Vehicle impacts on the biota of sandy beaches and coastal dunes

A review from a New Zealand perspective

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CONTENTS

Abstract

Previous research into vehicle impacts on the biota of sandy beaches and coastal dunes in other countries is summarised, and is examined for its relevance to the management of these resources in New Zealand. Vehicle impacts on the biota of the backshore of sandy beaches and on the biota of coastal dunes have been demonstrated to be severe and these areas are considered to have a nil 'carrying capacity' with respect to vehicle use. A similar situation can be expected for the backshore of sandy beaches and for coastal dunes in New Zealand. Vehicle impacts on the biota of the foreshore (intertidal) of sandy beaches have appeared to be minimal, at least when the vehicle use occurred during the day, but very few elements of the foreshore biota have been examined. The situation regarding vehicle impacts on the biota of the foreshore of sandy beaches in New Zealand remains uncertain. Although previous research provides a guide for management strategies with respect to vehicle use of sandy beaches and coastal dunes in New Zealand at a general level, some local research is considered desirable. Future research into vehicle impacts on the biota of sandy beaches and coastal dunes in New Zealand should include fundamental research to further underpin decision-making processes, and applied research to address problems and monitor the results of management at specific sites.

1. Introduction

1.1 BACKGROUND

In July 1996 the Science and Research, and Visitor Services Divisions of the Department of Conservation (DOC) held a workshop on the physical impacts of visitors on natural and historic resources (see Cessford & Dingwall 1997). The main purpose of the workshop was to identify the Department's research and information needs in this area. Work which assisted in the systematic definition of key conservation values, and concise state-of-knowledge reviews for these key conservation values, were considered to be among the priorities in a research action plan (Cessford 1997). The request for a review of vehicle impacts on the biota of sandy beaches and coastal dunes was representative of the many information needs raised at the workshop.

The intensity and extent of motorised vehicle use on the beaches and dunes of New Zealand has increased progressively since the 1950s as vehicles with off-road capabilities have become more readily available and more affordable. In an inventory of the vegetation of sand dunes and beach systems of the North, South, and Stewart Islands carried out between 1984 and 1988 (Johnson 1992; Partridge 1992), vehicles were recorded as a modifying factor and/or a threat to future stability for 24% of these resources expressed as alongshore distances. The proportion was higher in the North Island (35%) than in the South Island (15%), and these figures are probably conservative because of constraints to the inventory and the period of time which has elapsed since it was completed. Adverse effects reported as being associated with vehicle use in coastal ecosystems include destruction of dune vegetation, disturbance of wildlife, introduction of alien species, erosion, litter, and increased exploitation of marine animals.

The review summarises previous research into vehicle impacts on the biota of sandy beaches and coastal dunes and provides an annotated bibliography covering the period 1988–1997 (see Appendix 1). The sources used to locate material are listed (see Appendix 2). The research results are examined for their relevance to the management of these resources in New Zealand, taking into account recent advances in sandy beach ecology. Recommendations are made regarding future research into vehicle impacts on the biota of sandy beaches and coastal dunes in New Zealand.

1.2 AREA UNDER CONSIDERATION

Sandy shores consist of three components—nearshore zones, beaches and dunes—which are linked by the interchange of material, particularly sand. Together they comprise a single geomorphic system, termed the littoral active zone (Tinley 1985). This is the part of the coast characterised by wave- and wind-driven sand transport and it lies between the outer limit of wave effects on bottom stability (usually between 5 m and 15 m depth) and the landward limit of aeolian sand transport (i.e. the landward edge of the active dunes). The basic topography and features of the zone are illustrated in Figure 1.

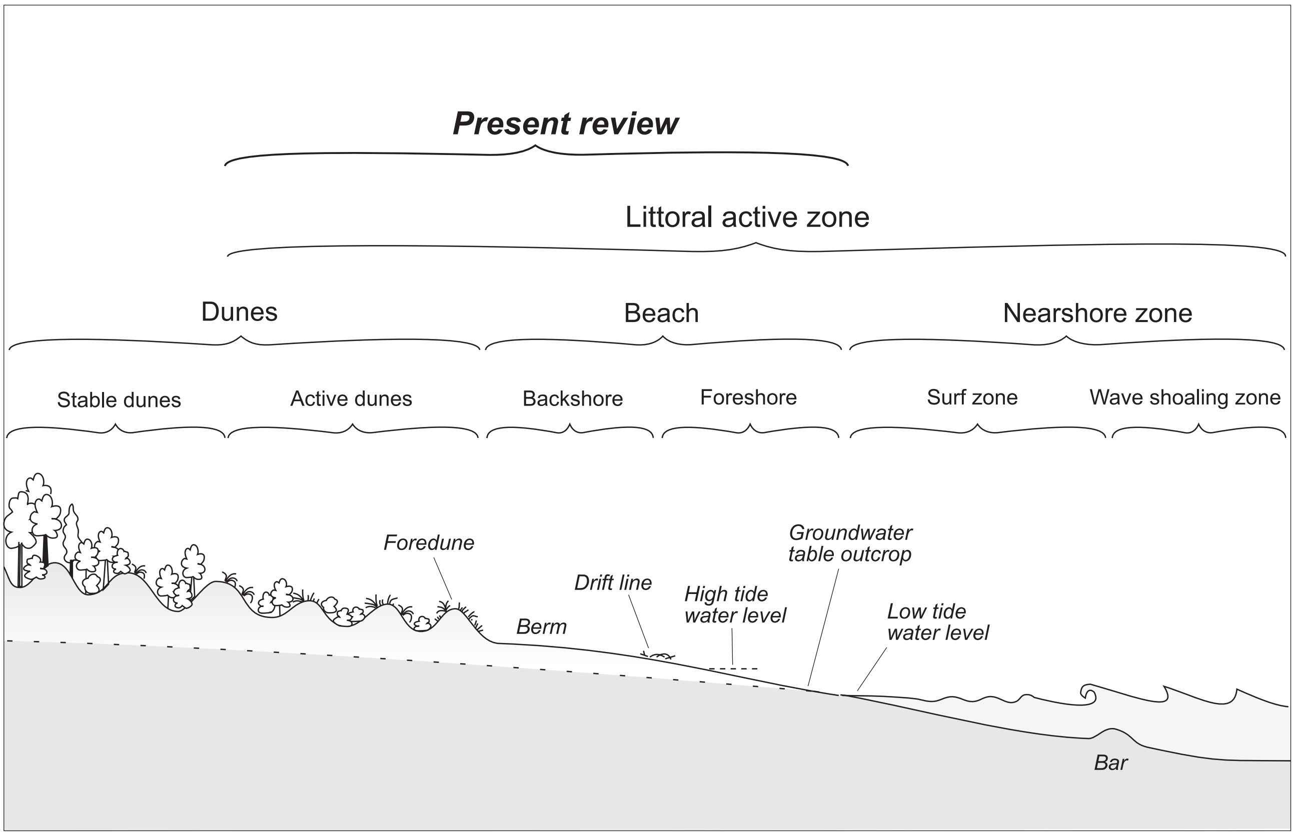


Figure 1. Profile of a typical sandy shore showing the features and divisions mentioned in the text.

Although the littoral active zone constitutes a single geomorphic system, ecologically it consists of two distinct systems: a marine foreshore/nearshore zone ecosystem populated by marine biota and controlled by wave energy, and a terrestrial backshore/dune ecosystem inhabited by terrestrial plants and animals and strongly influenced by wind energy (Brown & McLachlan 1990). The present review encompasses all of the backshore/dune ecosystem within the littoral active zone, but only the subaerial (or intertidal) portion of the foreshore/nearshore zone ecosystem. It should be noted, however, that many of the studies reviewed here describe the system differently, with the 'beach' considered to comprise the foreshore and backshore (e.g. Zaremba et al. 1978). As this coincides with the popular perception of a beach it is the method of description adopted here.

1.3 DUNE/BEACH EXCHANGES

Besides air and precipitation, four materials are exchanged across the dune/beach interface (Figure 2): sand, groundwater, salt spray, and living and dead organic material (McLachlan 1988). Virtually all coastal dunefields receive sand from and/or supply sand to beaches. Groundwater seeps from the land into the sea through confined or unconfined aquifers. This groundwater may be discharged in large volumes in some places and often contains very high nutrient levels, thereby adding significantly to the nutrient pool of the beach and surf zone. Salt spray blown inland has an important effect on dune vegetation, and together with sand movement is a major factor structuring plant communities and landward gradients in coastal dunes. Several types of organic materials may be exchanged across the dune/beach interface: insects are often blown from land towards the sea; carrion and wrack cast ashore may provide a food source for dune animals which move down to the beach to feed; larger animals in the dunes, such as birds, may be dependent on intertidal organisms for food; and litter from the dunes may be blown into the beach system.

