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Physical Impacts Caused by Off-Road Vehicles to Sandy Beaches: Spatial Quantification of Car Tracks on an Australian Barrier Island

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ABSTRACT

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Beach traffic can substantially modify the physical environment on sandy beaches. Vehicle impacts on beaches were quantified on North Stradbroke Island, a barrier island on the east coast of Australia where large volumes of recreational off-road vehicle (ORV) traffic are concentrated on two beaches (Flinders Beach and Main Beach). The distribution, density, and depth of vehicle ruts on these beaches were quantified during the peak holiday period around late December and early January 2005–06. The density of tyre tracks per meter of beach face ranged from 2.69 to 6.35 on Flinders Beach and from 2.38 to 8.06 on Main Beach, and substantial areas (54–61%) of each beach were covered withy tyre tracks up to a maximum of 90% in some areas. ORVs corrugated the sand as deep as 28 cm (mean depth: 5.86 ± 4.72 cm), with the deepest rutting occurring between the foredunes and the drift line. On a volume basis, vehicles 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. Traffic density was higher on the lower shore, but ruts were significantly deeper in the soft sand of the upper shore. Thus, half of all 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 infauna, and vehicles routinely disturbed the drift line and the base of the foredunes. This study emphasizes the need to develop multifaceted management strategies for recreational ORV use on beaches that balance ecological requirements with sociocultural and economic demands.

ADDITIONAL INDEX WORDS: *Human impact, recreation, habitat, sandy shores, management, 4 × 4 vehicles*

INTRODUCTION

Sandy beaches are prime sites for human recreation. Arguably, it is the strong attraction of beaches that underpins many coastal economies, and which continues to fuel commercial developments, tourism, and population shifts to coastal areas (Klein, Osleeb, and Viola, 2004). Such preeminence of sandy beaches for hedonistic pursuits in many modern societies is manifested by the emergence of distinct "beach cultures", and beaches have acquired icon status in Australia and elsewhere (James, 2000a; Jones, Gladstone, and Hacking, 2004). Recreational beach use encompasses a wide spectrum of pursuits including walking, swimming, surfing, beach camping, fishing, sunbathing, nature-based tourism, and adventure activities (Priskin, 2001).

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 because of the visually and audibly highly disturbing nature of ORVs on beaches (Priskin, 2003a). There is a growing body of evidence on the nature and extent of environmental degradation caused by ORVs on beaches, including geomorphological changes (Anders and Leatherman, 1987a, 1987b; Priskin, 2003b); destruction of dune vegetation (Hosier and Eaton, 1980; Rickard, McLachlan, and Kerley, 1994); and impacts on wildlife such as turtles (Hosier, Kochhar, and Thayer, 1981), birds (Watson and Kerley, 1995; Watson, Kerley, and McLachlan, 1996; Williams, Ward, and Underhill, 2004), and invertebrates (Moss and McPhee, 2006; van der Merwe and van der Merwe, 1991; Wolcott and Wolcott, 1984).

Beach traffic can cause ecological degradation via direct destruction of 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

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as habitat for a range of invertebrate species. Often, such physical disturbance is clearly manifested by vehicle tracks cut into the beach face. Therefore, a basic and fundamental step when assessing effects of ORVs on beach biota is to document the extent to which beach traffic modifies habitat properties on sandy beaches. Thus, the primary objective of this study was to quantify the magnitude of physical impacts caused by ORVs on sandy beaches. 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 disturbance of beaches by vehicles 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.

Physical impacts by ORVs were measured on North Stradbroke Island. North Stradbroke Island is a sand barrier island forming the southeastern rim of Moreton Bay off the coast of Brisbane, Queensland, Australia (Figure 1). The island is a popular tourist destination and receives large amounts of ORV beach traffic, especially during peak holiday periods (CARTER, 2005). Of the 46 km of open, oceanic beaches on the eastern and northern side of the island, 40 km (89%) are open to ORVs. 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 closed to vehicular traffic.

Flinders and Main Beach have camping areas in the dunes, but there are no back roads to reach these campgrounds. Thus, campers must travel in ORVs along the beach. Access points for ORVs are located on the northern and southern ends of Flinders Beach, and at the northern end and central part of Main Beach (Figure 1). 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 form of beach traffic is by day-trippers who travel on the beach to reach preferred swimming spots or simply for scenic drives on the shore, and commercial tour operators. Traffic volumes can reach up to 500 cars per day during the peak tourism season (SCHLACHER and THOMPSON, unpublished data).

