of the beach. Environmental impacts to the upper beach and dunes (Leatherman & Long 1978, Godfrey & Godfrey 1980, van der Merwe 1988, Atkinson & Clark 2003) are predicted to be more severe on beaches that receive high traffic volumes throughout the year, especially if traffic is not purely recreational and also occurs during high tides.

People use ORVs on these beaches for either recreational reasons or beaches simply serve as roads. All beaches surveyed here are popular fishing spots and allow at some stretches camping in the dunes. Access to these camping areas necessitates driving on the beach. In Queensland, the zoning of certain areas on the landward fringes of the stable dunes as conservation zones has meant that access roads along the back of the dunes have not been developed (Hockings & Twyford 1997, Banks & Skilleter 2002, Summers 2005, Moss & McPhee 2006).

The northern beaches are a designated road and provide the fastest route to popular tourist destination and coastal settlements compared with regular roads situated further inland (Summers 2005). Thus, beach traffic can be predominately recreational (Stradbroke Island), or a mix between “regular road usage” and recreational pursuits (Teewah and North Shore).

Most (65 %) taxa recorded were exposed to varying degrees to ORV traffic (Table 5, Fig. 18). Traffic overlapped most strongly with species whose habitat is the upper beach (the ghost crab *O. ceratophthalma* and the isopod *P. concinna*), or the upper section of the middle shore (the polychaetes *Nephtys longipes*, and *Scoloplos sp.*, the bivalve *D. deltoides*). All species are efficient burrowers and this may potentially afford some protection from vehicles.

Ghost crabs may suffer little mortality from ORVs when buried in the sand, but are killed in large numbers by ORVs when they forage at the surface at night (Wolcott & Wolcott 1984). On North Stradbroke Island, ghost crab numbers were reported to be significantly lower on beaches with ORV traffic, and this contrast is hypothesized to be due to nocturnal beach traffic crushing the surface-active crabs (Moss & McPhee 2006). No quantitative data on ORV-caused mortality to crabs either inside or outside their burrows are, however, available. Thus, a direct link to beach traffic is presently a possibility (Moss & McPhee 2006), but unproven explanation for observed declines in ghost crab populations on ORV beaches. Beach clams can suffer appreciable mortality (crushing) from ORVs (van der Merwe & van der Merwe 1991), but mortality rates probably depend on sediment properties, sensitivity of the organisms (e.g. shell thickness), and traffic volumes.

This information is currently not available for Australian beaches and species, and thus predictions about possible mortalities are speculative. Similarly, no data of possible ORV-induced mortality to polychaetes and isopods (which can overlap considerably with traffic) are presently available. Again, these are

burrowing organisms (5-10 cm into the sand) and burrowing may ameliorate direct crushing; shear stress of ORVs can, however, penetrate up to 30 cm into the sand (Atkinson & Clark 2003). Species whose distribution is centred below the effluent line and in the swash zone appear to occupy a 'spatial refuge' from ORV traffic, and impacts could apparently be considered negligible. Such a conclusion may, however, not be warranted if species of the swash zone are more susceptible to vehicle traffic (van der Merwe & van der Merwe 1991), implying that even occasional vehicle passes could inflict mortality.

The use of off-road vehicles (ORVs) on sandy shores presents a formidable management challenge (James 2000b, Celliers et al. 2004). Whether recreational beach traffic is appropriate or permissible depends to a large degree on the perceptions of different user groups, some of which view ORVs as highly environmental damaging (Priskin 2003a-b). In fact, the topic can spawn intense public debate (Carter 2005), and has the potential to create social conflict between different beach user groups (Priskin 2003a-b). At the core of such arguments lie reports about negative environmental impacts of ORVs (Moss & McPhee 2006), juxtaposed by economic benefits derived from recreational ORV traffic and the demand for recreational (e.g. fishing, camping) opportunities (Carter 2005).

This situation places considerable pressure on authorities responsible for managing beaches (e.g. regulation of vehicle access and traffic volumes) to meet the needs and aspirations of multiple users with often conflicting interests (James 2000a, Celliers et al. 2004, Carter 2005). On Queensland beaches open to ORVs, currently no rules govern total traffic volumes, areas of the beach-face open to driving, or the times when beach driving is permitted. There are, however, some suggestions to limit beach traffic to daylight hours (Moss & McPhee 2006), and to prohibit driving during high tides to protect the upper shore (Carter 2005). The basic rationale for such measures appears to be the notion that the more compact areas of the lower- and middle beach are less

prone to ORV damage. Yet, we have shown that concentrating beach traffic to this zone may expose a larger proportion of the intertidal fauna to vehicles.

Presently it appears, however, unjustified to implement concrete management responses based on these findings, because sound management of beach traffic is multi-faceted and requires the consideration of social- and economic factors (James 2000b, Celliers et al. 2004) - both un-quantified for the local situation. Similarly, a pattern – irrespective of how strong or convincing it is – of overlap between faunal habitat and beach traffic does not automatically demonstrate an ecological effect if the mechanisms are unknown or not quantified. While it stands to reason that ORVs may affect the intertidal invertebrates of beaches (van der Merwe & van der Merwe 1991), defensible and well-informed management actions require additional data on: a) the mechanisms which may produce any putative ecological impacts, b) the sensitivity of the fauna to traffic (biological response strength), and c) whether individual species responses to ORVs propagate to measurable effects for whole ecological communities.

Conclusion

Three key points emerged from this study: (1) traffic volumes on beaches can be considerable (up to 500 vehicles per day) and the position of beach traffic is principally governed by tides and driver behaviour, (2) the majority of ORV traffic was concentrated on the middle to upper shore, and 3) the majority of burrowing invertebrate species of the intertidal zone are directly exposed, at varying degrees, to traffic, save for species inhabiting the swash zone. The ecological impacts of beach traffic are, however, not predictable at present because the specific responses (e.g. mortality rates) of potentially impacted species to varying intensities of traffic remain un-quantified. Quantification of both traffic patterns and their concordance with invertebrate distributions is, however, a fundamental first step to identify whether such impacts are likely. It can also underpin the management of beach traffic by broadening the information base in

decision making through provision of quantitative data on both human pressures (e.g. traffic patterns) and their spatial relationship to biological resources on sandy shores.

Chapter 4: Estimating Direct Mortalities of Ghost Crabs by Off-Road Vehicle (ORV) Beach Traffic on North Stradbroke Island

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Summary

A recent study by Moss & McPhee (2006) suggested that beaches exposed to off-road vehicle traffic on North Stradbroke Island had significantly lower populations of the ghost crab *Ocypode cordimana* when compared with beaches that did not receive any vehicle traffic. Because of some ambiguity surrounding the results of this study, further research was undertaken to assess the extent to which ghost crabs are affected by direct impacts of recreational four wheel driving. During the course of the current study various aspects assessed included:

- 1) Vehicle traffic impacts under natural and experimental conditions during daylight hours when crabs are in burrows,
- 2) Impacts of nocturnal traffic on ghost crabs on the foreshore when they are foraging and actively out of their burrows,
- 3) The assessment of ghost crab populations (including both *Ocypode ceratophthalma* and *O. cordimana*) using active burrow counts between areas of low, moderate and heavy vehicle traffic.
- 4) Measurements of night-time vehicle traffic on Flinders Beach during a peak holiday period.

The results indicate that smaller crabs found in shallower burrows are quite susceptible to impacts, whereas larger crabs in deeper burrows are more immune to traffic. Populations of ghost crabs between the areas of different traffic intensity were found to be significantly different with the area of low/nil

traffic having a higher number of active burrows than the moderate, and heavy impact areas. Crab mortalities of nocturnal vehicle traffic after four separate experimental passes killed 78 crabs representing 0.5% of the affected population over 900m. Thus, declines in population sizes may not be directly influenced by low intensities of night vehicle traffic alone. Previous research on North Stradbroke Island (Schlacher & Thompson 2006b) and the current study indicate that combined indirect impacts of habitat destruction and direct impacts to crabs by ORVs may all be contributing to decreased numbers of crabs on beaches exposed to traffic.

Introduction

Due to their burrows being easily visible on the upper shore, ghost crabs would be one of – if not the most obvious organism living on beaches. During the day ghost crabs can be observed maintaining burrows and active crab burrows are noticeable by fresh excavated sand surrounding the burrow opening (Barrass 1963, Wolcott 1978, Davie 1998). Barros (2002) suggested and successfully tested the use of ghost crab burrow counts as a rapid measure of human influence on beaches. Some studies (Moss & McPhee 2006) and personal observations (Thompson pers. obs.) support this method where ORV-accessible beaches and ORV-free beaches are compared, if only active burrows are examined.

While Moss & McPhee (2006) suggest that mortalities caused by vehicles at night would be the main cause of the population decline, as seen in overseas studies (Wolcott & Wolcott 1984) this, along with other direct causes (e.g. crushing in burrows during the day) and indirect causes (e.g. destruction of habitat or changes to prey numbers) remains untested for beaches on North Stradbroke Island and Australia in general. Thompson (2005) found a much lower faunal abundance on the upper shore of beaches with ORV access compared to beaches without ORVs on the northern beaches of the Sunshine Coast. Similarly, Moss & McPhee (2006) report that ghost crab numbers are

lower on beaches receiving ORV traffic - their findings have added weight to local concerns about ORVs impacting on fauna of the island's drivable beaches. They suggest that night-time traffic might be the key factor driving this difference through vehicles killing the surface-active crabs at night. Although this is the authors' conclusion no measurements of night vehicle traffic on North Stradbroke Island have been undertaken. An additional mechanism that might cause direct mortality of ghost crabs by ORVs is direct crushing of the crabs while inside their burrows during the day. Both potential mechanisms of direct mortality to ghost crabs by ORVs (e.g. daylight crushing inside their burrows and nocturnal kills at the surface) have not been quantified for the local situation. Thus, this study aimed to quantify direct ORV vehicle impacts on ghost crabs (*Ocypode cordimana* and *O. ceratophthalma*) on North Stradbroke Island.