Other than sand, which may be transported in huge volumes in high energy situations, the absolute quantities of the above materials transported across most dune/beach interfaces are fairly small (Brown & McLachlan 1990). However, the impacts of these materials (groundwater nutrients, salt spray and organic materials) may be significant to both systems. Thus, although dunes and beaches are discrete, terrestrial and marine, wind-controlled and wave-controlled systems respectively, and although the interactions between them are quantitatively small, they are essentially interdependent and interacting.

1.4 BEACH MORPHODYNAMICS

The concept of beach morphodynamic states refers to the depositional forms of sandy beaches and their hydrodynamic processes (Short & Wright 1984). All sandy beaches possess three dynamic zones: a zone of wave shoaling seaward of the breaker point, a surf zone of breaking waves, and a swash zone of final wave dissipation on the subaerial beach. The nature and extent of each of these zones will ultimately determine the beach morphodynamics (Short 1996).

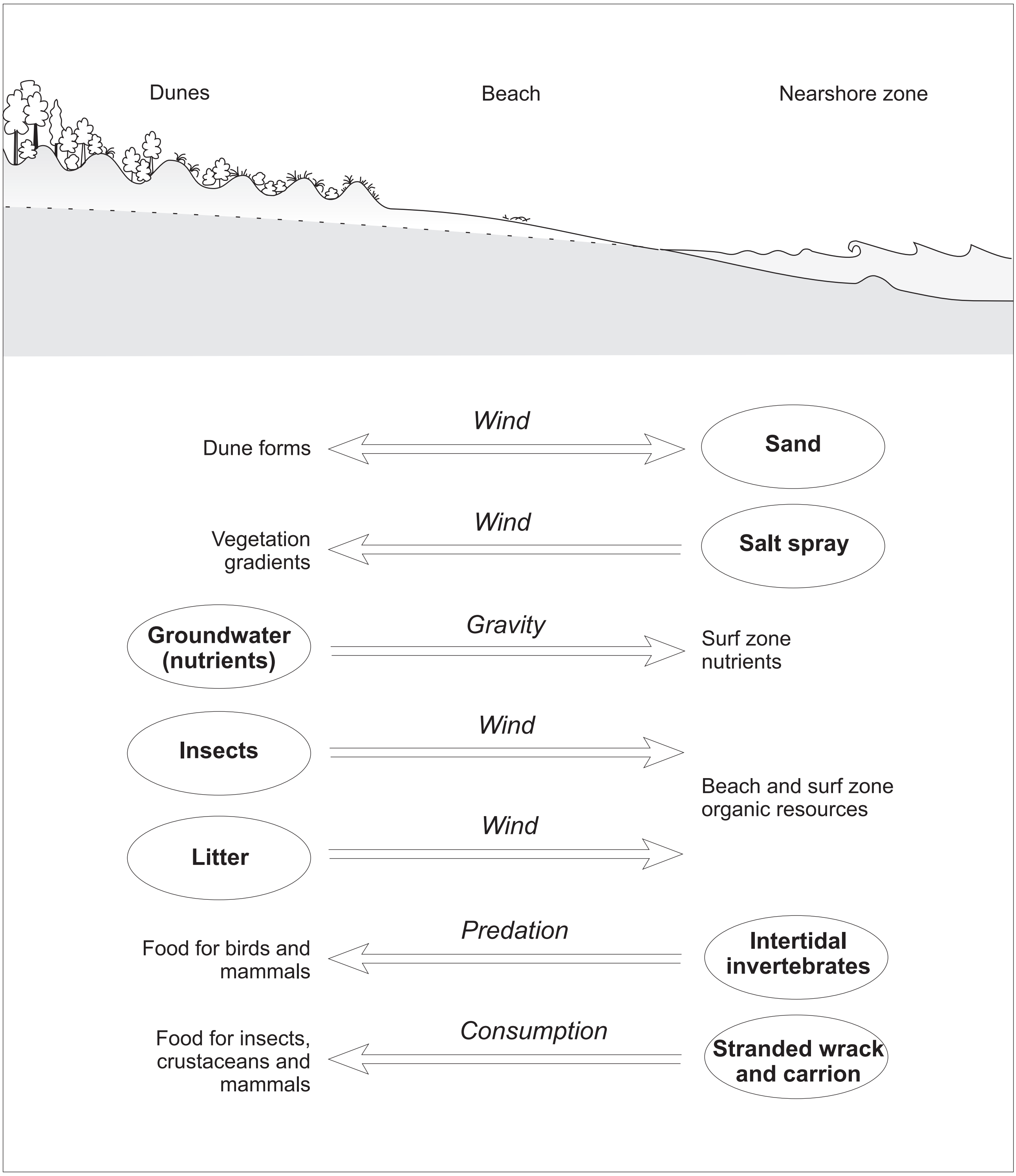


Figure 2. Exchanges of materials across a dune/beach interface. Adapted from McLachlan (1988).

In areas where the tide range is less than 2 m, the three dynamic zones are essentially stationary relative to the shoreline and the surf and swash zones play the dominant role in determining beach morphology. These beaches can be classified into six morphodynamic states (Figure 3) based upon the variables of breaker height, wave period, and sediment particle size (Short & Wright 1983). Reflective beaches are produced by the interaction of low waves (<1 m) and medium to coarse sands (mean particle size 0.25–2 mm). Such beaches have a relatively steep swash-dominated beach face, a low tide step, and a low gradient wave shoaling zone. There are no bar or surf zone features and waves surge or collapse over the low tide step with much of the incident wave-energy being reflected.

Combinations of high waves (>2.5 m) and fine to very fine sands (mean particle size 0.063–0.25 mm) result in dissipative beaches characterised by a wide low gradient beach face and a wide and even lower gradient surf zone containing several subdued shore-parallel bars and troughs. Waves break well to seaward of the shoreline and most of the wave-energy is dissipated in the surf zone.

The interaction of fine to medium sands (mean particle size 0.125–0.50 mm) and moderately high waves (1–2.5 m) result in beaches whose morphodynamic states—longshore bar and trough, rhythmic bar and beach, transverse bar and rip, and low tide terrace—represent a transition from dissipative to reflective. These beaches are characterised by high temporal variability, sediment