METHODS

We surveyed fives sites on each of the two beaches of North Stradbroke Island for beach morphological parameters and vehicle impacts (Figure 1). Beach profiles were measured using standard theodolite surveying techniques. These profiles included the first two to three ridges of the foredunes; 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 (five 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) halfway 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 December 2005 to 01 January 2006, coinciding with a peak holiday period on the island.

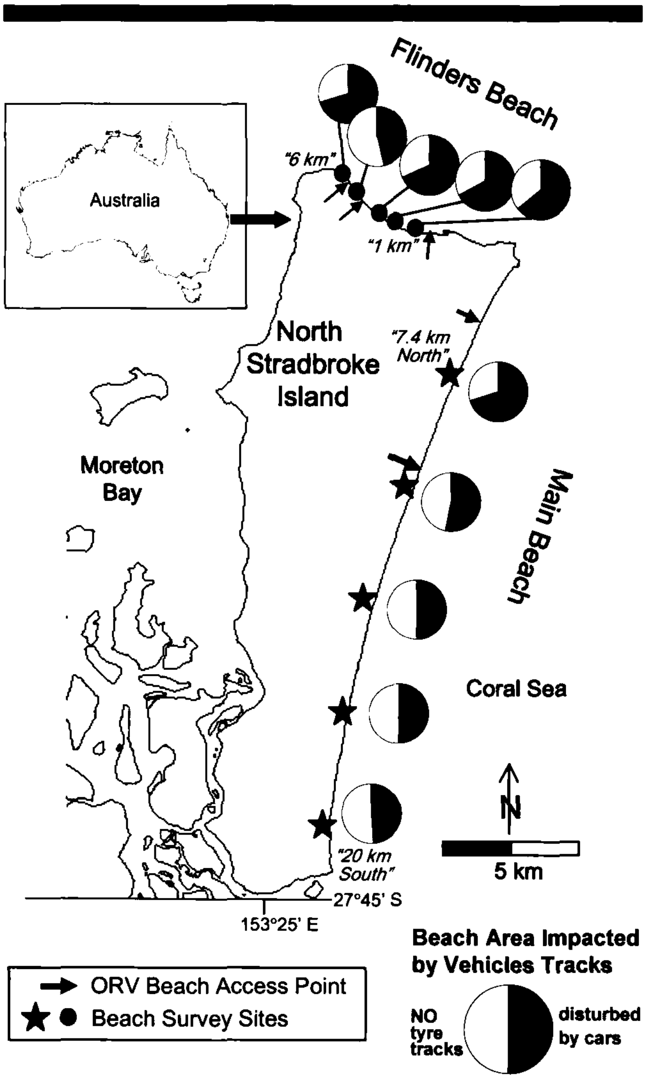

Figure 1. Map of North Stradbroke Island showing beach sites surveyed for physical damage caused by off-road vehicles. Pie-charts show the percentage of the surface area on each beach that was affected by vehicle tracks (black segments).

Physical disturbance by ORVs was quantified at each site by mapping the position, width, and depth of every vehicle rut found between the FD and the upper swash (Figure 1). 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 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 area that contained many overlapping or superimposed tyre treads, the reported number of recorded tracks is also a conservative value. All rut measurements were made within 2 hours of the predicted time of low water.

To compare the distribution of intertidal, benthic macroinvertebrates (*i.e.*, animals retained on a mesh with 1-mm aperture) with that of beach traffic, we measured the distribution of fauna on the unvegetated section of the beaches. Faunal surveys were conducted at two sites each on Flinders Beach and Main Beach. At each site, the distribution of macrobenthic species was determined by sampling 12 levels along three replicate transects spaced 30 m apart along the beach. Transects extended from the FD (level 12) to the low-water spring tide level (LWST, level 1). The 12 sampling levels were spaced equidistant along each transect. At each level, five replicate cores (inner diameter 154 mm, 200 mm deep) were taken and pooled into a composite sample. The fauna were separated from the sediment by washing through sieve bags with a 1-mm mesh aperture size in the swash and preserved in 75% ethanol in the field. Faunal sampling started ~3 hours after the last high tide at level 12 (*i.e.*, FD) and progressed in a down-shore direction until the lowest station (level 1) was sampled at the time of predicted low water. All macrobenthos samples were taken within 2 days of spring tides.

Spatial contrasts in the amount of beach damage caused by ORVs were tested with a two-factorial analysis of variance, using beach (Flinders Beach and Main Beach) and zone (upper and lower section) as crossed factors. The relation between beach width and the amount of sediment displaced was tested with nonparametric Spearman correlation analysis. Multivariate patterns in beach damage and traffic intensity between the upper and lower sections of beaches were analysed with nonmetric multidimensional scaling ordinations, followed by tests of significance between groups with analysis of similarities. This is a standard approach in marine community analysis where species abundance or biomass data are used across multiple samples (CLARKE, 1993; CLARKE and WARWICK, 2001); our approach is conceptually similar, except that variables on "traffic intensity and beach damage" replace species data.