Methods

Difference in ghost crab population size between traffic areas

To determine whether densities of intertidal ghost crabs are reduced in areas impacted by beach traffic, counts of burrow openings were compared between three adjacent sections of Main Beach that differ substantially in the volume of vehicle traffic. The northernmost section of Main Beach is closed to all non-essential ORV traffic, except for life-saving and police patrols. This traffic 'no-go' area is clearly marked by a large sign on the beach (Figs. 19 & 20). The great majority of recreational 4x4 users obey this exclusion zone and do not travel north into the exclusion zone, except for occasional vehicles that visually appear to miss the sign at night. The "No-vehicle" sign was used as the local reference point in this study, and the section to the north of this sign is designated as the "Low/Nil impact zone" for the purpose of this study. Most ORVs enter Main Beach through a large (ca. 50 m wide) access corridor cut through the dunes approximately 200 m to the south of the exclusion zone (Fig. 20) The vast majority of traffic entering the beach through this corridor turns south and this section consequently receives the greatest volume of traffic

and is designated here as “heavy impact zone”. Much fewer vehicles turn north from the access corridor, but some volume of traffic was observed between the access point and the exclusion zone further north. This central section is designated here as the “moderate impact zone” (Fig. 20).

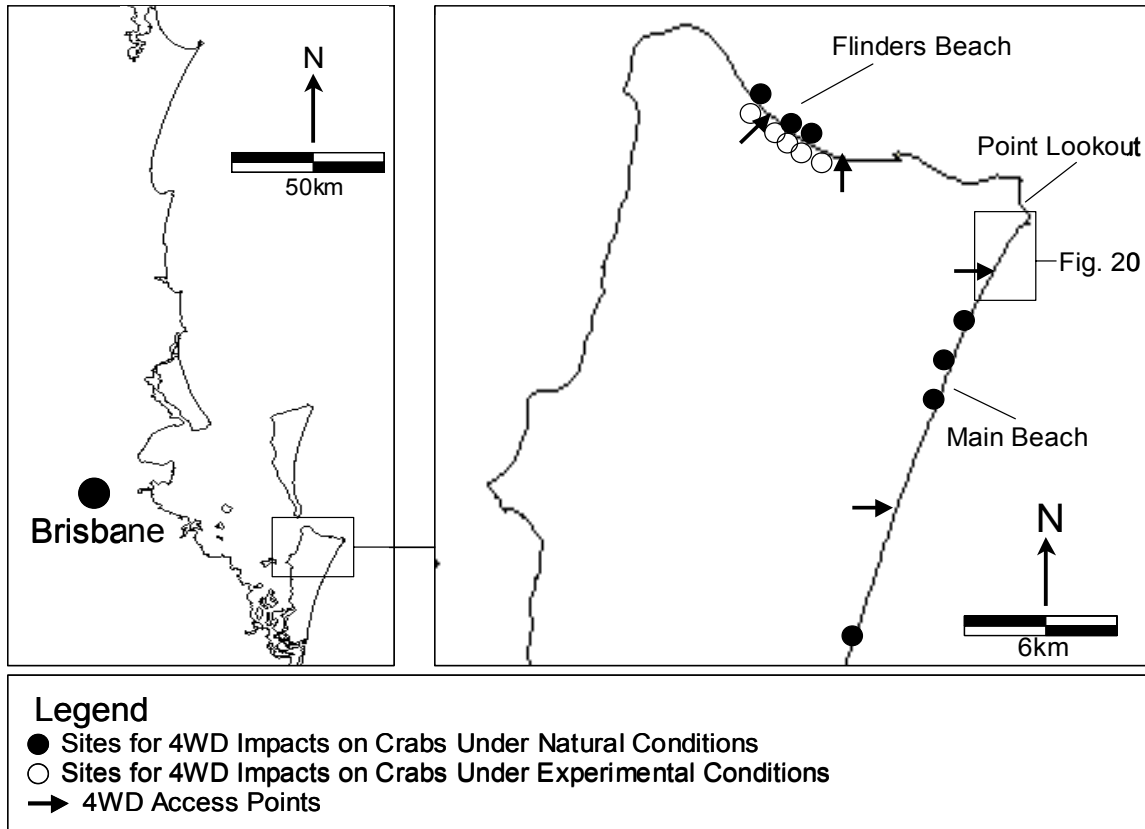


Fig. 19 Location of study sites at which experiments were conducted to determine the proportion of ghost crabs crushed by ORVs inside their natural burrows (open symbols) and in simulated burrows the primarily test the effect of depth (solid symbols). “Fig. 20” in right panel denotes the area where experiments were run at night to measure the number of crabs killed by night-time traffic.

Crab densities were assessed from counts of burrow openings. In each of the three traffic zones, counts were made at 4-7 sites spaced 50 m apart along the beach. At each site, burrow openings were counted in 10 m wide shore-perpendicular transects. Transects were divided into 3 m wide strips, starting at the base of the foredune and progressing down-shore to the limit of the crab distribution. All active burrow openings were counted in each of these 3 x 10 m

sections and the diameter each burrow opening measured to the nearest millimetre.

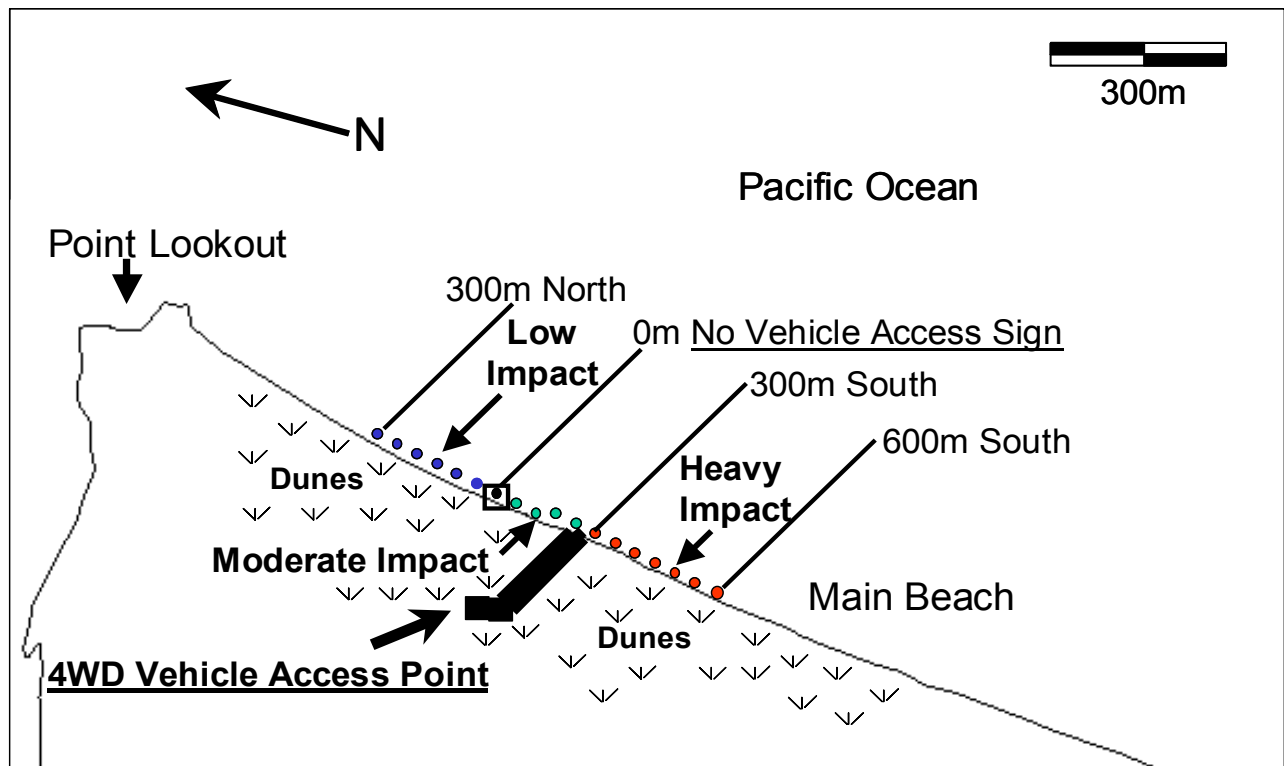


Fig. 20 Spatial layout of traffic zones for which the density of ghost crabs was compared at the Northern tip of Main Beach. ORVs access the beach via a corridor cut into the dunes. The bulk of the traffic travels south through the “heavy impact” zone, while much fewer vehicles travel north from the access point and none into the designated exclusion zone at the northernmost end. Each point presents a survey site at which crab densities were assessed through counts of active burrow openings.

Direct impacts of ORVs on ghost crabs: experiments to quantify crushing rates

We ran three types of experiments to quantifying direct mortalities inflicted by ORVs on ghost crabs. All experiments were conducted from April to June 2006 on Main- and Flinders Beach at North Stradbroke Island (Fig. 20). In experiments 1 and 2 we measured the proportion of crabs crushed inside their burrows during daylight hours at various intensities of traffic and at different depth inside the sediment. In experiments 3 we quantified the number of crabs

run-over by night-time traffic after the crabs had emerged from their burrows to feed on the surface of the beach.

Experiment 1: crushing of ghost crabs by ORVs inside natural burrows

Mortality of crabs inside their burrows during the day that is inflicted directly by ORVs via physical crushing of individuals when cars pass over crab burrows was measured in six experimental runs. For each experimental run we first chose a site on the middle to upper beach that showed no obvious signs of recent vehicle passes but had a reasonable number of active crab burrow openings. A 10-20 m long (depending on burrow density) and 20 cm wide (corresponding to the tyre width of vehicles) plot that ran parallel to the foredunes was marked out.

Each crab burrow opening in a plot was numbered and the opening diameter measured. The length (depth) of the burrow was measured by inserting a soft, pliable vine and the angle of the burrow with a protractor. After burrow dimensions had been recorded, a soft marking ribbon (textile flagging tape) was inserted into each burrow down to the base, using the same soft vine to avoid damage to crabs. A procedural control treatment indicated that crabs were not harmed by this procedure (Table 11). Excess ribbon was left on the sand surface in order to re-locate burrow openings after the vehicles passes. After all burrows had been marked as above, an ORV vehicle (Nissan Patrol) was driven repeatedly over the burrows. Six traffic densities were tested at 5, 10, 15, 20, 25, 30 and vehicle passes over the burrows.

Following the application of the vehicle treatments, each burrow was carefully excavated by hand and all ghost crabs retrieved were inspected for damage and their carapace width recorded. In most cases mortality was highly obvious (e.g. completely crushed or macerated specimens, most limbs missing or carapace badly dented, etc.). In a few cases where the retrieved crabs were immobile but

showed no gross external sign of physical damage, these immobile individuals were placed on the sand free to run or burrow: crabs that did not re-gain mobility after one hour were judged to be dead.