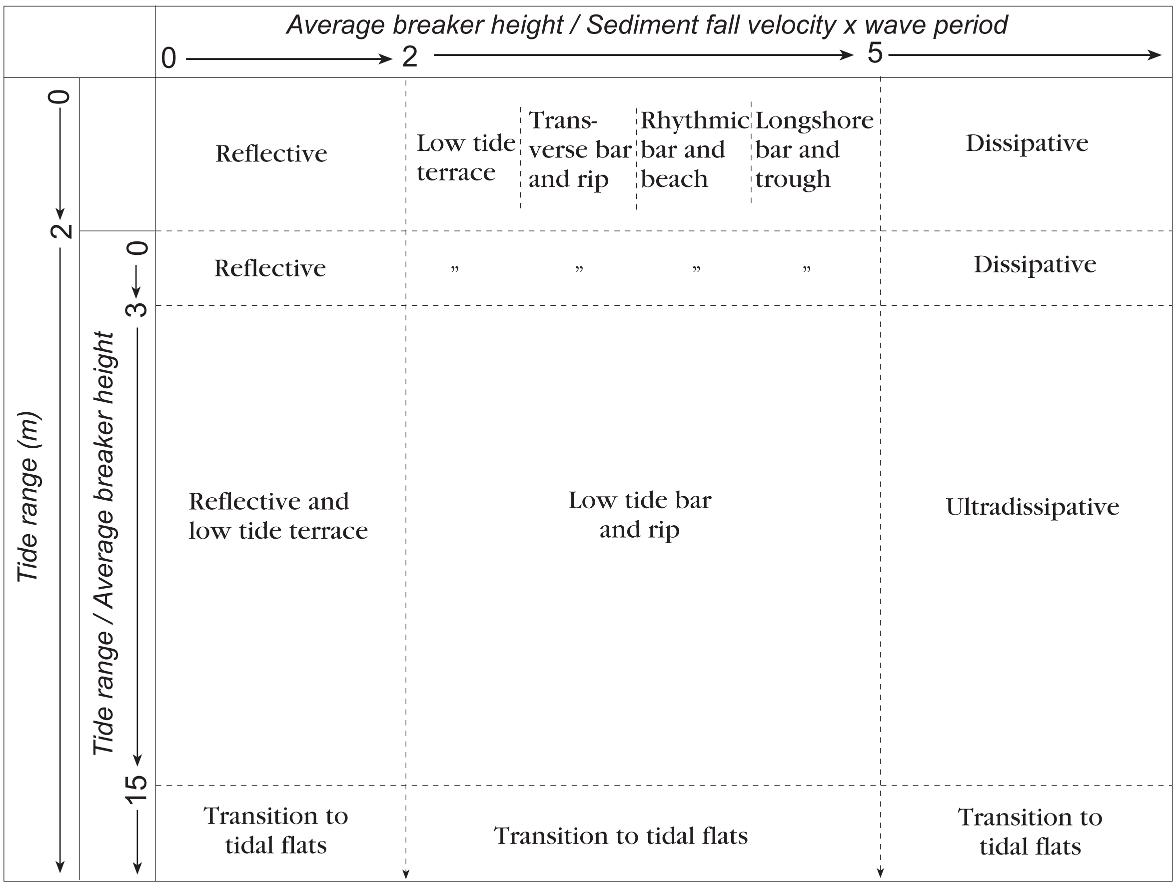


Figure 3. Classification of beaches into morphodynamic states based upon the interaction of breaker height, wave period, sediment particle size (expressed as fall velocity) and tide range. Adapted from Short (1996).

constantly being shifted between the beach face and surf zone, and bars and troughs in a surf zone displaying well-developed rip currents.

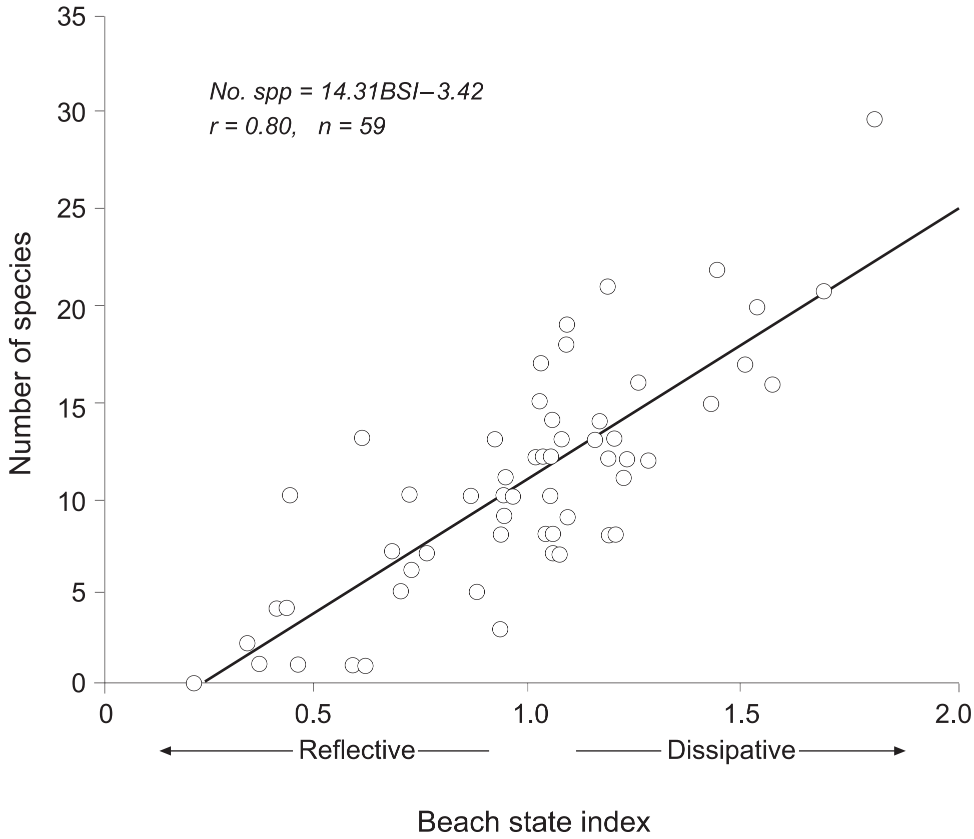
In areas where the tide range is greater than 2 m, the extent to which the three dynamic zones are daily translated to and fro across the intertidal and subtidal results in the surf and swash zones decreasing, and the wave shoaling zone increasing, in morphological dominance as the tide range increases. Eventually the swash zone is restricted in impact to the high tide beach and the wave shoaling zone overrides the surf zone and determines the intertidal and subtidal morphology. The morphodynamic states described for tide ranges less than 2 m persist until the tide range exceeds three times the average breaker height (Figure 3), after which three further morphodynamic states—ultradissipative, low tide bar and rip, and reflective + low tide terrace—can be identified based upon the variables of breaker height, wave period, and sediment particle size (Masselink & Short 1993). When the tide range exceeds 15 times the average breaker height the transition from beach to tidal flat environments begins.

1.5 BIOTA OF SANDY BEACHES

The biota which may be present on a sandy beach includes both macrofaunal and interstitial forms, the latter consisting of epipsammic diatoms, bacteria, protozoans and meiofauna. Most invertebrate phyla are represented on sandy beaches, either as interstitial forms or as members of the macrofauna, or both (Brown & McLachlan 1990). Among the macrofauna, polychaetes, bivalves, and crustaceans (principally amphipods, decapods and isopods) predominate, with changes in the gross taxonomic composition occurring which are related to exposure (Dexter 1992). Exposed sandy beaches are dominated by crustaceans, while polychaetes increase in relative abundance with decreasing exposure and become dominant in very protected situations. In addition, the number of species of macrofauna on an exposed sandy beach has been shown to be related to beach morphodynamic state (McLachlan 1990; McLachlan et al. 1993), the trend being for an increasing number of species towards dissipative conditions (Figure 4). This control appears to be a conservative feature of sandy beaches, differing little between zoogeographic provinces (McLachlan et al. 1993) and extending to beaches with tide ranges of at least 6 m (McLachlan et al. 1996). Macrofaunal abundance and biomass follow a similar pattern, but are more variable as factors other than beach morphodynamic state also play a role in their determination.

McLachlan (1990) and McLachlan et al. (1993) have argued that it is not the beach morphodynamic state itself which is important for the macrofauna, but the swash climate associated with it. There is a consistent relationship between beach morphodynamic state and swash climate features (McArdle & McLachlan 1991, 1992). As reflective conditions are approached swash periods shorten and approach wave period, swash speeds increase and tend to be high throughout the tidal cycle, and there is increasing swash activity above the groundwater table outcrop. Dissipative beaches display the opposite features. Physical stress in the swash zone thus increases from dissipative to reflective beaches and excludes more and more species until, in the fully reflective situation, only supralittoral forms (talitrid amphipods, insects) which live ‘outside’ the swash zone remain.

Figure 4. Relationship between the number of species of macrofauna and beach morphodynamic state. For an explanation of the Beach State Index see McLachlan et al. (1993).