RESULTS

Beach Morphodynamics

In terms of physical beach characteristics, the main difference between Flinders Beach and Main Beach is the degree of exposure to the dominant southeast swell: Flinders Beach is more protected with generally smaller waves, <1 m, whereas Main Beach is more exposed with larger waves, usually >1.5 m. Flinders Beach has a more variable slope (1.82–5.36°), whereas Main Beach has a more uniform slope (2.04–3.60°). Both beaches can be broadly categorised as intermediate, with beach index values (MCLACHLAN and 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 mm at Main Beach) that is generally moderately well sorted.

Magnitude of Damage by Vehicles

A total of 398 vehicle ruts (197 and 201 on Flinders Beach and Main Beach respectively) were mapped, comprising a minimum of 2078 individual tyre tracks. The number of tyre tracks per linear meter of beach face ranged from 2.69 to 6.35 on Flinders Beach, and 2.38 to 8.06 on Main Beach. This large number of vehicle ruts and tracks is reflected in the extensive area of the beach face that is visibly disturbed by beach traffic. On Flinders Beach, 61% of the beach surface was affected by vehicle tracks. Similarly, cars had rutted 54% of the sand surface on Main Beach (Figure 1). The mean surface area disturbed per individual survey site was similar for Flinders Beach (mean ± standard error [SE] = 62% ± 7%) and Main Beach (51% ± 4%; analysis of variance, $F_{(1,16)}$ = 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 (±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 m^3 of sand in a single day on Main Beach, and 12,573 m^3 on Flinders Beach. These volumes of displaced sand represent approximately 1.3–2% of the total sand wedge of the unvegetated beach from the FD to LWST (Table 1). 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 (FD to DL) and lower beach (DL to swash; Table 2, Figures 2–4). Vehicle ruts were wider on the lower shore (Table 2). Vehicle ruts on the lower shore also contained more individual tyre 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 (Figures 3 and 4): at two survey sites of Flinders Beach, cars had rutted 91% of the lower shore (Figure 3). The average area corrugated by vehicles was

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 30 cm of the sand that is the primary habitat for most of the benthic infauna, and (B) the total volume of sand encompassed between the low-water spring tide (LWST) and the base of the foredune (subaerial sand wedge).*

		Flinders Beach Sand Volume Disturbed			Main Beach Sand Volume Disturbed	
Section/ zone	Site	A Top 30 cm	*B* (Total Sand Wedge)	Site	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%)

Table 2. *Comparison of the severity of disturbance caused by vehicles to beaches between the upper part of the intertidal zone (drift line to foredune) and the lower beach (swash to drift line). Contrasts are calculated for (1) properties of individual vehicle ruts recorded in each zone, and (2) damage integrated over each beach zone.*

	Upper Beach (n = 148)		Middle-Lower Beach (n = 245)			
	Mean	(±SE)	Mean	(±SE)	F-value	$p_{(2)}$
(1) Rut width (m)	0.487	(0.253)	**1.063**	(2.146)	11.26	0.001
Rut depth (cm)	**9.103**	(3.950)	3.922	(4.086)	145.17	<0.001
No. of tracks per vehicle rut	2.054	(1.287)	**7.220**	(16.216)	15.08	<0.001
No. of tracks per linear meter of vehicle rut	4.334	(2.031)	**6.972**	(4.395)	48.52	<0.001
	Upper Beach (n = 10)		Middle-Lower Beach (n = 10)		F-value	$p_{(2)}$
(2) Percentage of surface area disturbed	46%	(17%)	**67%**	(15%)	9.76	0.007
No. of tyre tracks per metre of beachface	1.773	(1.033)	**4.606**	(1.141)	34.13	<0.001
Sand volume displaced per metre of beachface (m^3)	**0.051**	(0.016)	0.020	(0.029)	8.46	0.010

generally lower on the upper shore (Table 2). Substantial disturbance (80%) was, however, recorded on the upper beach at narrow sections where the DL was close to the FD (Figures 2–4).

At several sites, the ruts became markedly deeper around the DL, and these deep corrugations continued upshore toward the FD (Figure 2). Vehicles cut significantly more deeply into the sand on the upper shore (Table 2, Figure 2), resulting in much higher rates of sand displacement above the DL (Figure 5). ORVs corrugated the beach to a greater depth on the upper shore, principally because of the softer sand in this zone (Figure 6).