In each experiment, sand compactness (kgf cm^{-2}) was measured at 7-10 positions along the vehicle track using a pocket penetrometer before and after the application of the vehicle treatments. Triplicate sand cores (10 cm deep) were collected from each plot to determine sand moisture content and granulometry. After the vehicle passes, the depth of the tyre tracks was recorded at 7-10 positions along the track. We also recorded the position of each experimental plot relative to the low-water spring tide (LWST) mark and surveyed the beach profile with a theodolite. All experiments were done during off-peak holiday periods when beach traffic is lighter. Experiments were run in the early morning to enable ready identification of burrow openings before they could be obliterated by wind.

Experiment 2: crushing of ghost crabs by ORVs in simulated burrows: effects of depth and traffic intensity

This experiment's principal aim was to determine the effect of burrow depth in ameliorating crushing impacts of ORVs on ghost crabs; the predictive hypothesis was that fewer crabs would be killed when burrowed deeper as the overlying sediment matrix should offer protection from the physical impacts of vehicles.

The experimental procedure was generally similar to experiment 1 (e.g. selection of undisturbed plots, recording of sediment parameters, use of flagging tapes to re-located burrows, inspection of damage after vehicle passes etc), except that crabs were first captured from natural burrows and then introduced to experimental burrows at various depths (5, 10, 15, 20, and 30 cm). Crabs used in these experiments were carefully excavated from their natural burrows within 50 m of the experimental plot and used within 30 minutes of capture.

We made the experimental burrows by removing sediment plugs to the desired depth with a corer of 5 cm diameter, introducing the crabs to the bottom of these burrows, and loosely covering them with sand. Crabs were randomly allocated to treatments and all individuals used in single experimental run were introduced to the burrows within 10 min of each other. After all crabs had been introduced to the burrows, the vehicle treatments were applied by repeatedly driving over the experimental burrows.

Two intensities of traffic were tested, with 10 passes corresponding to “low-medium” traffic and 40 passes to “heavy traffic”. Ten experimental individuals were used per traffic x depth combination. To check for any possible handling errors that might have injured crabs in the absence of vehicle impacts, we conducted six procedural controls in which crabs were introduced to burrows and retrieved after 10-30 min without the application of vehicle passes; these procedural controls were run at the same time as the vehicle treatments and in the same location about 1 m from the experimental vehicle tracks.

Experiment 3: ghost crabs killed by night-time traffic while surface-active

To quantify the number of crabs killed by night-time traffic, a ORV was driven down the beach on four occasions. On each occasion a single vehicle pass was completed. We aimed to cover the entire beach section that was surveyed for ghost crab population sizes (Fig. 20), but this was logistically not possible because of hazardous driving conditions (e.g. soft sand, strong swash, etc). Night time traffic counts were conducted on Main Beach and Flinders Beach over the Christmas/ New Year holiday period. Traffic counts were conducted 300m south of the middle 4WD access point on Flinders Beach and at 100m south of the causeway access point on Main Beach. The beach was carefully divided into 10m zones so that researchers could observe traffic, but did not influence driver behaviour. The counts were conducted as a preliminary analysis to get a general idea of traffic intensity during a peak holiday period.

Results

Ghost crab population size in relation to areas of different traffic intensity

Habitat variables

Key habitat variables did not differ significantly between sections of different traffic volumes (Table 6, Fig. 21), sand moisture was highly similar between traffic sections (ANOVA, $F_{(2,51)} = 0.41$, $P_{(2)} = 0.66$), as was sediment grain size (ANOVA, $F_{(2,51)} = 1.87$, $P_{(2)} = 0.16$), and slope of the intertidal zone where crab burrows were encountered (ANOVA, $F_{(2,15)} = 2.73$, $P_{(2)} = 0.10$). Thus, differences in habitat characteristics are unlikely to be the primary drivers of differences in ghost crab densities.

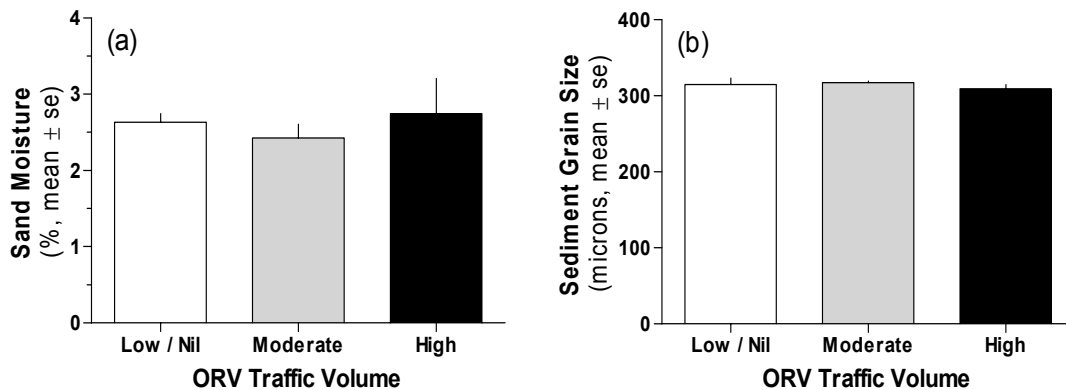


Fig 21 Comparison of (a) sand moisture content and (b) sand grain size between sections of the beach with different traffic volumes in which ghost crab densities were assessed.

Crab abundance and distribution

Densities of ghost crabs (as judged from counts of active burrow openings) were significantly higher on those sections of the beach located north of the ORV access point that received only very low or moderate amounts of traffic (Table 7, Fig. 22; 2-way-ANOVA, effect traffic intensity: $F_{(2,90)} = 15.68$, $P_{(2)} < 0.001$). By contrast, ghost crab numbers were reduced by 42 to 48% on the section south of the access point, which received high volumes of beach traffic (Table 7);

Table 6: The physical variables tested for the sites where burrow counts were completed. Analysis of variance showed no significant difference ($P>0.05$) between slope 1/100, % sand moisture content, and grain size (ϕ , mm) between the different sites.

Zone	(m) from No Vehicle Access Sign	Slope (1/100)	% Sand Moisture Content			Grain Size (ϕ , mm)		
			mean	SD	n	mean	SD	n
Heavy Traffic Area	600	10.0	1.6	± 0.48	3	297.9	± 7.27	3
	550	9.4	2	± 0.58	3	311.2	± 25.5	3
	500	9.9	1.9	± 0.67	3	293.9	± 3.91	3
	450	12.6	5	± 1.88	3	318.9	± 20.8	3
	400	12.8	2.5	± 0.35	3	295.1	± 15.4	3
	350	10.3	3.8	± 2.38	3	331.4	± 7.62	3
	300	11.9	2.4	± 0.54	3	315	± 19.9	3
Moderate Traffic Area	200	12.8	2.2	± 0.34	3	319.7	± 12.4	3
	150	11.6	2.1	± 0.4	3	311.7	± 7.85	3
	100	12.4	2.5	± 0.28	3	315.9	± 18.9	3
	50	12	2.9	± 0.53	3	320.6	± 7.96	3
No Vehicle Area	0	10.2	3	± 0.49	3	295.2	± 4.63	3
	50	9.9	2.4	± 0.2	3	277.4	± 27.3	3
	100	12.5	2.4	± 0.4	3	336.8	± 1.29	3
	150	10.9	2.3	± 0.29	3	318.6	± 16.5	3
	200	11.2	3	± 0.25	3	308	± 4.98	3
	250	8.7	2.5	± 0.43	3	331.5	± 6.28	3
	300	6.9	2.8	± 0.26	3	333.7	± 6.57	3

Table 7: Comparison of ghost crab abundances between three sections of the beach receiving different amounts of beach traffic.

(tabulated values are the number of active burrow openings per 30 m² counted in 10 m long plots sequentially distributed at 3 m interval from the base of the foredune to the lowest downshore position at which crabs were found).

Distance downshore from foredune	Low / No Traffic (7 Sites)		Moderate Traffic (4 Sites)		Heavy Traffic (7 Sites)	
	mean	± (s)	mean	± (s)	mean	± (s)
0-3 m	132.6	± (45.15)	134.0	± (36.80)	85.71	± (60.88)
3-6 m	55.4	± (26.30)	38.3	± (24.54)	19.14	± (19.49)
6-9 m	20.3	± (11.86)	18.5	± (19.97)	6.43	± (7.41)
9-12 m	9.3	± (9.72)	7.5	± (5.80)	3.43	± (4.61)
12-15 m	1.6	± (1.72)	1.3	± (1.89)	0.43	± (1.13)
15-18 m	0.7	± (1.50)	0.3	± (0.50)	0.00	± (0.00)
Entire beachface	219.9	± (84.97)	199.8	± (64.49)	115.14	(87.03)

this effect of lower ghost-crab abundance in the area of heavy beach traffic was consistent across all levels of the beach (i.e. ANOVA interaction term - traffic x level: $F_{(10,90)} = 0.75$, $P_{(2)} < 0.68$). This decrease in ghost crab numbers in areas with heavy traffic was most pronounced for the upper shore abutting the base of the foredunes (Table 7, Fig. 23). The distribution of ghost crabs across the beachface also differed between traffic sections (Fig. 22). A significantly (ANOVA, $F_{(2,15)} = 4.97$, $P_{(2)} = 0.02$) smaller percentage of the population was found living below the drift line in the area of heavy traffic. At four out of seven sites surveyed in the heavy traffic area, no active burrow openings were encountered below the drift line, whereas all sites in both the moderate and low traffic area had 2 – 13 % of the intertidal population of crabs located below the drift line (Fig. 22 & 23). Most beach traffic is concentrated below the drift line, a pattern that mirrors the more pronounced decline of ghost crab numbers in this zone.

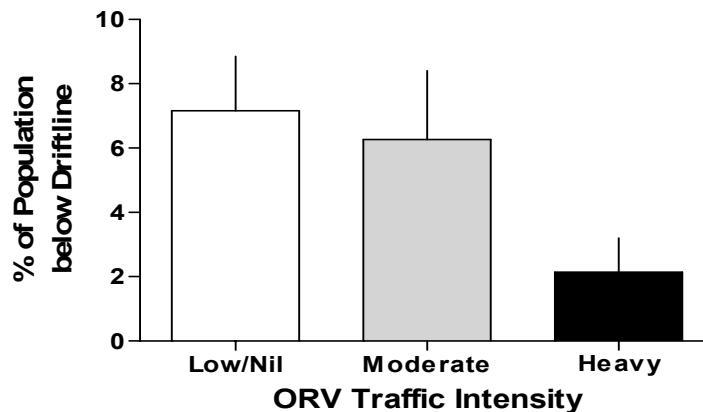


Fig 22: Proportion of ghost crabs distributed below the drift line which corresponds broadly to the area of heaviest traffic concentration across the beachface.