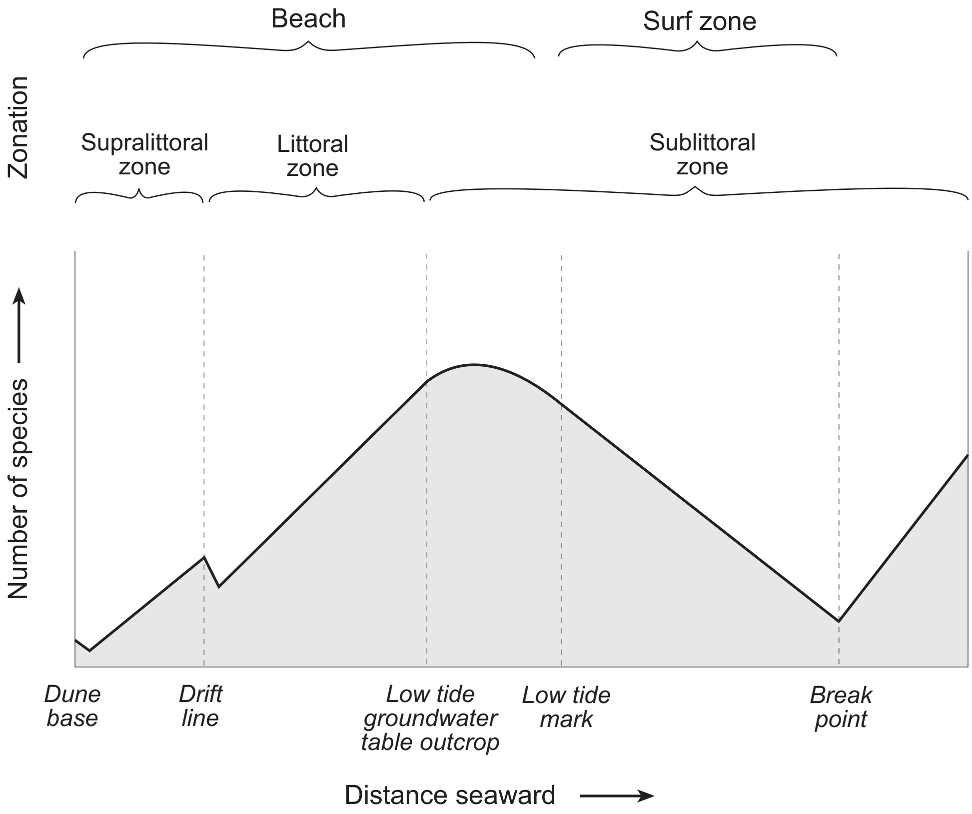


The distribution of macrofaunal animals on an individual sandy beach exhibits patchiness, zonation, and fluctuations related to tidal and other migrations (Brown & McLachlan 1990). Patchiness results from passive sorting by waves and swash, from localised food concentrations, variations in the penetrability of the sand, and from active biological aggregations. The principal causes of zonation across a sandy beach are exposure, changing wave energy levels, and sand water content and stability. The two key boundaries are the drift line and the groundwater table outcrop (Figure 5). Above the drift line is the supralittoral zone, characterised by air-breathing crustaceans such as ocypodid crabs (in the tropics and subtropics), talitrid amphipods (on temperate beaches) and the isopod *Tylos.* Insects are often important, particularly where macrophyte detritus is common. Wind is an important physical factor in this zone.

Between the drift line and the groundwater table outcrop is the littoral zone containing the truly intertidal species, all aquatic breathers which are never found higher up the beach but occasionally may be found subtidally. The littoral zone may be subdivided into bands dominated by different species. Swash action is the dominant physical factor here. Below the groundwater table outcrop is the sublittoral zone, where waves are the dominant physical factor and the bottom is unstable. Macrofaunal species richness is generally highest in the area between the groundwater table outcrop and the low tide swash zone, then declines landwards to near the dune margin, apart from a small peak at the drift line.

Meiofaunal communities of sandy beaches are diverse in taxonomic composition and have complex three-dimensional distribution patterns. The

Figure 5. Zonation of the macrofauna and hypothetical pattern of macrofaunal species richness across a sandy beach and surf zone. Adapted from Brown & McLachlan (1990).



dominant taxa are nematodes and harpacticoid copepods, with other important groups including turbellarians, oligochaetes, mystacocarids, gastrotrichs, ostracods, mites and tardigrades. Species richness is much higher than that of the macrofauna and is usually greatest on the mid- to upper shore and decreases downshore, the opposite trend to that of the macrofauna. Horizontal distributions may take the form of zones (sheltered beaches) or layers (exposed beaches), while the vertical distribution of meiofauna is determined by the degree of drainage and oxygenation of the sediment. In low energy situations and on flat beaches of fine sand, oxygen is the major limiting factor among the vertical physical and chemical gradients and the meiofauna is concentrated in the surface layers. In high energy situations and on beaches of coarse sand the meiofauna can extend deep into the sediment.

Birds which may be found feeding on sandy beaches include those of the families Laridae (gulls and terns), Scolopacidae (godwits, sandpipers, sanderling, snipes), Chionididae (sheathbills), Haematopodidae (oystercatchers), Charadriidae (dotterels and plovers), Ardeidae (herons), and Threskiornithidae (ibises and spoonbills). A number of birds also breed on the backshores of sandy beaches, including terns (Blodget 1978; Davies 1981), oystercatchers (Skead 1966) and plovers (Summers & Hockey 1980; Warriner et al. 1986; Buick & Paton 1989).

Reptiles and mammals recorded as invading sandy beaches include snakes, lizards, marine turtles, mongooses, water mongoose, otters, baboons and jackals. Marine turtles use the backshores of sandy beaches for egg-laying; the other species are predators or scavengers and little is known of their impact except for a few specific cases, such as predation on turtle eggs (Brown & McLachlan 1990).

1.6 BIOTA OF COASTAL DUNES

The primary colonisation of aeolian sand along the coast is usually by micro-organisms and fungi (Webly et al. 1952). These organisms promote aggregations of sand grains, and the presence of such aggregates reduces wind erosion, increases soil moisture and increases the nutrient status of the sand. Colonisation by higher plants is frequently initiated by succulent annual herbs, while higher up the shore perennial grasses or sedges are usually responsible for the establishment of a foredune. Behind this a zone of shrubland or dune heath usually develops in which a moderate amount of sand movement still occurs. The flora of this zone may include annuals, forbs, creepers, succulents and shrubs. Further inland still, zones of woody vegetation with closed canopies develop where rainfall and shelter are sufficient (Figure 6).

The fauna of coastal dunes is dominated by arthropods and vertebrates, particularly insects, birds and mammals (McLachlan 1991). Arachnids are common and crustaceans may be important near the beach. Among the insects, the orders Hymenoptera, Coleoptera, and Diptera are especially well represented. Rodents are the principal mammalian residents; most larger mammals traverse dunes temporarily for feeding or to gain access to the beach to forage among wrack or for carcasses. Dune soils, especially in areas of high moisture content, may support rich interstitial biotas consisting of bacteria, fungi, actinomycetes and algae (Webly et al. 1952), as well as meiofauna (van der Merwe & McLachlan 1991).

The fauna of coastal dunes may display high diversity but limited endemism, the latter related to the small size of most coastal dunefields and their extensive sea and landward boundaries, which allow free exchange of fauna (McLachlan 1991). In addition, coastal dune systems are geologically young and thus have had little time for the evolution of unique inhabitants. Faunal species richness responds to changes in vegetation and habitat complexity primarily along a gradient perpendicular to the shore. Geographical variations in coastal dune faunal taxonomic composition are largely unknown due to the paucity of information from most parts of the world.