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 m^3 of sand displaced by vehicles on Flinders Beach, 6161 m^3 (49%) originate 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 beach face, but 55% (21,139 m^3) of the 38,018 m^3 of sand dislodged by cars came from this zone (Table 1).

Overall, the upper and lower shores could be clearly delineated in terms of the intensity and nature of physical impacts caused by beach traffic (Figures 6 and 7). It is truly remarkable that such a distinct zonation of the beach is evident solely as a result of human disturbance.

DISCUSSION

Beach traffic caused widespread and substantial physical disturbance to sandy beaches, including: (i) large areas (up to 90%) of the beach face being rutted by vehicle tracks (Figures 2–4), (ii) compaction and displacement of significant volumes of sand by ORVs (Figure 5, Table 1), and (iii) considerable disturbance of the back shore, the DL, and the FD (Figures 3 and 4). Remarkably, a clear zonation of the beach face into upper and lower sections was evident solely on the basis of differences in the intensity and nature of vehicle disturbance (Figure 7).

Vehicles can cause a net displacement of sand down-shore and enhance sand mobility through increased bottom turbulence caused by ruts—both processes that possibly enhance beach erosion (ANDERS and LEATHERMAN, 1987b). Our estimates of sand displacement and compaction do indeed indicate that vehicles can disturb considerable volumes of beach sand in a single day (Table 1). It does, however, not necessarily follow that ORVs contribute to increased shoreline erosion in this particular situation—this would be speculative. Published evidence on vehicle effects on beaches does, however, clearly show that physical disturbance of the beach environment is a form of severe environmental degradation (HOSIER, 1980; PRISKIN, 2003b) that has ramifications for the biota (GODFREY and GODFREY, 1980; STEPHENSON, 1999), the economic values of beaches linked to tourism and other uses (PRISKIN, 2003a), and environmental management (BROWN and MCLACHLAN, 2002; JAMES, 2000b; JONES, GLADSTONE, and HACKING, 2004).

Disturbances differ mainly in their temporal pattern of impact duration and intensity, and are most frequently classified as pulse or press disturbance (GLASBY and UNDERWOOD,