Size structure

Burrow openings were significantly smaller in areas with beach traffic compared with the reference area from which recreational ORVs are banned (Figs. 23 & 24, Table 8).

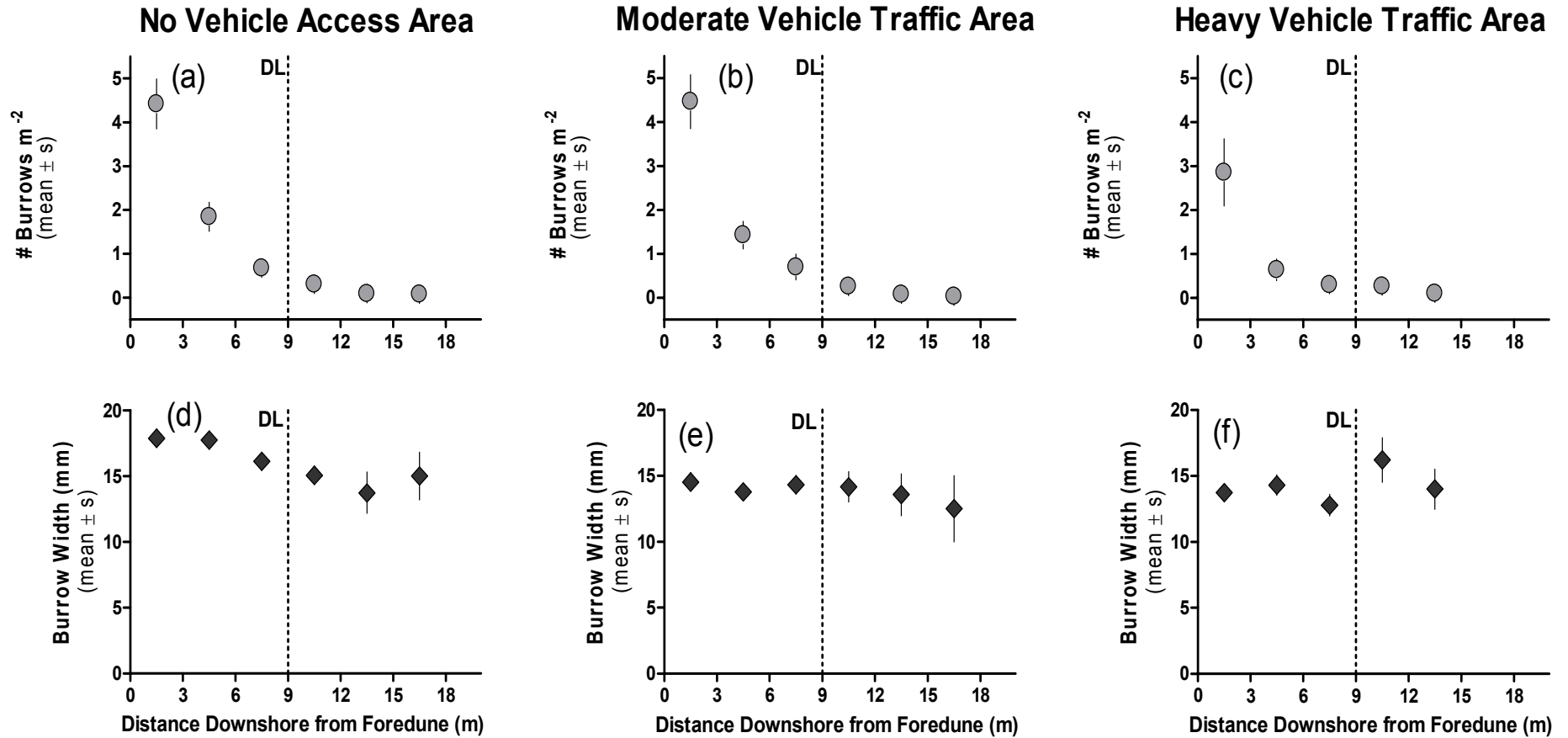


Fig. 23 Comparison of burrow openings between sections of the beach receiving different volumes of traffic (top panels) and size of burrow openings (bottom panel).

Since the size of burrows is a function of crab size (correlation between surface burrow diameter and carapace width of crabs $r = +0.67^{***}$), spatial differences in burrow dimensions indicate shifts in population size structure. In fact, in areas heavily impacted by ORVs, fewer large crabs were found and the populations were more strongly dominated by juveniles. This shift in population structure might be a consequence of large individuals being killed in disproportional high numbers by ORVs. This reduction of burrow opening size was most pronounced on the upper shore close to the foredunes (Table 8; Figs. 23 & 24).

Table 8: Comparison of the size of ghost crab surface burrow openings (mm) between three sections of the beach receiving different amounts of beach traffic, at varying distance downshore from the base of the foredunes.

Distance from foredune	Traffic Area	mean \pm (s)	n	ANOVA	SNK post-hoc test
0-3m	Very Low	17.88 \pm (10.18)	928	F = 51.70	A
	Moderate	14.53 \pm (8.02)	438	df = 2, 1943	B
	Heavy	13.72 \pm (7.27)	580	P = <0.001	B
3-6m	Very Low	17.72 \pm (9.35)	388	F = 22.80	A
	Moderate	13.78 \pm (7.65)	171	df = 2, 690	B
	Heavy	14.31 \pm (8.94)	134	P = <0.001	B
6-9m	Very Low	16.13 \pm (6.85)	142	F = 11.38	A
	Moderate	14.32 \pm (6.59)	84	df = 2, 270	A
	Heavy	12.23 \pm (5.98)	47	P = <0.001	B
9-12m	Very Low	15.06 \pm (4.90)	65	F = 3.515	A
	Moderate	14.28 \pm (6.39)	32	df = 2, 123	Ab
	Heavy	13.97 \pm (9.68)	29	P = <0.033	B
12-15m	Very Low	10.79 \pm (7.42)	14	F = 2.70	A
	Moderate	9.63 \pm (6.86)	8	df = 2, 28	A
	Heavy	4.67 \pm (7.12)	9	P = <0.084	A
15-18m	Very Low	7.50 \pm (8.36)	10	F = 2.96	A
	Moderate	6.25 \pm (7.50)	4	df = 2, 18	A
	Heavy	0.00 \pm (0.00)	7	P = <0.077	A
Entire Beachface	Very Low	17.43 \pm (9.58)	1547	F = 2.96	A
	Moderate	14.22 \pm (7.73)	737	df = 2, 3087	B
	Heavy	13.52 \pm (7.73)	806	P = <0.001	C

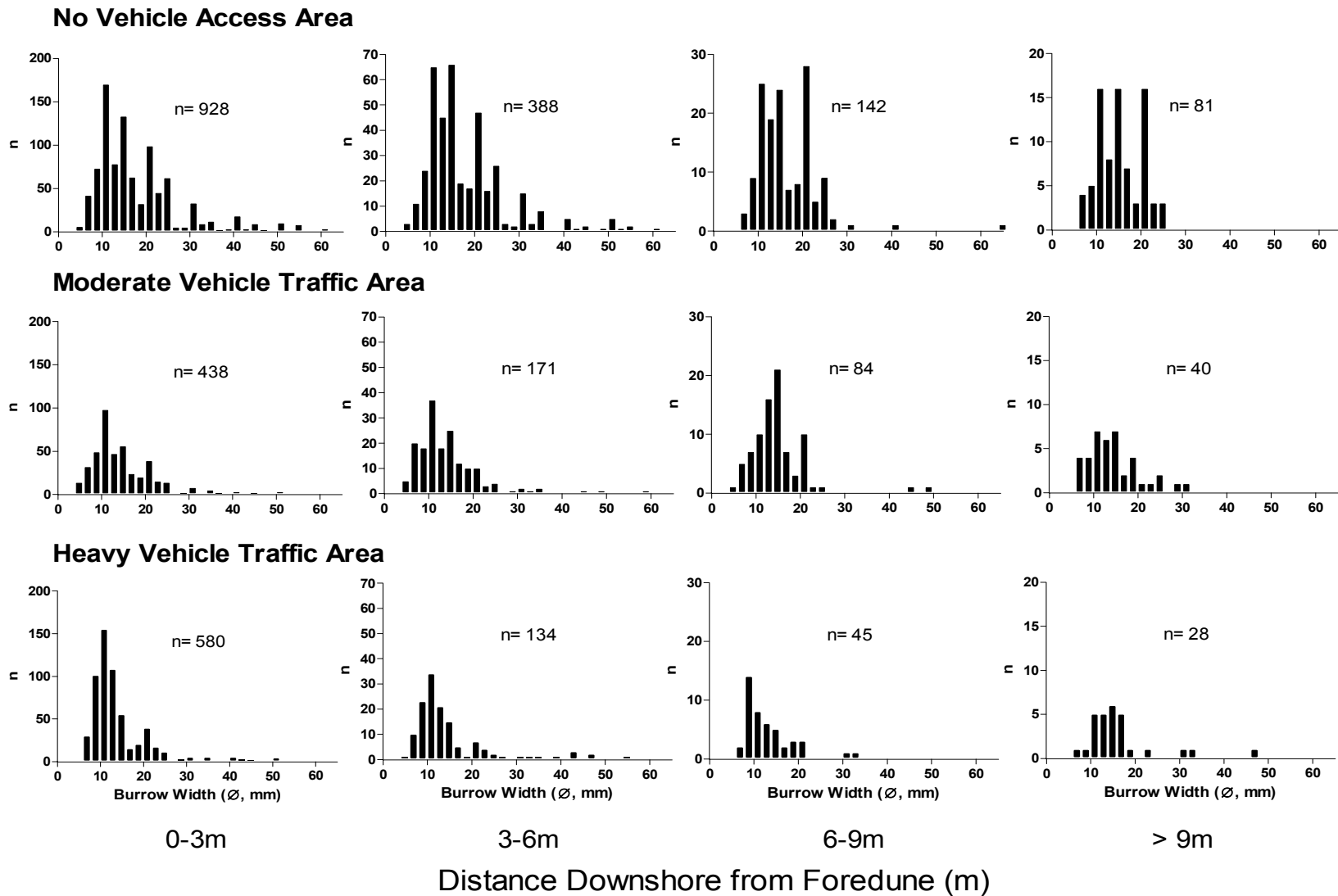


Fig 24: Comparison of size frequencies of ghost crab burrow openings (Ø, mm) between traffic areas.