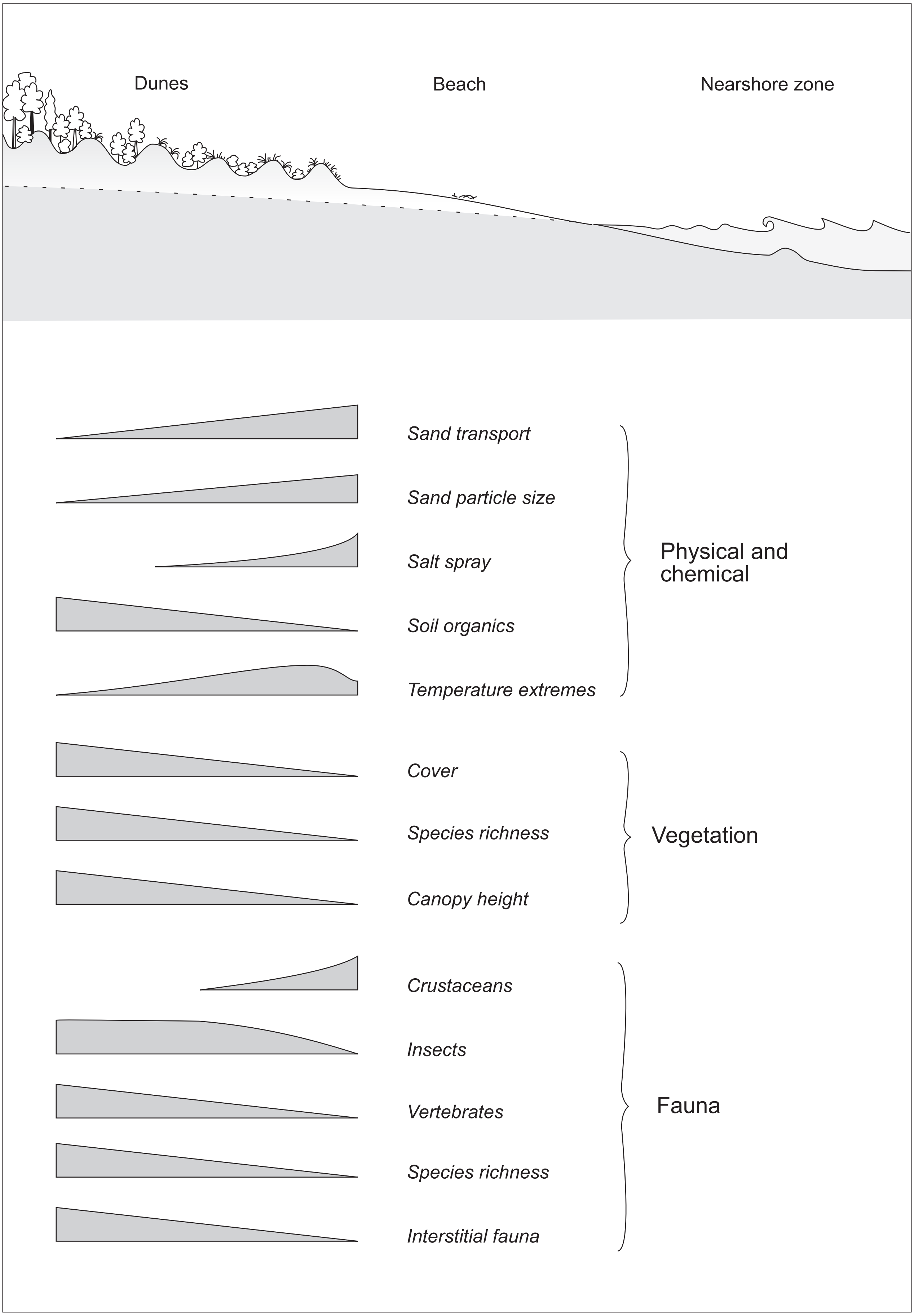


Figure 6. Conceptual model of selected physical, chemical and biological gradients across coastal dunes in a non-arid region. Adapted from McLachlan (1991).

2. Previous research

2.1 HISTORY OF RESEARCH

One of the first major investigations into the impact of vehicles on coastal ecosystems was a survey by Liddle & Moore (1974) of the microclimatic changes caused by the creation of a track in sand dune vegetation at Aberffraw, North Wales, and evaluation of the relative effects of the two major components of track creation (vegetation removal and soil compaction) in producing these changes. This was followed by a survey of the soil bulk density and penetration resistance of tracks and paths in the Aberffraw dune system, a field experiment to determine the relationship between these characteristics and a known amount of wear, a study of the effect of compaction on soil water, and an experiment to investigate the effects of compaction on the availability of water to plants in dry conditions (Liddle & Greig-Smith 1975a). Contemporaneously, a study to describe the vegetation of the Aberffraw sand dunes in relation to the effects of trampling and vehicles, and an experiment to determine the relative effects of shoot damage and soil compaction on *Festuca rubra*, were also carried out (Liddle & Greig-Smith 1975b).

In 1974 the University of Massachusetts/National Parks Service Cooperative Research Unit began a multidisciplinary experimental analysis of off-road vehicle impacts in Cape Cod National Seashore, Massachusetts, USA. Beach, dune, salt marsh and tidal flat ecosystems were impacted in a controlled fashion so that rates of deterioration and recovery of both physical and biotic characteristics could be measured (Brodhead & Godfrey 1977; Blodget 1978; Zaremba et al. 1978; Brodhead & Godfrey 1979a, 1979b; Leatherman & Godfrey 1979; Wheeler 1979). The research findings were summarised by Godfrey et al. (1980) and Godfrey (1981), and an annotated bibliography on the effects of off-road vehicle and pedestrian traffic on coastal ecosystems was produced (Steiner & Leatherman 1979).

Research into vehicle impacts on coastal ecosystems continued in the USA into the 1980s, principally on the beaches and dunes of barrier islands along the eastern seaboard (Hosier & Eaton 1980; McAtee & Drawe 1980, 1981; Anders & Leatherman 1981; Steiner & Leatherman 1981; Wolcott & Wolcott 1984; Anders & Leatherman 1987; Carlson & Godfrey 1989).

In 1977 the Nature Conservation Society of South Australia published the results of a multidisciplinary study of the beaches, dunes, and other habitats of the southern Coorong and lower Younghusband Peninsula in South Australia, which included observations on the impact of vehicles taken off-road in that area for recreational purposes (see Gilbertson & Foale 1977). Beaches in the Coorong region were also the site for a study of the impact of off-road vehicles on the nesting success of hooded plovers (Buick & Paton 1989).

In South Africa, more than 80% of the approximately 3000 km-long coastline consists of sandy beaches backed by mobile or stable sand dunes (Tinley 1985). Concern about damage to coastal ecosystems caused by off-road vehicles led to a review of their impacts by van der Merwe (1988), and to a number of studies designed to quantify these impacts and advance suggestions to ameliorate or prevent further damage (Heath 1987; Jeffery 1987; Els & McLachlan 1990; van der Merwe & van der Merwe 1991; Avis 1992; Watson 1992; Rickard et al. 1994).

2.2 VEHICLE IMPACTS ON THE BIOTA OF SANDY BEACHES

2.2.1 Foreshore

The foreshore (or intertidal) is defined as that part of the beach between the spring low water level and the spring high water level (see section 6. Glossary). At Cape Cod National Seashore, Massachusetts, USA, attempts to determine whether off-road vehicles had an impact on meiofauna populations, interstitial algae or bacteria in the intertidal zone were unsuccessful, because the high variability within the sample areas masked any correlation with vehicle damage (Leatherman & Godfrey 1979). There were very few macrofaunal invertebrate organisms in this northern beach, so that vehicular impacts were minimal in this respect (Godfrey et al. 1980).

Further south on Assateague Island, Maryland/Virginia, USA, Steiner & Leatherman (1981) conducted a study to determine the relative number of ghost crabs (*Ocypode quadrata*) on beaches subject to different recreational uses. Ghost crabs inhabit the upper shore and are nocturnal, occupying semi-permanent burrows in the sand during daylight hours. They found areas subjected to off-road vehicle traffic had significantly lower densities and a smaller physical size of crabs than undisturbed areas or areas with pedestrian traffic only. A similar relationship between the observed densities of ghost crabs and off-road vehicle traffic had been noted by Leggat, and later by Brokensha, on the beaches in northern Natal, South Africa (see van der Merwe 1988).

A more direct investigation of the impact of off-road vehicles on beach macroinvertebrates was carried out by Wolcott & Wolcott (1984) in the Cape Lookout National Seashore, North Carolina, USA, where vehicle use was light and virtually no vehicle use occurred at night. Samples taken inside and outside vehicle tracks showed that mole crabs (*Emerita talpoida*) and coquina clams (*Donax variabilis*) were not damaged. Ghost crabs (*Ocypode candida*) also were completely protected by burrows as shallow as 5 cm and therefore not subject to injury during the day, but could be killed in large numbers by vehicles when feeding on the surface of the foreshore at night. Predicted mortalities calculated from observed kills of ghost crabs per vehicle-kilometre ranged from 14–98% for 100 vehicle passes (Wolcott & Wolcott 1984).

The effects of off-road vehicles on a further four intertidal macrofaunal species, the gastropod *Bullia rhodostoma*, the bivalves *Donax serra* and *D. sordidus*, and the benthic mysid *Gastrosaccus psammodytes*, were investigated experimentally on Sundays River Beach, South Africa (van der Merwe & van der Merwe 1991). For large *Bullia rhodostoma* (>25 mm) the mean percentage of damaged individuals at a low intensity of impact (5 passes) was 0.9%; at a high intensity of impact (50 passes) it was 0.6%. The corresponding figures for small individuals (<20 mm) were 12.3% and 3.1%. For *Donax serra* the mean percentage of damaged individuals at a high intensity of impact was 7.4% for large individuals and 6.3% for small individuals; for unspecified sizes of *D. sordidus* it was 2.9%. The response of *Gastrosaccus psammodytes* was complicated by the experimental procedure used, and in an attempt to determine the impacts of off-road vehicles on this species under natural conditions, samples were taken directly under vehicle wheels and next to the wheels (control) on the open beach. No significant differences were found and no animals were damaged. It was concluded that the intertidal animals examined in this study appeared to be safe from damage by vehicles, even at relatively high traffic intensities, provided they were buried and the sand was reasonably compact. Individuals of *Bullia* were robust enough to withstand being run over even if placed on the surface of the beach, but individuals of the other three species were easily crushed in this situation.