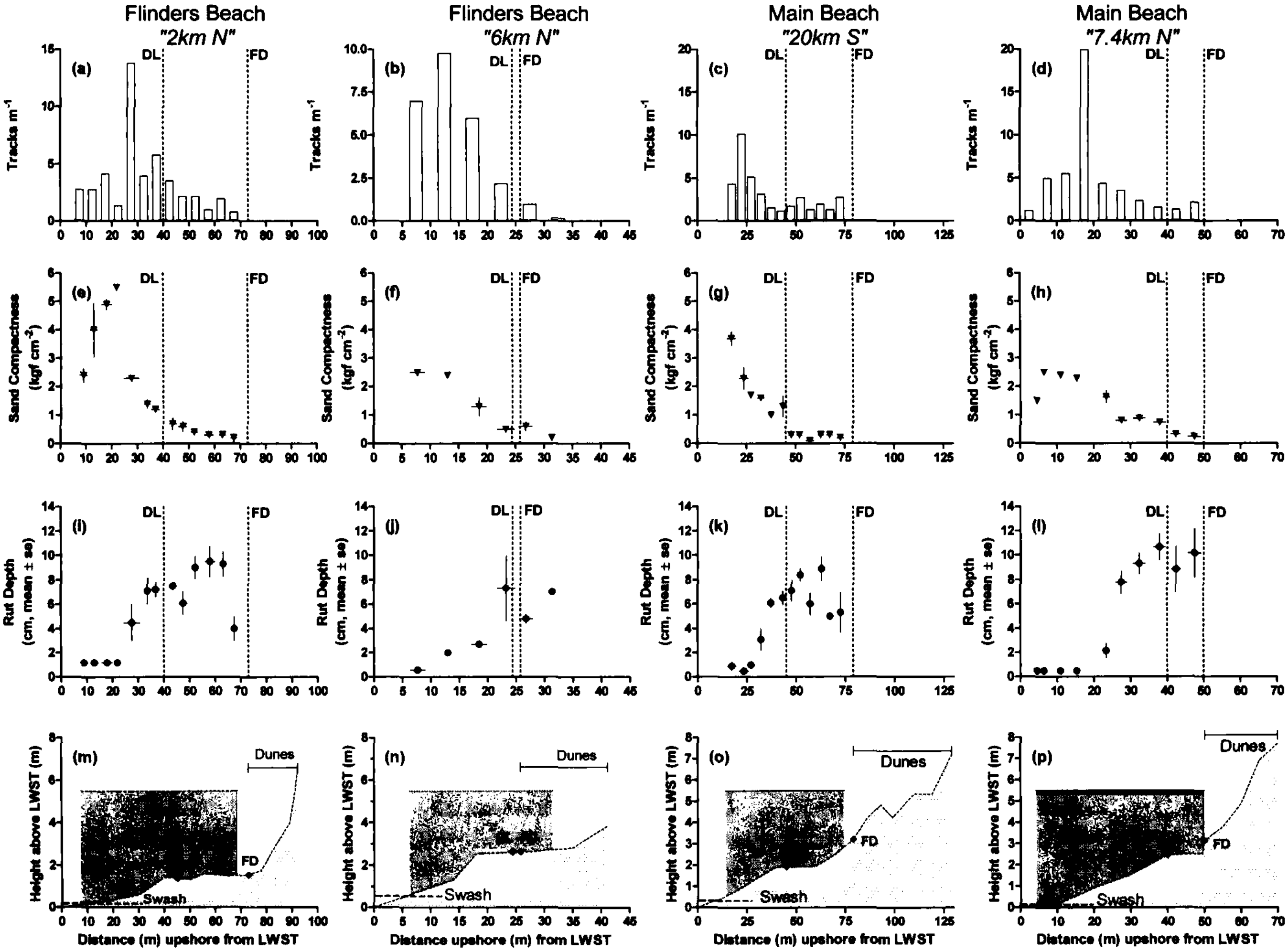

Figure 2. Examples of the spatial distribution of vehicle impacts across the shore in terms of the number of vehicle tracks (top row, a–d) and the depth of vehicle ruts (third row from top, i–l) compared with the compactness of the sand (second row from top, e–h) and the beach profiles for each site (bottom row, m–p). The shaded area in the bottom-row panels shows the zone within which vehicle ruts were observed (DL = drift line, FD = base of foredune).

1996; Lake, 2000). Full characterisation of the input properties of disturbances also encompasses the form and intensity of the forces, frequency and predictability, and the spatial extent and duration (Lake, 2000). In this respect, ORV disturbances on beaches are neither strictly of the pulse nor press type: although traffic volumes on local beaches show fairly predictable patterns of several peak ("pulse") events each year (*e.g.*, Christmas/New Year, school holidays, Easter weekend, fishing competitions, public holidays, *etc.*), considerable volumes of beach traffic occur throughout the year ("press disturbance") outside these peak periods (Schlacher and Thompson, unpublished data). Essentially, ORVs traverse the beaches on any given day of the year, except in unusually rough conditions during rare storm events. Disturbance forces applied by beach traffic are thus predictable and consist of continuous press impacts amplified by pulse events. They affect most of the beaches (large spatial extent) and are of long duration.

Ecological Consequences of Habitat Disturbance

Off-road vehicles driven on beaches can cause considerable ecological damage (Godfrey and Godfrey, 1980). Impacts caused by vehicles range from the destruction of dune vegetation (Rickard, McLachlan, and Kerley, 1994) and direct crushing of intertidal invertebrates causing lower population sizes (Steiner and Leatherman, 1981; van der Merwe and van der Merwe, 1991; Wolcott and Wolcott, 1984) to reduced reproductive success and hatchling survival in shorebirds (Williams, Ward, and Underhill, 2004). The actual ecological impacts 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 on beaches with vehicle ruts: freshly hatched turtles have