Crushing of crabs by ORVs inside their burrows

Natural burrow conditions: effects of varying traffic intensity

A total of 97 burrows were examined in the experiments that measured mortality from ORVs while the crabs were inside their natural, un-manipulated burrows. Of these 34% (33 burrows) were occupied by crabs. The mean burrow diameter per experimental site ranged from 10.4 to 26.6 mm and mean depth of crab burrows varied from 20 to 40 cm (Table 9). Compactness of the sand was not measurably affected by low-intensity traffic of 5 vehicle passes, but all traffic intensities above 10 vehicle passes significantly softened the sediment matrix (Table 10). In all cases, the top 5 to 15 cm of the burrows had completely collapsed following the vehicle impact. The mean depth of ruts made by the ORVs ranged from 44 mm after 20 passes in relatively compact sand to 100 mm after 30 passes in soft sand.

Table 9 Locality of experimental plots in which mortalities of ghost crabs inside their un-manipulated burrows were measured.

Beach	Site	# Vehicle Passes	Distance from LWST (m)	Height above LWST (m)	# Burrows examined	Burrow Diameter (mm)		Burrow Depth (cm)	
						mean ± s	mean ± s		
Flinders	1km North of Adder Rock Access	0	76	1.78	12	10.4 ± 3.53	20.3 ± 12.23		
Main	3km North of Causeway Access	5	47	1.59	13	17.2 ± 4.88	37.4 ± 12.11		
Main	4km North of Causeway Access	10	31	1.27	9	12.4 ± 3.40	29.6 ± 5.39		
Flinders	200m South of Middle Access	15	50	1.64	19	14.6 ± 6.70	30.4 ± 13.52		
Flinders	3.5km North of Adder Rock Access	20	53	1.34	11	11.4 ± 2.19	20.2 ± 10.52		
Main	6km South of Causeway Access	25	43	1.64	20	26.6 ± 9.94	38.3 ± 13.44		
Main	3.2km North of Causeway Access	30	47	1.59	13	18.8 ± 6.41	39.8 ± 13.51		

Table 10: Changes in sediment compactness at varying intensities of ORV traffic applied to experimental plots that contained un-manipulated ghost crab burrows. (n = 12 for moisture and granulometry samples).

Vehicle Passes	Sand Moisture (%)	Grain Size (mean, microns)	n	Compactness Before (kgf cm ⁻²)		Compactness After (kgf cm ⁻²)		Δ: After-Before	t	P ₍₂₎
				mean ± s	mean ± s					
5	2.4	260	9	0.7 ± 0.18	0.7 ± 0.06	0	0	1.00		
10	2.8	210	9	2.4 ± 0.32	1.1 ± 0.09	-1.2	11.73	<0.001		
15	3.2	225	15	1.3 ± 0.30	1.0 ± 0.50	-0.3	1.99	0.058		
20	2.0	215	12	2.4 ± 0.36	1.2 ± 0.16	-1.2	10.55	<0.001		
25	1.9	303	15	0.7 ± 0.33	0.4 ± 0.12	-0.3	3.31	0.004		
30	2.1	217	9	0.9 ± 0.24	0.6 ± 0.05	-0.3	3.67	0.006		

Table 11: Summary of experimental results on mortality of ghost crabs impacted at intensities of ORV traffic.

Beach	# Vehicle Passes	Height above LWST (m)	Carapace Width (mm)		# of Crabs Retrieved	Crabs Crushed	% of Burrows Occupied
			mean	SD			
Flinders	0*	1.78	8.0	2.12	5	0 (0)	41.7
Main	5	1.59	12.5	0.70	4	0 (0)	30.8
Main	10	1.27	7.0	0.00	1	0 (0)	11.1
Flinders	15	1.64	7.5	0.58	4	1 (25)	21.1
Flinders	20	1.34	6.6	1.81	7	2 (29)	63.6
Main	25	1.64	12.4	4.50	8	0 (0)	40.0
Main	30	1.59	11.0	5.23	4	0 (0)	30.8

* procedural control

Three crabs out of total of 28 crabs retrieved (11%) were crushed by the experimental vehicle treatments using natural, un-manipulated burrows (Table 11): a single crab was found to be killed at a depth of 23 cm after 15 passes, and 20 vehicle passes killed two crabs at depths of 11 cm and 23 cm. No crab mortalities were recorded at higher intensities of traffic (e.g. 25 and 30 passes), but crabs were buried deeper (39 cm) in these experimental plots (Table 9). In general, smaller crabs were buried shallower in the sediment, while larger crabs construct deeper burrows (correlation between body size and burrow depth: $r = +0.47$, $P_{(2)} < 0.01$). Thus, young individuals may be more vulnerable to traffic impacts when inside their burrows during the day, and the slightly smaller size of killed crabs found in these experiments does suggest this possibility (Fig. 25).

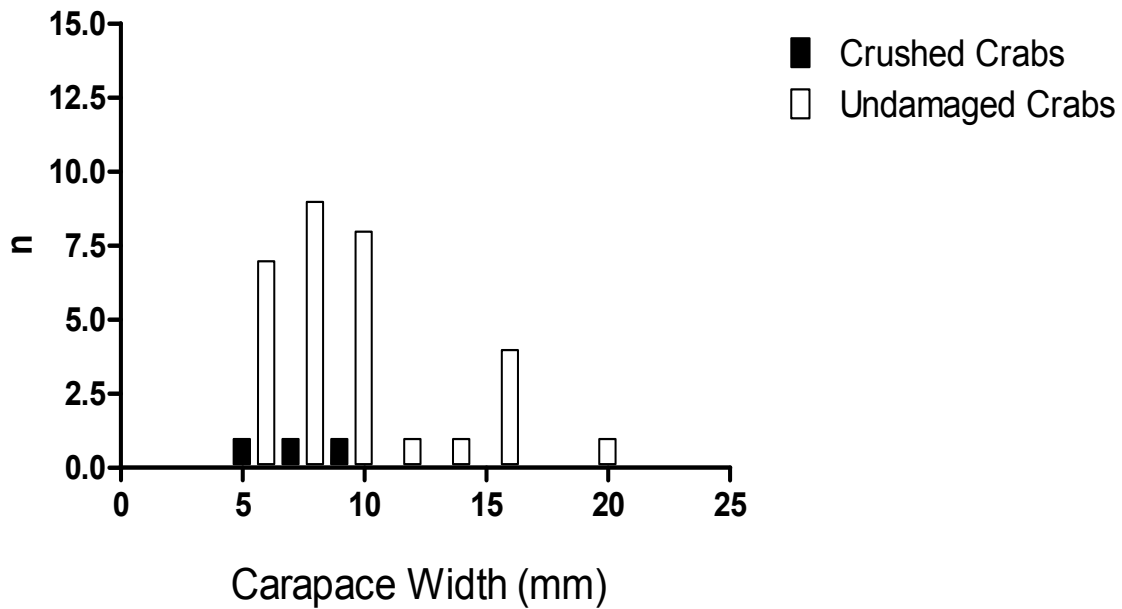


Fig. 25: Size distribution of crushed and undamaged crabs following experimental application of ORV traffic to ghost crab populations under natural conditions. No significant difference was found between the mean of crabs crushed and the population mean ($P=0.31$).

Crab mortality by ORVs at different depths

Changes in sediment compactness following application of vehicle treatments were variable depending on local conditions (e.g. moisture, position on shore) of the experimental plots, but generally resulted in softer sand after ORVs had traversed the beach (Table 12).

Table 12: Changes in sediment compaction following the application of vehicle treatments. The physical properties of the each site (% moisture, sand grain size μm) are also shown.

Vehicle Passes	Depth (cm)	Sand Moisture (%)	Grain Size (microns)	n	Compactness (kgf cm ²) Before		Compactness (kgf cm ²) After		Δ : After-Before	t	P ₍₂₎
					mean	\pm s	mean	\pm s			
10	5	3.0	231	10	2.9	\pm 1.64	1.8	\pm 0.66	-1.1	1.97	0.070
10	5	2.6	271	10	2.3	\pm 0.67	1.7	\pm 0.51	-0.6	2.25	0.038
10	10	3.7	283	15	2.3	\pm 0.46	0.7	\pm 0.33	-1.6	10.95	<0.001
10	10	4.0	243	15	1.5	\pm 0.63	0.9	\pm 0.15	-0.6	3.59	0.003
10	20	2.6	231	10	2.9	\pm 1.64	1.8	\pm 0.66	-1.1	1.97	0.075
10	30	4.0	271	15	1.5	\pm 0.63	0.9	\pm 0.15	-0.6	3.56	0.003
10	30	3.0	243	10	2.3	\pm 0.67	1.7	\pm 0.51	-0.6	2.25	0.039
40	5	3.3	231	15	0.2	\pm 0.12	0.3	\pm 0.15	+0.1	2.02	0.054
40	10	4.1	246	15	3.2	\pm 1.19	1.5	\pm 0.38	-1.7	5.27	<0.001
40	10	2.8	203	10	2.3	\pm 0.29	1.4	\pm 0.46	-0.9	5.23	<0.001
40	15	2.5	185	10	1.1	\pm 0.3	1.2	\pm 0.64	+0.1	0.45	0.662
40	20	3.3	231	15	0.2	\pm 0.12	0.3	\pm 0.15	+0.1	2.02	0.054
40	20	2.5	185	10	1.1	\pm 0.3	1.2	\pm 0.64	+0.1	0.45	0.662
40	30	4.1	246	15	3.2	\pm 1.19	1.5	\pm 0.38	-1.7	5.27	<0.001
40	30	2.8	203	10	2.3	\pm 0.29	1.4	\pm 0.46	-0.9	5.23	<0.001

The passage of ORVs killed all ghost crabs if they are buried shallow (5 cm) into the sediment (Fig. 26a). This severe mortality of shallow-living crabs occurred at both moderate- (10 vehicle passes) and high (40 vehicles passes) traffic

intensities (Fig. 26a). Indeed, burial depth appears to be the key factor in determining mortality rates of ghost crabs by beach traffic. We did not observe a significant (F test to compare non-linear regression models between treatments: $F_{(2,11)} = 1.091$, $P_{(2)} = 0.37$ and Aikake Information Criterion Ratio = 11.91) difference in mortality rates between 10 and 40 vehicle passes, but mortalities declined exponentially with increasing depth at both traffic intensities (Fig. 26a). Crabs that were buried 30 cm in the sand were generally not killed save for a single individual (Fig. 26a, Table 13).