2.2.2 Backshore

The backshore is defined as that part of the beach between the spring high water level and the dune margin. It is here that drift accumulates, sea birds nest, and new dunes form along accreting beaches (Godfrey et al. 1980). Drift lines often contain considerable amounts of organic matter, which macrofaunal invertebrates, bacteria and fungi break down, releasing nutrients into the sand and eventually back to the sea. Drift lines also contain fragments and seeds of dune plants and are therefore significant sites for new dune development on open sand.

On the lower Younghusband Peninsula of South Australia, Gilbertson (1977) reported that extensive off-road vehicle use had retarded or prohibited the development of drift line vegetation and inhibited the development of a low foredune by the pioneer plants spinifex (*Spinifex hirsutus*) [= *S. sericeus*], sea spurge (*Euphorbia paralias*) and sea rocket (*Cakile maritima*).

At Cape Cod National Seashore, Massachusetts, USA, direct displacement experiments showed that vehicle traffic compacted beach sand at depth, but loosened the surface of the beach, thus rendering it more susceptible to aeolian and/or swash activity (Anders & Leatherman 1981). The shearing and compressional effects of vehicle passage extended to a depth of approximately 20 cm (Niedoroda 1979). The shear stresses of turning wheels disaggregated the drift and broke underground rhizomes (Zaremba et al. 1978) as well as crushing seedlings of annuals and young plants of perennials such as *Ammophila* (Leatherman & Godfrey 1979). Vehicle impact also decreased the rate of decay of organic material. Bacterial counts associated with the drift were normally very high, but were markedly reduced when vehicles pulverised the organic deposits (Leatherman & Godfrey 1979).

On northern Padre Island, Texas, USA, backshore areas subjected to either short- or long-term heavy vehicular and pedestrian traffic were demonstrated to have decreased top and root production, percent cover, and diversity of vegetation compared with unimpacted areas (McAtee & Drawe 1980). Impacted areas were also characterised by a lack of embryo dunes and microclimatic changes: as the intensity of human activity increased, average wind velocities near the ground surface, evaporation, atmospheric salinity near the ground surface, wind-carried sand particles near the ground surface, soil salinity, soil pH, average soil temperature and range in temperature, soil bulk density, and soil-water content all increased (McAtee & Drawe 1981). These changes made environmental conditions more demanding for remaining plants in the immediate area as well as for plants further inland.

On Fire Island, New York, USA, Anders & Leatherman (1987) showed that even low-level off-road vehicle impact (one pass/week) severely damaged the primary colonising plants—American beach grass (*Ammophila breviligulata*) and dusty miller (*Artemisia stellariana*)—and prevented seaward advance of the vegetation front onto the backshore. This occurred even where the levels of impact were too low to shear off the underground rhizomes of American beach grass, as vehicles crushed emerging tillers.

The impact of off-road vehicles on the nocturnal supralittoral isopod *Tylos capensis* was investigated experimentally on Sundays River Beach, South Africa (van der Merwe & van der Merwe 1991). It was found that the number of *T. capensis* completely crushed or with cracked exoskeletons increased linearly with increase in intensity of vehicle impact. Ten percent of the animals were damaged by approximately 17 vehicle passes even though they burrowed 20–30 cm below the surface of the sand during the day. The animals were even more susceptible to damage by vehicles when on the surface at night.

Off-road vehicle impacts on the colonial beach-nesting least tern (*Sterna albifrons*) and on transient populations of other migratory shorebirds at Cape Cod National Seashore, Massachusetts, USA, were studied by Blodget (1978). It was found that least terns could get used to vehicles passing close to their nests, but flushed when persons or dogs approached, increasing the risk of eggs overheating or being taken by predators. Vehicles passing directly through the colonies ran over the highly camouflaged eggs and chicks. Disruption of feeding plovers and sandpipers by vehicles was minimal, but vehicles were a constant menace to resting flocks at high tide.

Pairs of African black oystercatchers (*Haematopus moquini*) often nest on or just above the drift line in the eastern Cape, South Africa (van der Merwe 1988). Observations of this species made along a 12 km section of coastline over a period of 14 years from mid 1971 to March 1985 revealed that from 1978–79 the number of nests recorded annually decreased and the number of chicks fledged fell from more than ten chicks per year to zero during the last two seasons of the study. The sharp decrease in fledged birds was directly correlated with the observed increasingly frequent vehicular traffic (Jeffery 1987).

The impact of off-road vehicles on the nesting success of hooded plovers (*Charadrius rubricollis*) in the Coorong region of South Australia was examined by Buick & Paton (1989). Passing vehicles were found not to cause a reduction in nest attentiveness, but measurements using artificial nests showed that on average 6% of nests were run over per day. This rate was equivalent to 81% of the nests on beaches being run over during the incubation period. Coupled with the observed low rate of fledgling success, this suggested that the use of off-road vehicles potentially reduced the reproductive output of hooded plovers in the region.

Vehicles also have been reported as influencing the reproductive success of several other beach-nesting bird species, including white-fronted plover (*Charadrius marginatus*) in northern Natal and the eastern Cape, South Africa (Brokensha 1984; Watson 1992), and snowy plover (*Charadrius alexandrinus*) in California, USA (Warriner et al. 1986).

Marine turtles come ashore on tropical and subtropical beaches to lay their eggs close to the foredunes. Hosier et al. (1981) found that the tracks made by vehicles in the sand tended to present insurmountable obstacles to the progress of loggerhead turtle (*Caretta caretta*) hatchlings towards the sea, thus making them more susceptible to predation and dessication.

2.3 VEHICLE IMPACTS ON THE BIOTA OF COASTAL DUNES

2.3.1 Vegetation

Vehicular traffic has been shown in a number of studies to decrease the height, biomass and total cover of vegetation on coastal dunes, these changes occurring irrespective of the successional status of the vegetation. However, both location within the dune system and successional status have been demonstrated to influence the rate of recovery following vehicle impact.

At Cape Cod National Seashore, Massachusetts, USA, tracks along the foredune and the top of the main dune through vegetation dominated by American beach grass (*Ammophila breviligulata*) were surveyed, then driven on at different levels of intensity and the effects measured in terms of above-ground biomass (Brodhead & Godfrey 1977). Subsequent recovery of the vegetation was also monitored. Beach grass above-ground biomass in the tracks declined rapidly when subjected to an impact of 25 vehicle passes per day: to 25% of the initial biomass in the foredune track and to 15% of the initial biomass in the main dune track after a cumulative total of 675 vehicle passes. Recovery in the following twelve months was to 59% and 32% of the initial biomass respectively. A similar pattern of reduction and recovery in above-ground biomass was observed under an impact totalling 270 vehicle passes (10/day), after which the biomass was reduced to 42% in the foredune track and to 34% in the main dune track. A year later the biomass in the foredune track had recovered to 99% of its former value and that in the main dune track to 45%. Beach grass is dependent on a source of nutrient-rich sand for optimum growth, and it was concluded that a lack of fresh sand at the top of the main dune (due to prior capture of sand by foredune grass stands or deflation by wind) was responsible for the observed differences in recovery rates between the sites.

Plant communities dominated by bear-berry (*Arctostaphylos uva-ursi*), hair-grass/lichen (*Deschampsia caespitosa/Cladonia*) and beach heather (*Hudsonia tomentosa*) respectively were present on stabilised dunes at Cape Cod. These were subjected to similar tests, which showed that each vegetation type broke down at approximately the same rate when compared to *Ammophila* dune vegetation (Brodhead & Godfrey 1979a). The rates of recovery, however, were very different, with the bear-berry and hairgrass communities returning to pre-impact biomass levels within four years, while tracks through the beach heather were still largely bare after a similar period of monitoring. The growth habits and reproductive strategies of the individual species were considered to be important factors in relation to recovery rates.