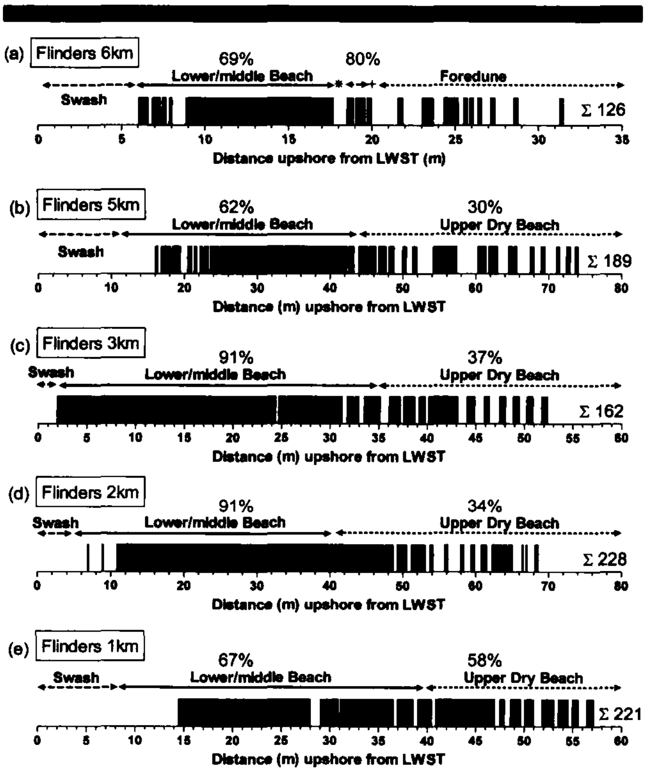

Figure 3. Distribution of vehicle ruts across the beach face at four sites (a–e) at Flinders Beach. Solid, black bars denote vehicle ruts and open bars areas without visible tyre tracks. Percentage values denote the surface area of each zone that was visibly rutted with vehicle tracks (total number of tracks observed is denoted by Σ).

a slower rate of movement when travelling over beach sections rutted by cars, which makes them more vulnerable to predation (Hosier, Kochhar, and Thayer, 1981).

On the beaches studied here, vehicle ruts overlapped to a large extent with the distribution of macrobenthic invertebrate species (Figure 8). We predict that species that inhabit mainly the upper shore (*e.g.*, ghost crabs, isopods, some polychaetes) are likely to experience considerable habitat modification from the deep corrugations left by vehicles. 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 the majority of species (Figure 8). By contrast, few vehicles drive in the swash; species concentrated in the swash (*e.g.*, mysids) should be less affected 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 and van der Merwe, 1991). In addition to the putative impacts on the larger invertebrates of the intertidal zone, meiofaunal organisms (*e.g.*, animals in the size range 0.063–1 mm) that inhabit the interstitial spaces may also be negatively affected by changes to the sediment matrix caused by cars. In fact, meiofauna have been shown to be sensitive to mechanical disturbance of beach sediments applied during mechanical beach cleaning (Gheskiere *et al.*, 2006).

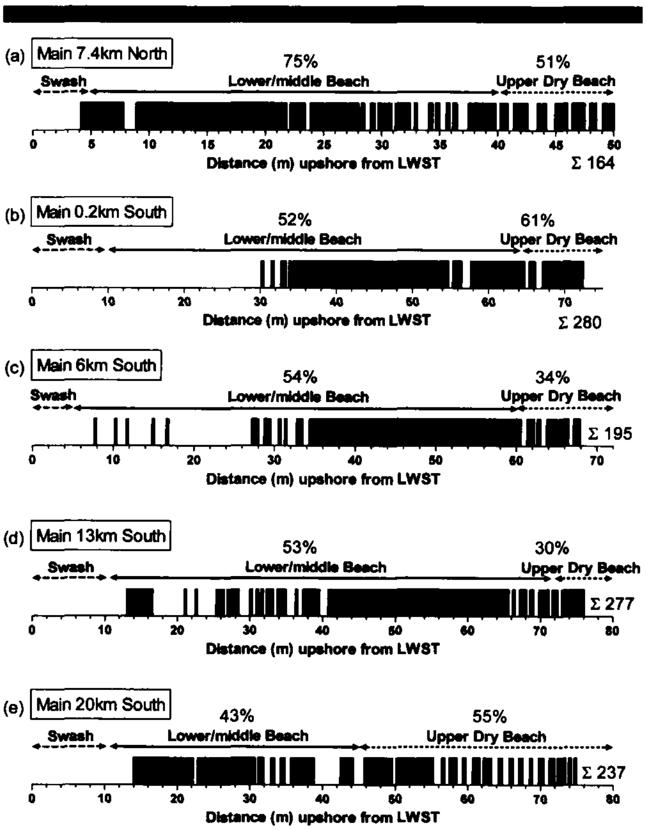

Figure 4. Distribution of vehicle ruts across the beach face at four sites (a–e) on Main Beach. Solid, black bars denote vehicle tracks and open bars areas without visible tyre tracks. Percentage values denote the surface area of each zone that was visibly rutted with vehicle tracks (total number of tracks observed is denoted by Σ).

On Stradbroke Island densities of ghost crabs are lower on beaches with ORVs compared with beaches that are closed to traffic (Moss and 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 and 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. This less cohesive sand may be less suitable for burrow construction (T.A. Schlacher, personal observation) 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.