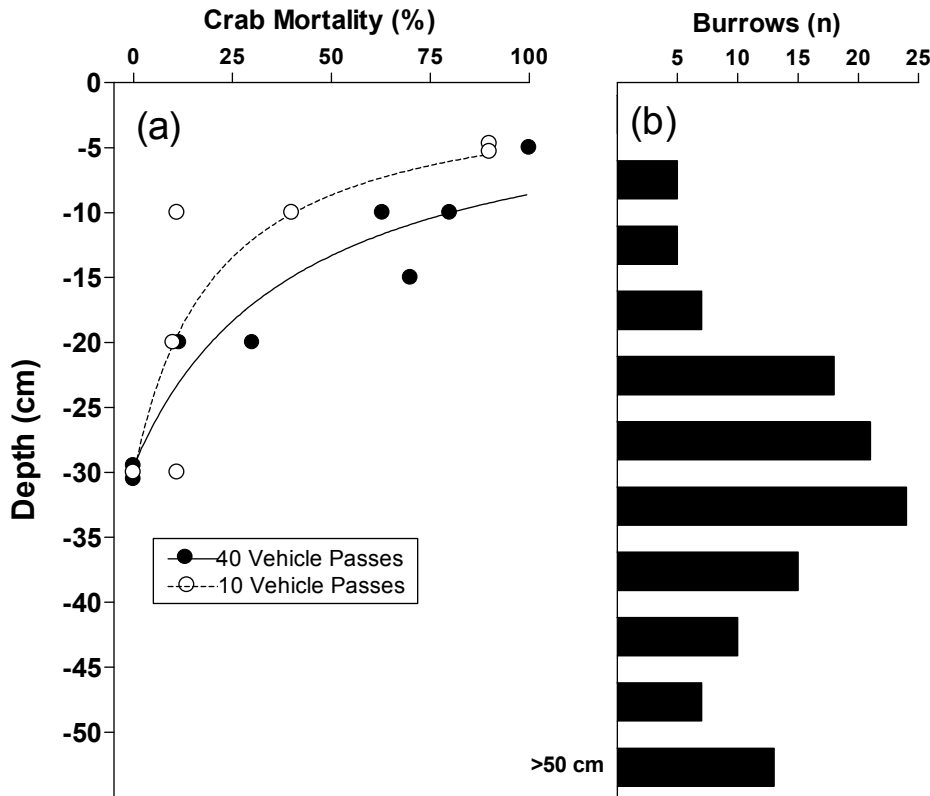


Fig 26 Mortality of ghost crabs through direct crushing by ORVs at different depth in the sediment at two traffic intensities of 40 (solid symbols) and 10 (open symbols) overpasses by a vehicle (a) compared with the distribution of burrow depths of the crab population (b).

Table 13: Percent crab mortalities observed at the different treatment intensities. Mean carapace width and distance and height of each transect above low water spring tide (LWST) are also displayed.

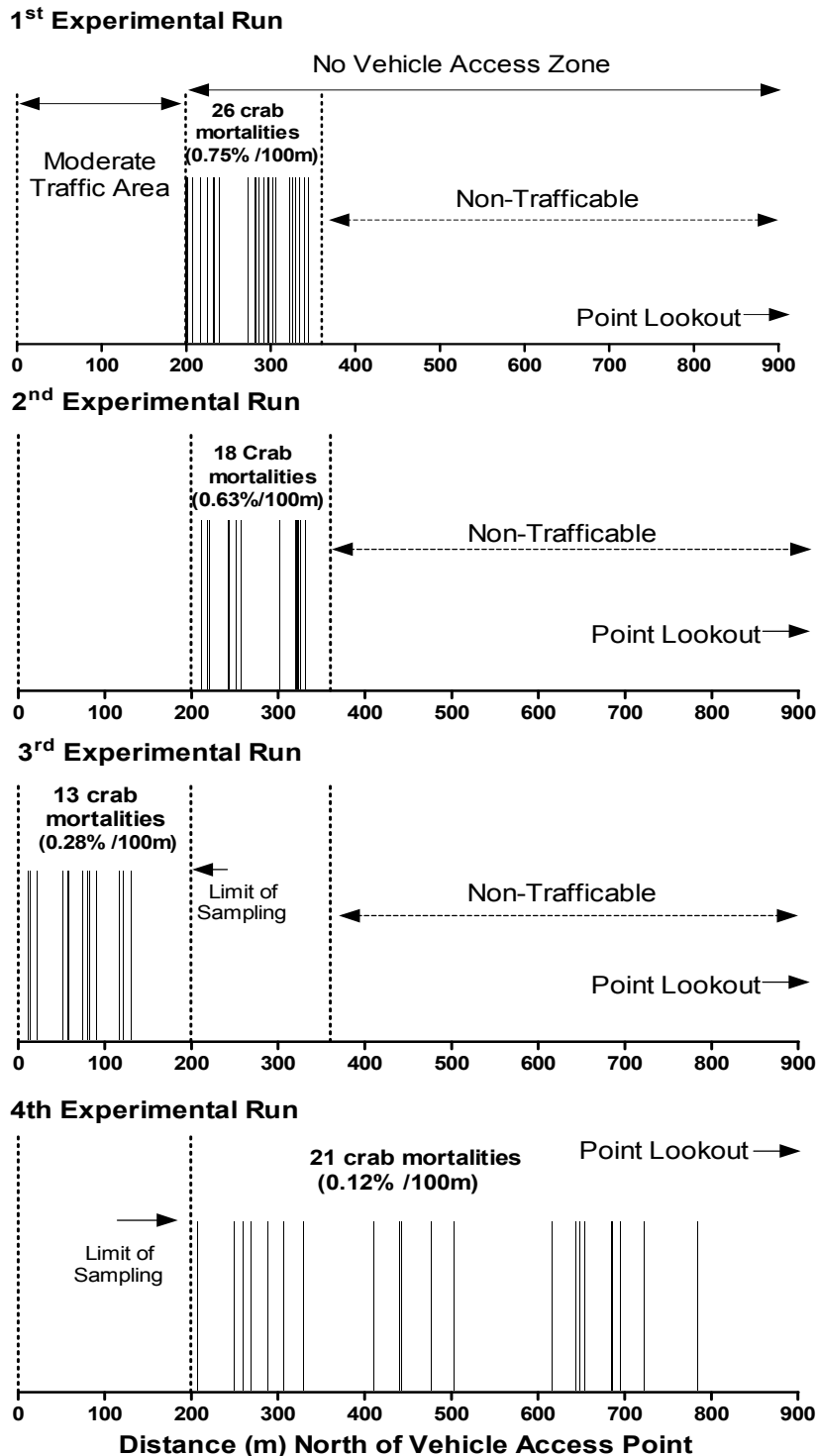
Sites on Flinders Beach	# Passes	Treatment	Distance	Height above	Carapace Width			Crabs Crushed	
		Depth (cm)	from LWST (m)	LWST (m)	mean	SD	n	n	(%)
1km North of Adder Rock Access	0 (Control)	5	73	1.42	9.8 ± 2.47		2	0	0
1.5km South of Middle Access	0 (Control)	10	41	1.51	10.5 ± 2.12		5	0	0
100m North of Middle Access	0 (Control)	10	36	1.3	13.0 ± 4.24		2	0	0
1km North of Adder Rock Access	0 (Control)	20	73	1.42	9.9 ± 2.25		4	0	0
1.5km South of Middle Access	0 (Control)	30	41	1.51	10.8 ± 1.26		3	0	0
100m North of Middle Access	0 (Control)	30	36	1.3	9.5 ± 0		1	0	0
2km South of Middle access	10	5	32	0.71	8.5 ± 3.67		10	9	90
2km South of Middle Access	10	5	35	0.31	7.8 ± 1.36		10	9	90
100m North of Middle Access	10	10	26	1.24	14.7 ± 4.01		10	4	40
1.5km South of Middle Access	10	10	42	1.57	8.3 ± 2.14		9	1	11
2km South of Middle access	10	20	32	0.71	7.6 ± 1.83		10	1	10
1.5km South of Middle Access	10	30	42	1.57	9.0 ± 2.44		9	1	11
2km South of Middle Access	10	30	35	0.36	9.7 ± 3.96		10	0	0
1km North of Adder Rock Access	40	5	74	1.49	11.6 ± 3.78		8	8	100
100m North of Middle Access	40	10	37	1.35	12.1 ± 3.99		8	5	63
2km South of Middle Access	40	10	33	0.36	8.7 ± 1.49		10	8	80
3km North of Adder Rock Access	40	15	48	1.40	11.5 ± 4.35		10	7	70
1km North of Adder Rock Access	40	20	74	1.49	9.6 ± 3.55		9	1	11
3km North of Adder Rock Access	40	20	48	1.4	9.4 ± 3.69		10	3	30
100m North of Middle Access	40	30	37	1.35	11.2 ± 4.08		9	0	0
2km South of Middle access	40	30	33	0.31	8.8 ± 1.76		10	0	0

Nocturnal Vehicle Impacts on Ghost Crabs

In four experimental runs where a vehicle travelled at night along the beach, we found that a considerable number of crabs can be crushed by nocturnal beach traffic. A single pass of an ORV killed 13 – 26 crabs over a relatively short distance of 200 – 300 m (Fig. 27); this mortality equates to 0.12 – 0.75 % of the intertidal population. However, on a number of occasions no ghost crabs were active at night on the beach surface, and hence any nocturnal beach traffic would not kill ghost crabs in the same numbers compared to nights when crab activity is high (Table 14). Preliminary observations indicate that crab activity could be related to moon cycles and weather patterns (Table 14). Crabs that remain inside their burrows even at night are, however, still vulnerable to a lesser degree to impacts by vehicles (see results on mortality inside the burrows during the day).

Table 14: Crab activity when in relation to weather and moon cycles.