At the R.T. Crane Jr Memorial Reservation, Massachusetts, USA, Carlson & Godfrey (1989) surveyed 14 sites on semi-stabilised dunes with a vegetation dominated by American beach grass. Sites which had been subject to human recreational activity were found to have significantly lower mean percentages of plant cover than a nominated relatively undisturbed control site. A resurvey of nine of the sites three years later, following the implementation of a management plan, revealed significant increases in mean percentage plant cover at five sites and that mean percentage plant cover had not decreased significantly at any of the resurveyed sites. A contemporaneous survey of ten sites on stabilised dunes with a vegetation dominated by beach heather also showed that, at all sites with human disturbance, there was a significant reduction in mean percentage plant cover, relative to a nominated undisturbed control site. The most severe reduction was at those sites subject to off-road vehicle impact. However, no significant increase in mean percentage plant cover was recorded at any of the eight stabilised dune sites resurveyed three years later, a result consistent with the observations of Brodhead & Godfrey (1979a) concerning post-vehicle-impact on beach heather communities at Cape Cod.

On the Cape Fear barrier island system of North Carolina, USA, transects across the dunes showed that at a site widely used by vehicles, the dune vegetation cover was 45% lower than at an unimpacted site (Hosier & Eaton 1980). The dominant plant species of the dunes were sea-oats (*Uniola paniculata*), *Oenothera humifusa*, *Erigeron canadensis*, *Euphorbia polygonifolia* and, at the vehicle-impacted site, *Triplasis purpurea*. Transects across the foredune at four sites with different intensities of vehicular and pedestrian usage on northern Padre Island, Texas, USA, showed that the transect with the least usage had vegetation with the greatest top and root weights and foliar cover, and the transect receiving the most traffic had the lowest values for these parameters (McAtee & Drawe 1980). In this case the vegetation was dominated by *Ipomoea pes-caprae*, *I. stolonifera*, *Croton punctatus*, *Uniola paniculata*, and *Ambrosia psilostachya*.

The effects of different intensities of off-road vehicle and pedestrian traffic on vegetation height and percentage cover has been investigated experimentally at two sites representing pioneer and climax dune communities in South African dune systems (Rickard et al. 1994). The vegetation at the pioneer site was composed predominantly of *Arctotheca populifolia*, *Gazania rigens*, *Sporobolus virginicus*, *Scirpoides nodosa* and *Juncus krausii*, while the climax site vegetation was a *Ficinia/Restiod* community containing shrubs such as *Metalasia muricata*, *Passerina rigida*, *Rhus crenata*, *Euclea racemosa*, *Myrica quercifolia* and *Phylica ericoides*. In all cases, a decreasing trend in vegetation height and percentage cover subsequent to application of the treatments was evident, although this was clearer in the climax than in the pioneer community. The impact on the vegetation variables increased with increasing intensity of vehicle and pedestrian treatments, and vehicles driven along a curved path resulted in greater vegetation destruction than those driven along a straight path. The pioneer vegetation showed a greater capacity to recover following the impact, with the percentage cover similar to the site's starting cover values after ten months, while the percentage cover of the climax vegetation remained significantly below starting cover values.

2.3.2 Plant species richness and composition

Other reported vehicle impacts on dune vegetation are a reduction in the number of plant species where the impacts are long-term, and changes in species composition. The number of plant species present on vehicle-impacted dunes of the Cape Fear barrier island system, North Carolina, USA, was reported to be 13.3% lower than on dunes where there was no vehicle use (Hosier & Eaton 1980). On northern Padre Island, Texas, USA, comparison of transects across the foredune at four sites with different intensities of vehicular and pedestrian usage showed that the transect with the least usage had the highest number of plant species and the transect receiving the most traffic had the lowest number of plant species (McAtee & Drawe 1980). At the R.T. Crane Jr Memorial Reservation, Massachusetts, USA, Carlson & Godfrey (1989) found that several American beach grass-dominated dune sites which had been subject to human recreational activity had significantly fewer plant species than an undisturbed control site. Three years later, following implementation of a management plan, two of these sites showed significant increases in the number of plant species and the number of plant species had not decreased significantly at any resurveyed site. By comparison, dune sites dominated by beach heather showed no significant increase in the number of plant species over the same three-year period.

On vehicle tracks in the Aberffraw dune system, North Wales, Liddle & Greig-Smith (1975b) found that the number of plant species tended to be higher on the track margins and lowest under the wheel ruts, that is, where soil compaction was greatest. Moving from relatively unimpacted regions to one of greater compaction there was first a reduction in the proportion of monocotyledonous species and an increase in dicotyledonous species. As compaction was further increased the trend reversed and monocotyledonous species completely replaced the dicotyledonous species where the compaction was greatest. Liddle & Greig-Smith (1975b) considered these changes were the result of differences in the susceptibility of the two groups to mechanical damage and the possession by monocotyledonous species of relatively protected apices and intercalary meristems.

Kuss (1986) reviewed the major factors influencing plant responses to recreation impacts and noted that responses to the mechanical effects of trampling appear to be strongly associated with the morphological characteristics of plants. The hemicryptophyte life form, which has its perennating buds located at or just below the surface of the soil, has been shown to be the most resistant to trampling stresses in sand dune vegetation (Liddle & Greig-Smith 1975b; Slatter 1978). Tufted and rosette growth forms are considered to be well-adapted to trampling (Liddle & Greig-Smith 1975b). Plant turgor and succulence, length of seasonal activity, height, and phenology are other factors that appear to influence the vulnerability of species to trampling.

Avis (1992) suggested that vegetative spread of pioneer plants by rhizomes (e.g. *Sporobolus virginicus*), stems that can tolerate burial (e.g. *Scaevola plumieri*) or stolons (e.g. *Ipomoea* spp.) may be important dispersal mechanisms, allowing rapid recovery of pioneer vegetation following disturbances. At the Cape Cod National Seashore, Massachusetts, USA, American beach grass (*Ammophila breviligulata*) recovery following vehicle impacts occurred from underground rhizomes and began within weeks even when above-ground portions of the plants within the vehicle tracks were completely destroyed (Brodhead & Godfrey 1977). Plant species in climax shrub communities, however, generally grow slowly and recovery occurs through seedlings rather than by vegetative means. Vehicles may decrease the reproductive potential of climax shrub species by damaging the upright portions carrying the sexual organs, thus adversely affecting recovery. Repeated impacts further inhibit recovery of such communities by destroying any seedlings which may have begun to establish since the previous impact (Rickard et al. 1994). Changes in microclimate and soil properties as a result of vegetation removal and compaction can also affect the rate of recovery of plant communities and lead to changes in species composition.

2.3.3 Microclimate and soils

Microclimate and plant cover are interdependent, and microclimatic changes caused by track creation in several types of sand dune vegetation were first examined by Liddle & Moore (1974) at Aberffraw, North Wales. They found that track formation increased both soil strength (top 30 cm) and soil bulk density (top 6 cm) to a similar extent in both wet and dry areas. Diurnal soil and air temperature ranges were also increased: at 2 cm depth the increase in soil temperature range on dry sites could be as much as 15°C in summer, but was not so extreme on wet sites. When the relative effect of vegetation removal and soil compaction were investigated, it was found that on a dry sand dune area the total effect of track creation on soil temperature was the result of a dynamic balance between the major effect of vegetation removal and the lesser and opposite effect of soil compaction, whereas in a wet dune area soil compaction augmented the effect of vegetation removal.

A survey of soil bulk density and penetration resistance of established tracks in the Aberffraw dune system by Liddle & Greig-Smith (1975a, 1975b) showed that both of these parameters were significantly higher under tracks than under the adjacent vegetation, that the degree of soil penetration resistance varied with depth with the maximum compression occurring beteen 15 and 35 cm depth, and that the soil was compacted to a depth of at least 48 cm. A field experiment to determine the relationship between soil bulk density and penetration resistance and a known amount of wear found both parameters had a linear relationship with the logarithm of the number of vehicle passages. The reduction in pore space was sufficient to produce anaerobic conditions in wet dune slacks during the winter (Liddle & Greig-Smith 1975a).

The soil water content under tracks in dry areas at Aberffraw was greater than under adjacent undisturbed areas, the difference being 6.4% volumetric (3.9% gravimetric): that is, compaction increased the water content of dry sand dune soils (Liddle & Greig-Smith 1975a). There was no significant difference between soil water content under tracks and under adjacent undisturbed areas for wet dune soils. A wilting experiment using *Festuca rubra* suggested that under dry conditions the growth of plants may be enhanced by the greater availability of water in a compacted dry sandy soil (Liddle & Greig-Smith 1975a).