Ghost crabs, whose centre of distribution is on the upper

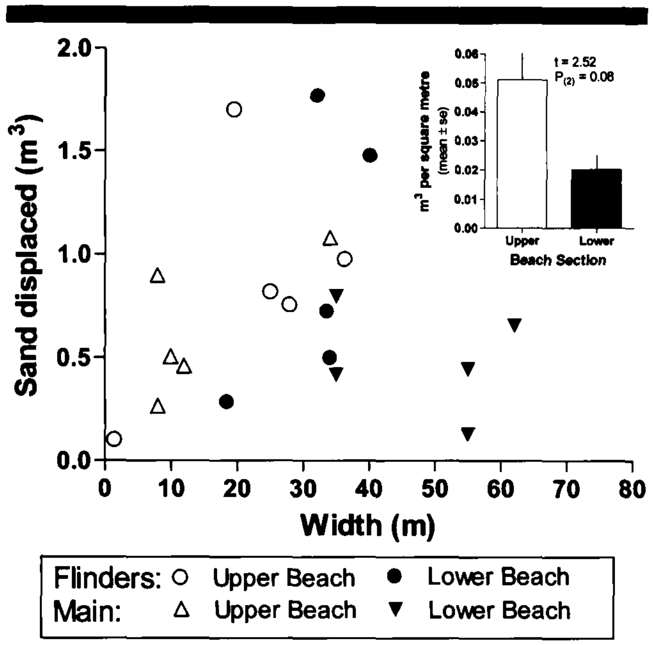

Figure 5. Comparison of sand displaced by vehicles in each beach zone *vs.* beach width. Main graph shows total volume of sand displaced summed over each section. Insert shows the mean volume of sand (m³) displaced per square metre of beach.

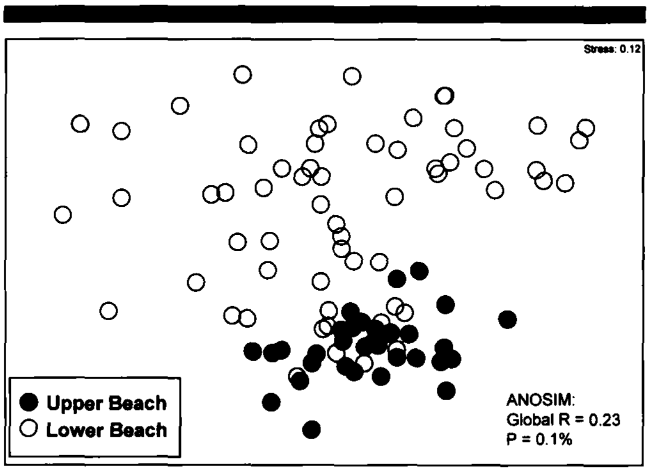

Figure 7. Ordination (nonmetric multidimensional scaling) and analysis of similarity (ANOSIM; Clarke, 1993) of beach sites on the basis of physical vehicle disturbance to the sand matrix. Analysis based on normalised Euclidean distance matrix including the following 10 variables: (1) traffic intensity: (i) total no. of vehicle ruts, (ii) total no. of tyre tracks, (iii) no. of tyre tracks per rut, (iv) no. of tyre tracks per metre of rut, and (2) impact intensity: (v and vi) mean and maximum width of ruts, (vii and viii) mean and maximum depth of ruts, (ix and x) mean and maximum volume of sand displaced per vehicle rut.

shore, are apparently protected from vehicle damage when inside their burrows during the day (Wolcott and Wolcott, 1984). Ghost crabs construct relatively deep burrows (mean burrow depth = 32 cm, SE = 1.24, n = 125) on the local beaches (T.A. Schlacher, unpublished data). Although most burrows are deeper than vehicle ruts measured in this study, 15% of crabs live in burrows shallower than 20 cm and 4% of crab burrows are only 10 cm deep or shallower. Also, at beach access points ruts can be much deeper (>0.5 m from visual estimates as the high traffic intensity made it unsafe for us to survey these areas), which could kill ghost crabs directly inside their burrows. Vehicle 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 (T.A. Schlacher, personal observation). Direct crushing of recruits and juveniles cannot therefore be exclud-