Date	Tide Height (m)	Ghost Crab Activity on Beaches Investigated			Time of Moon Rise	Weather Conditions
		Flinders	Main (at no vehicle access sign)	Home		
28/12/2005	0.32	Low	High	High	1:46am	New moon, no wind, fine & humid
29/12/2005	0.23	Low	High	High	2:40am	New moon, no wind, fine & humid
6/03/2006	0.35	Low	Low	Moderate	12:06pm	1 st quarter Moon, light winds, fine & mild temp.
7/06/2006	0.44	Low	Low	Moderate	1:07pm	1 st quarter Moon, light winds, fine & mild temp
14/04/2006	0.25	None	None	None	5:42pm	Full moon moderate, winds, fine & cool
15/04/2006	0.28	None	None	None	6:15pm	Full moon moderate, winds, fine & cool
16/04/2006	0.33	None	None	None	6:54pm	Full moon moderate, winds, patchy cloud, windy & cool
20/04/2006	0.43	-	Moderate	-	10:54pm	Last quarter Moon, moderate winds, fine & cool
21/04/2006	0.45	-	Moderate	-	11:41pm	Last quarter Moon, moderate winds, fine & cool
5/06/2006	0.47	None	None	-	2:05pm	1 st quarter Moon, moderate winds, cloudy & cool



Pilot Assessment of Night Beach Traffic

Fig. 27 Ghost crab mortalities caused by simulated night-time traffic. Each bar represents a single individual found crushed in the tyre tracks after a single vehicle pass. Percentage values are calculated based on the total number of crabs sampled in a single vehicle pass.

Observations of night traffic during the peak Christmas holiday period showed that nocturnal traffic volumes are low. On Flinders Beach, 27 vehicle traversed the beach in the early evening from 6:00pm to 10:00pm and 5 vehicles from 4:00am to 6:00am (Fig. 28). On Main Beach, even less traffic was observed with 10 vehicle passes being recorded from 6:00pm until midnight and 4 vehicle passes occurring from 12:00am to 6:00am. While these traffic numbers seem low, a single vehicle has the potential to kill large numbers of crabs if the crabs are active on the surface of the beach.

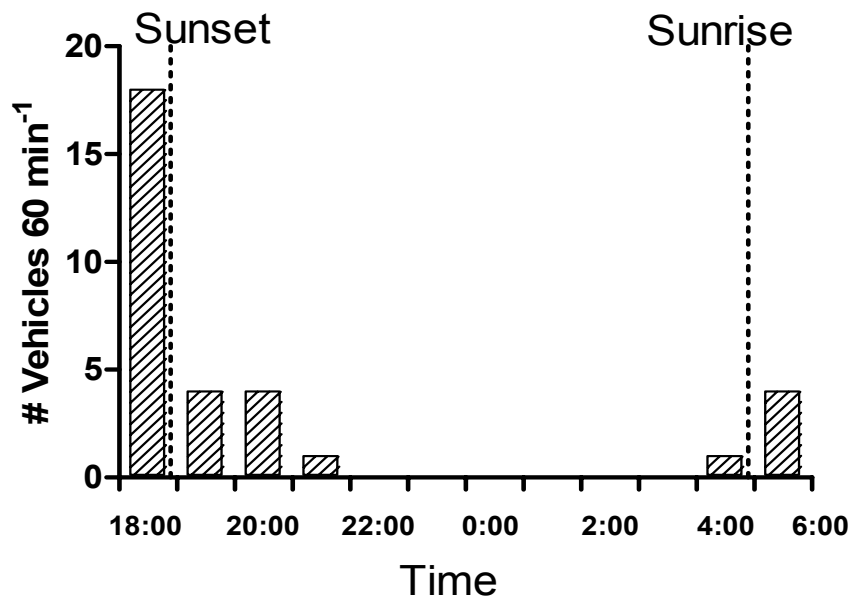


Fig. 28 Nocturnal vehicle counts on Flinders Beach. The site of the vehicle counts was located approximately 300m south of the middle 4WD access point between Amity and Adder Rock.

Discussion

Two distinct species of ghost crabs occur on the beaches: *Ocypode ceratophthalma* and *O. cordimana*. *O. cordimana* tend to inhabit the upper areas of the beach whereas *O. ceratophthalma* was more often found on the lower areas of the beach. However, this distributional pattern is based on observations only but has not yet been quantified. It was observed that the larger species, *O. ceratophthalma* was the more active and aggressive crab, and was found to be a lot more energetic on the foreshore at night. These preliminary observations tend to be at odds with Moss & McPhee (2006) who only identified one species (*O. cordimana*) of ghost crab inhabiting the intertidal foreshore. Whilst undertaking the experiments under natural conditions on Flinders Beach, it was observed that after a heavy storm many of the crabs caught around the drift line were postlarvae or juvenile *O. ceratophthalma*. These smaller crabs were also found to be buried shallower in the sand and were consequently more susceptible to vehicle impacts.

Damage or mortality to crabs when they are buried greater than 20 cm into the sediment matrix tends to be minimal under both experimental and natural conditions. The crabs are most vulnerable to crushing by cars when they are either on the surface foraging at night or when maintaining their burrows during the day. Crabs that are buried between 10 and 15 cm of the surface can be killed in considerable numbers and crabs found in the shallow layers of the sand (< 5-10cm) will most likely be crushed regardless of traffic intensity. Thus, during a peak holiday period if enough vehicles drive on the mid- to upper shore while crabs are maintaining their burrows they stand a moderate to high risk of being crushed by vehicle traffic. However, under natural conditions the majority of crabs found burrow quite deep within the sediment matrix. During the day the crabs would be most at risk to vehicle impacts when they emerge to maintain their burrows.

Even very low traffic intensities at night can cause substantial crab mortalities. We found that a single vehicle pass killed between 13 and 26 crabs over a distance of 200 – 700 m. While these direct kills of crabs by a single ORV seem to remove only a small (0.12 - 0.75 %) percentage of the crab population, more dramatic effects results from cumulative impacts of traffic: at the upper estimate (0.75 % per single car traverse) of mortality caused by nocturnal ORVs it takes fewer than 100 vehicle passes to reduce the intertidal population of ghost crabs by half. 300 vehicle passes at night would kill 90 % of the population – this is less than a single ORV travelling along the beach at night. These preliminary estimates are broadly in-line with Wolcott & Wolcott (1984) who reported that crab kills per vehicle-kilometre could range from 14-98 % for 100 vehicle passes.

During the course of the current study it was observed that nocturnal crab kills by vehicles are directly related to the activity of the crabs. On some nights it was observed that crab activity can be quite low although weather conditions and tides seem to be optimal for foraging on the foreshore. On other nights, crab activity was much higher and kills could be expected to increase when the crabs are more active. It is unclear what factors (weather conditions, moon phases) determine activity patterns of ghost crabs, although some “local knowledge” implicates lunar cycles. Active ghost crab burrows can also be found up to 9m down-shore from the drift line (Fig. 23) indicating that their distribution on the shore is not strictly localised to above the drift line and dunes as stated in other studies (Moss & McPhee 2006).

Our findings on mortality during the day inside the burrows do not concur with the results of (Wolcott & Wolcott 1984), who found that crabs buried 5 cm or greater within the sand were immune to vehicle traffic. This study has shown that that crabs buried between 5 – 20 cm are highly vulnerable to beach traffic with mortalities reaching 100 % for very shallow living crabs.

Conclusion

It is not yet understood how long it takes crab populations to recover after an impact has occurred, or if this impact is substantial enough to be the sole cause of reduced populations of crabs on beaches that receive ORV use. Night traffic intensities on North Stradbroke Island tend to be low and spread across a relatively broad time period, but it is still uncertain how many vehicle passes may occur over a particular stretch of beach at night on an annual basis. In relation to this, peaks in nocturnal crab activity would have to be quantified to gain an understanding as to when crabs would be most at risk to night traffic.

During daylight hours heavy traffic intensities can cause mortalities to crabs in their burrows but this is extremely dependant on the depth of the burrows. Crab activity may also play a role in mortality rates (ie, when maintaining burrows they may more susceptible to impacts, as they are closer to the surface). The results also indicated that the smaller crabs were more prone to impacts as they burrow shallower into the sand. Larger crabs that burrow deeper into the sand (>15-20cm) seem to be relatively immune to daylight traffic intensity. But, although they may survive the initial direct impact, the consequent destruction to their habitat may cause more indirect effects such as crab migration up the shore or to other areas of less intense use. Claims that nocturnal vehicle traffic on North Stradbroke Island as the sole cause of declines in ghost crab populations may be unfounded.

Recommendations and Proposal

Recommendations:

The key findings from the present pilot investigations can be summarised as follows:

1. At present there exist insufficient data to accurately assess the putative impacts of 4x4 vehicles on the ecological health of sandy beaches at North Stradbroke Island.
2. This situation is not unique to the local situation, as ecological information on Australian sandy beaches does generally not cover human effects such ORV traffic.
3. There exist, however, a need to manage the use of 4x4 vehicles on beaches to by developing practices that equitable balance the requirements of ecological sustainability of beaches with socio-cultural issues, economic considerations and recreational demands. Given the data-poor situation on ecological effects of recreational activities, such management practices can currently not be developed based on actual and locally-applicable information.
4. Field investigations undertake during this – limited – study do indicate, however, that ORVs can cause environmental harm under certain situations, including: (a) significant physical disturbance of faunal habitat through deep rutting of the sand that covers a large proportion of the beach, (b) significant overlap of traffic with the distribution of intertidal fauna, and (c) crushing of ghost crabs by ORVs particularly at night and crabs that are buried only shallow into the sand.

Based on the present findings, the following **RECOMMENDATIONS** are put forward to progress the development of management practices for ORVs on North Stradbroke Island (see also proposal on the biological effects on following pages)

Recommendation 1

Quantify direct **mortalities of ORVs to key species** of the intertidal beach, particularly the suite of invertebrate species buried in the sand.

Recommendation 2

Comprehensively gauge the **social acceptance** of various types of recreational uses of sandy beaches, including ORV driving, the potential for social conflict between competing user groups, and related socio-cultural issues.

Recommendation 3

Determine biological attributes and **behaviour patterns** of key species that influence their potential **vulnerability** to beach traffic, particularly patterns of activity and changes in distribution, to be used in the development of management practices aimed at minimizing overlap (both temporal and spatial) between fauna and beach traffic.

Recommendation 4

Obtain defensible and robust quantitative information on whether ORVs can substantially **change** the composition and structure of **ecological communities** on sandy beaches to advance discussion about alleged or real “impacts”, including the identification of beach areas of high conservation significance.

Recommendation 5

Quantify the **economic costs and benefits** of ORV use on the island’s beaches, including effects on local businesses and alternative income sources.

Recommendation 6

Develop **management practices** for the use ORVs on sandy beaches based on ecological, socio-cultural and economic considerations.