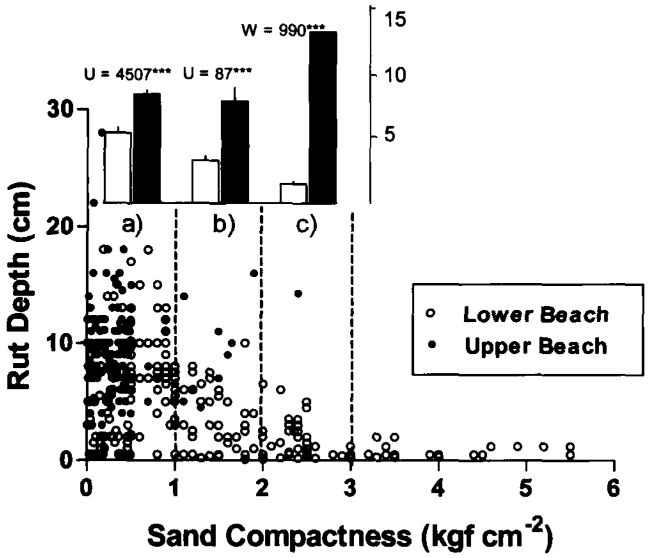

Figure 6. Depth of ruts in relation to compactness of the sand in each of the two major beach zones. Insert (bar graphs) compares mean rut depth between upper (solid, black bars) and lower (open bars) sections of the beach pooled over three compactness classes: (i) <1 kilogram-force (kgf) cm⁻², (ii) 1–2 kgf cm⁻², and (iii) 2–3 kgf cm⁻².

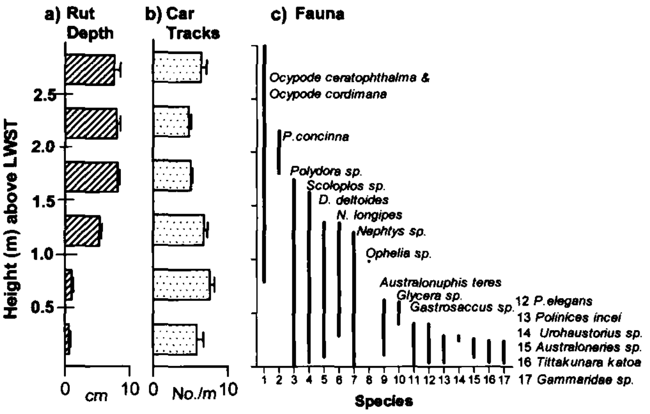

Figure 8. Distribution of macrobenthic species (c) across the beach face in relation to depth of vehicle ruts (a) and the density of tyre tracks per metre of rut (b). Data for species distribution are pooled for both Flinders Beach and Main Beach from repeated transect surveys.

ed given the rut depths measured in this study. To which extent vehicles cause direct crushing of beach invertebrates in the present situation certainly warrants more detailed quantification to unambiguously determine direct effects of ORVs on beach invertebrates.

Back-Shore Impacts and Driver Behaviour

Although traffic density was generally lower above the DL (*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 with the lower shore (Table 2, Figure 8). Thus, on both beaches, the deepest rutting occurred between the FD and the DL or just downshore of the DL (Figure 2).

Conventional wisdom holds that the FD and backshore areas of beaches are much more sensitive to environmental impacts by humans compared with the more resilient foreshore (ANDERS and LEATHERMAN, 1987a; RICKARD, MCLACHLAN, and KERLEY, 1994; BROWN and 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 DL 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 DL, and a few vehicle ruts extended into the FD (Figures 2–4). 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.* 3 m wide × 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 back shore to test the capabilities of their vehicles. Beach traffic can also be forced above the DL 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 back shore. Yet, the magnitude of physical rutting on the back shore and the DL 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 sociocultural 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, Stradbroke Island is one of the closest ocean beaches for the people of the larger 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 and fundamental right 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). 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 offset 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 multidimensional (JAMES, 2000a). GODFREY and GODFREY (1980) poignantly summarize the dilemma of regulating ORV use on sandy beaches: "There can be no doubt that ORVs do environmental damage in just about any ecological setting. The problem is to decide where the least damage will occur, and how much, if any is acceptable".

To minimize conflicts between user groups, traffic management on beaches has to embrace the multifaceted 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 regulating beach traffic (JAMES, 2000b). Statewide legislative controls on beach driving are limited to traffic regulations that normally 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 that may: (i) limit access to beaches to times of low water to reduce impacts to the back shore caused by driving during high tides (THIS STUDY), (ii) prohibit night traffic to reduce mortalities of beach fauna that are surface-active at night (WOLCOTT and WOLCOTT, 1984), and (iii) enforce no-go areas above the high-water mark on beaches to protect the environmentally sensitive backshore areas and dunes (ANDERS and LEATHERMAN, 1987a, 1987b; GODFREY and GODFREY, 1980).

While such management actions—taken on environmental grounds—have been suggested (MOSS and MCPHEE, 2006), there are several caveats to be considered: (i) a variety of people use beaches for different purposes, spanning a broad spectrum from ORV enthusiasts to the enjoyment of pure wilderness experiences that exclude motor vehicles. Thus, for management to be inclusive, social and cultural factors need to be quantified; (ii) 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; (iii) 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; (iv) although a range of detrimental effects of ORVs on beach biota has been documented (GODFREY and GODFREY, 1980; 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 socioeconomic corollaries of vehicle traffic on sandy shores.

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