PROPOSAL for Biological Effects Assessment of ORVs on North Stradbroke Island

**Quantifying the responses of sandy beach invertebrates to beach traffic:
towards the formulation of ecologically-informed management and
conservation measures on North Stradbroke Island.**

Proponent: Dr Thomas Schlacher, University of the Sunshine Coast

Background

Sandy beaches dominate the coastline of SE Queensland (Banks & Skilleter 2002), both on the mainland and the offshore barrier islands, such as North Stradbroke Island. Sandy beaches are the most intensively used coastal habitat by humans (Priskin 2003a-b), particularly in South-East Queensland. This region ranks amongst Australia's fastest growing areas, and the majority of the rapid development is concentrated in the coastal strip. Arguably, it is the attractiveness of sandy beaches that drives much of this regional growth, and beaches underpin much of the regional economy.

The physical environment of beaches can be broadly summarised as the result of the dynamic interactions between waves, tides, and sediment, producing a range of physical beach types (Short 2001). Beaches provide habitat to a diverse and abundant range of invertebrate species buried in the sand, the fauna being usually dominated by Crustaceans, Polychaetes (bristle worms) and Molluscs (Brown & McLachlan 1990, Brown 2001). Conventional wisdom holds that the fauna of beaches is primarily controlled by physical processes of their habitat (e.g. wave regimes, sediment type), while biological interactions between species are thought to play a more minor role (McLachlan et al. 1993, McLachlan & Dorvlo 2005).

The continued expansion of coastal populations and the associated physical alterations of coastal habitats is a global phenomenon, and negative ecological impacts are no exception on sandy beaches (Brown & McLachlan 2002). Ecological impacts are diverse and range from severe disruption of sand transport and erosion to chemical pollution, but several anthropogenic pressures may be associated with recreational pursuits (Arthukhin 1990, Brown & McLachlan 2002, Atkinson & Clark 2003). Beaches are used for a variety of recreational pursuits including, walking, swimming, surfing, beach-camping, fishing and four-wheel driving. In contrast to the intense human use of beaches, data are generally limited to accurately gauge whether these activities are inimical to the biota of beaches, particularly benthic invertebrates of the intertidal zone (Fairweather 1990, James 2000b).

Driving of off-road-vehicles (ORVs) on beaches is a prominent human use of sandy shores, particularly on North Stradbroke Island, which is a highly popular destination for 4x4 drivers. The vast majority of this beach traffic is of a recreational nature, similar to several other regions in Australia and overseas (Priskin 2003a-b, Celliers et al. 2004). While negative ecological consequences of beach traffic have been uncritically reported and publicized (Moss & McPhee 2006), research on the actual nature of ORV's influences on sandy beach invertebrates is in fact inadequate (James 2000a). Importantly, different invertebrate species on beaches may differ considerably in their sensitivity to beach traffic (Steiner & Leatherman 1981, van der Merwe & van der Merwe 1991, Stephenson 1999). Thus, ecological impacts of beach traffic may be primarily related to the fauna's tolerance to vehicles (van der Merwe 1988). However, in the absence of quantitative information on the sensitivity of invertebrate species to beach traffic, predictions about vehicle impacts on the faunal assemblages on beaches are presently tenuous and speculative. In Australia, virtually no data are available on the impacts of ORVs on invertebrates of sandy shores (Moss & McPhee 2006).

Several critical aspects of the interaction between beach traffic and fauna await quantification. These include amongst others:

1. traffic patterns and driver behaviour in relation to biological resources of the beach,
2. tolerance of species to vehicle traffic, and
3. changes to faunal assemblages brought about by continuous ORV use

This critical information does currently not exist for beaches on North Stradbroke Island, and hampers the formulation of effective and biologically-informed management and conservation measures. Because local biological and ecological data on sandy beaches are very scant, environmental management of beaches is mostly restricted to physical and geo-morphological aspects.

In contrast to the data-poor situation with respect to biological resources on N-Stradbroke's beaches, and the possible effects of human beach use on the biota, a number of management issue of concern have been identified in relation to Four-Wheel Driving on Flinders Beach (Carter 2005). These include:

1. * **Destruction of invertebrate fauna by ORVs.**
2. * Disturbance of shorebirds and turtle nesting by ORVs.
3. (*Lack of education and awareness amongst the ORV community.
4. Destruction of vegetation and increased erosion by ORVs.
5. Law enforcement of speed limits and pedestrian safety.
6. Increased traffic volume on beaches.

This project will focus on the putative impacts of ORV traffic on beach invertebrates (issue #1) for the following reasons:

1. The question to which extent invertebrates are directly killed by ORV traffic is the key-stone argument in determining the ecological impacts for most beach species being subjected to vehicle traffic.
2. This is the area of highest data deficiency.
3. The issue of ORVs impacting on invertebrates has recently been publicly raised by Moss & McPhee (2006) for Flinders Beach.
4. Disturbance to vertebrates (shorebirds and turtles) is well documented in the literature (Hosier et al. 1981, Buick & Paton 1989, Watson & Kerley 1995, Watson et al. 1996, Leseberg et al. 2000, Williams et al. 2004).
5. Effects of ORVs on dune vegetation are similarly well documented in the literature (Hosier 1980, Rickard et al. 1994).
6. The issue of enforcement of speed limits on the beach and the resulting risks to pedestrian safety can be addressed by comparatively straightforward management responses if properly resourced.

In addition to the primary focus on quantifying invertebrate mortality as a consequence of ORV driving, we also propose to: a) broadly gauge the potential for shorebird disturbance by beach traffic, and b) assess the social acceptance and attitudes towards beach traffic in the community.

Consultation with Council staff in the formulation of this proposal has also raised the issue of an economic cost-benefit analysis of ORV on the beach of North Stradbroke Island – this fall outside the scope and resources available to this project. It is proposed to scope a complementary project on the economic issues associated with ORV use of beaches on North Stradbroke Island.

Aims and Objectives:

Despite public concerns about the possible negative environmental consequences of beach traffic, arguments tend to be often confined to dunes and vertebrates (e.g. birds), or they are primarily driven by ethical motives only.

This is understandable, given the lack of public awareness about beach invertebrates and the limited ecological information for beaches in SE-Queensland. Yet, benthic invertebrates are the most species-rich component of the beach fauna (Brown & McLachlan 1990), and their habitat is the very area of the shore which receives most of the ORV traffic (Thompson 2005). Furthermore, management and conservation measures of intertidal areas can currently not efficiently mitigate ORV effects, because the way ORV may impact on populations of these animals is not known. Hence the current proposals seeks to:

1. Quantify the rates of direct mortality to invertebrate species inhabiting sandy beaches on North Stradbroke Island caused by ORVs.
2. Determine which environmental conditions are likely to cause species distributions across the intertidal shore that result in substantial overlaps between biota and areas of highest traffic.
3. Broadly gauge the potential for disturbance of shorebirds by ORVs.
4. Assess the social acceptance and attitudes towards 4x4 driving on beaches amongst a cross-spectrum of the community.
5. In collaboration with Redland Shire Council formulate management measures which result in mitigating effects (if any) of beach traffic on beach fauna.
6. In collaboration with Redland Shire Council, qualitatively model the efficiency of management scenarios in reducing any adverse ecological consequences of beach traffic on biota on North Stradbroke Island.

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Appendix 1

The classification systems of beach morphodynamic state using compound indices are:

- (Deans): microtidal reflective, < 2.0; intermediate, 2.0-5.0; macrotidal dissipative >5.0 (Short 2001)
- BI (Beach Index): microtidal reflective, < 1.5; intermediate, 1.5-3.0; and macrotidal dissipative, > 3.0 (McLachlan & Dorvlo 2005)
- BSI (Beach State Index): microtidal reflective, <0.5; low to medium energy intermediate, 0.5-1.0; high energy intermediate to dissipative, 1.0-1.5; fully dissipative, 1.5-2.0; and ultra-dissipative macrotidal >2.0 (Hacking 1998)
- RTR (Relative Tide Range): wave dominated beaches, < 3.0; tide-modified beaches, 3.0-15.0; tide-dominated beaches, > 15.0 (Short 2001)

Appendix 2

Year	Location	Study Area	Response Variable	Reference
1974	Wales, U.K.	Stable dunes, active dunes	Soil, vegetation	Liddle & Moore (1974)
1975	Wales, U.K.	Stable dunes, active dunes	Soil, vegetation	Liddle & Greig-Smith (1975)
1975	USA	Foreshore, backshore, active and stable dunes	Physical variables	Niedoroda (1975)
1977	USA	Foreshore, backshore	Physical variables	Tauman (1977)
1977	USA	Dunes	Vegetation	Broadhead & Godfrey (1977)
1977	USA	Dunes	Physical variables	Letherman (1977)
1978	USA	Foreshore, backshore, dunes	Physical variables	Leatherman & Long (1978)
1980	USA	Dunes	Vegetation	Hosier & Eaton (1980)
1981	USA	Foreshore, backshore	Macrofauna	Steiner & Leatherman (1981)
1981	USA	Backshore, foreshore	Turtles	Hosier et al (1981)
1984	USA	Backshore, foreshore	Macrofauna	Wolcott & Wolcott (1984)
1984	USA	Coastal zone	Vegetation, physical variables	Abele et al (1984)
1984	South Africa	Foreshore, backshore, dunes	Turtles	Brokensha (1984)
1987	USA	Foreshore, backshore	Physical variables	Anders & Leatherman (1987)
1989	Australia	Backshore, dunes	Birds	Buick & Paton (1989)
1989	USA	Dunes	Vegetation	Carlson & Godfrey (1989)
1990	South Africa	Foreshore, backshore, dunes	Birds	Els & McLachlan (1990)
1991	South Africa	Foreshore, backshore	Macrofauna	van der Merwe & van der Merwe (1991)
1994	South Africa	Dunes	Vegetation	Rickard et al (1994)
1996	South Africa	Foreshore, backshore, dunes	Birds	Watson et al (1996)
1997	Australia	Dunes	Vegetation	Hockings & Twyford (1997)
2000	South Africa	Dunes, backshore	Birds	Leseberg et al (2000)
2001	South America, Chile	Dunes, backshore	Birds	Cornelius et al (2001)
2002	South Africa	Foreshore, backshore	Physical variables	Smith & Guastella (2002)
2003	Australia	Backshore, dunes	Vegetation	Priskin (2003)
2004	South Africa	Dunes, foreshore, backshore	Physical variables	Celliers et al (2004)
2006	Australia	Foreshore, backshore	Macrofauna (Ghost Crabs)	Moss & McPhee (2006)
2006	Australia	Foreshore, backshore	Macrofauna	Schlacher & Thompson (2006) In Press.
2006	Australia	Foreshore, backshore	Physical variables	Schlacher & Thompson (2006) In Press.