Research by other workers has confirmed the soil and microclimatic changes observed by Liddle & Moore (1974) and Liddle & Greig-Smith (1975a, 1975b), and described a variety of other atmospheric and soil parameters affected by the loss of vegetation on dunes. Wilshire et al. (1978) found the impacts of off-road vehicles on very sandy soils in the San Francisco Bay area of California, USA, included decreased surface strength, increased bulk density (average about 8%) and soil moisture (average 23% to 30 cm depth), extension of the diurnal temperature range in the top 10 cm (by as much as 12ºC), and a reduction in organic carbon (average 42%). On the Cape Fear barrier island system, North Carolina, USA, Hosier & Eaton (1980) found that soil penetration resistance near the surface (1 cm depth) was twice as high in non-impacted areas of the dunes as that in vehicle-impacted areas, whereas at 15 cm depth the soil penetration resistance was 2.42 times higher in the vehicle-impacted areas than in the non-impacted areas. On the foredunes of northern Padre Island, Texas, USA, it was shown that as the intensity of vehicular and pedestrian traffic increased, average wind velocities near the ground surface, evaporation, atmospheric salinity near the ground surface, wind-carried sand particles near the ground surface, soil salinity, soil pH, average soil temperature and range in temperature, soil bulk density and soil-water content were increased (McAtee & Drawe 1981).

2.3.4 Fauna

The loss of dune vegetation, and changes in soil properties and microclimate, in addition to the direct impact of vehicles, can cause changes in the animal populations of coastal dunes. However, there have been very few studies of vehicle impacts on the fauna of coastal dunes to quantify these changes. Soil arthropods, earthworms and molluscs have been shown to exhibit a general reduction in population density as a result of trampling by humans and vehicular compaction in a chalk grassland ecosystem in England (Chappell et al. 1971), and Greenslade & Greenslade (1977) reported that soil surface arthropods showed a decline both in population density and in numbers of species present on vehicle tracks through grassland and coastal wattle (*Acacia sophorae*) scrubland in South Australia. In the inland Algodones Dunes of California, USA, Luckenbach & Bury (1983) found that arthropod (mostly beetle) tracks were 24 times more abundant in unimpacted control areas than in vehicle-impacted areas. Luckenbach & Bury (1983) also found 1.8 times the number of species, 3.5 times the number of individuals, and 5.9 times the biomass of lizards in unimpacted control areas than were present in vehicle-impacted areas. Direct evidence of death of lizards due to vehicles was found and tail loss by one species was appreciably greater in vehicle-impacted areas than in undisturbed areas.

Baccus (1977) reported a more diverse rodent fauna in areas of the beach and dunes of Padre Island National Seashore, Texas, USA, where vehicular traffic was absent. In the inland Algodones Dunes of California, USA, Luckenbach & Bury (1983) recorded 1.5 times the number of species, 5.1 times the number of individuals, and 2.2 times the biomass of rodents in unimpacted control areas than were present in vehicle-impacted areas. The control areas also had twice the number of kit fox (*Vulpes*) tracks and ten times the number of cottontail rabbit (*Sylvilagus*) tracks as the vehicle-impacted areas.

2.4 LIMITATIONS OF PREVIOUS RESEARCH

A major drawback of previous research into vehicle impacts on the biota of sandy beaches and coastal dunes is its restricted taxonomic coverage of invertebrates. Representatives of only a few of the invertebrate groups potentially present on sandy beaches have been studied in relation to vehicle impacts, and there has been no research into vehicle impacts on the invertebrates associated with the above-ground portions of dune plants. Furthermore, all the previous studies of vehicle impacts on soil surface and subsurface invertebrates have been carried out in inland situations rather than on coastal dunes.

3. New Zealand perspective

3.1 VEHICLE IMPACTS ON THE BIOTA OF SANDY BEACHES

3.1.1 Vegetation

New Zealand has few specialised strand plants. The native sand sedge (*Carex pumila*) can occur on damp portions of the backshore of sandy beaches, as can the introduced sea rocket (*Cakile edentula*, accompanied in northern areas by *C. maritima*). The rare native *Theleophyton billardieri* grows on drier beaches just beyond the reach of normal tides (Wardle 1991). *Carex pumila* has slender underground rhizomes which, based on the observations of damage to rhizomatous pioneer sand-binding species elsewhere, would be easily sheared by vehicle wheels. The *Cakile* spp. and *Theleophyton* are succulents whose above-ground portions would be particularly susceptible to being crushed.

3.1.2 Invertebrates

General descriptive accounts of New Zealand's sandy beach macrofauna can be found in Oliver (1923), MacIntyre (1963), Knox (1969), Morton (1973), and Morton & Miller (1968). Riser (1984) has made some general observations on the interstitial fauna found in the intertidal. Autecological studies have been carried out on toheroa and its relatives (Mestayer 1921; Cassie 1951; Rapson 1952, 1954; Cassie 1955; Waugh & Greenaway 1967; Greenaway 1969; Street 1971), the beetle *Pericoptus truncatus* (Dale 1963), the anomuran *Callianassa filholi* (Devine 1966), the intertidal sand-dwelling peracarid fauna of Stewart Island and the North Island (Fincham 1974, 1977), the amphipod *Talorchestia quoyana* (Marsden 1991a, 1991b), and the isopod *Scyphax ornatus* (Quilter 1987). Some autecological data on species from sandy beaches can also be found in various taxonomic works (e.g. Hurley 1956; Dawson 1959; Hurley & Murray 1968; Cooper & Fincham 1974; Probert 1976; and Jansen 1978). Inglis (1989) has studied the colonisation and degradation of stranded bladder kelp (*Macrocystis pyrifera*) by the macrofauna of a New Zealand sandy beach. There have been few quantitative synecological studies on New Zealand's sandy beach macrofauna (Wood 1963; Morgans 1967a, 1967b; Morton & Miller 1968; Wood 1968) and none on the meiofauna.

The information currently available on the macrofauna and interstitial biota of New Zealand sandy beaches is insufficient to permit an assessment, at a national level, of any changes in the number of species or composition of these constituents in relation to latitude or exposure. However, a recent study of exposed sandy beaches in the northern North Island has confirmed that the relationship between number of macrofaunal species and beach morphodynamic state observed for exposed sandy beaches elsewhere does apply here (Stephenson & McLachlan in prep.). The study also found some northern North Island beaches had a high macrofaunal diversity, with the number of species comparable to those reported for exposed sandy beaches in tropical areas, and that species of terrestrial origin (e.g. insects) made up an unusually high proportion of the total macrofauna. The latter observation suggests that in New Zealand the backshore might remain an important habitat for macrofauna even on beaches where environmental conditions in the intertidal are limiting the faunal diversity there.

The possible impacts of vehicles on the various groups making up the invertebrate biota of New Zealand sandy beaches are assessed below.

Nemerteans

Several species of nemerteans occur on the foreshore of New Zealand sandy beaches (Knox 1969; Riser 1984; Stephenson unpubl. data). No research results are available to enable an assessment of the possible impact of vehicles on the nemertean fauna of New Zealand sandy beaches.

Nematodes

Little is known of the nematode fauna of New Zealand sandy beaches and no research results are available to enable an assessment of the possible impact of vehicles on them. Any such assessment may prove difficult: attempts to determine whether off-road vehicles had an impact on meiofauna populations in the intertidal zone at Cape Cod National Seashore, Massachusetts, USA, were unsuccessful as the high variability within the sample areas masked any correlation with vehicle damage (Leatherman & Godfrey 1979).

Polychaetes

In terms of numbers of species polychaete worms are a significant component of the macrofauna of New Zealand sandy beaches in both exposed and sheltered situations, and individual species can sometimes be the numerical dominants at particular levels on the shore. The meiofauna also contains many species (Riser 1984). No research results are available to enable an assessment of the possible impact of vehicles on the polychaete fauna of New Zealand sandy beaches.

Oligochaetes

One species of earthworm has been reported from the backshore of New Zealand sandy beaches (Lee 1959; Pilgrim 1969; Stephenson 1993), and one species from the intertidal (Riser 1984). Earthworms have been shown to exhibit a general reduction in population density as a result of vehicular compaction of soil in an inland terrestrial ecosystem in England (Chappell et al.

1971) and, as compaction of beach sand by vehicles has been demonstrated in the USA (Anders & Leatherman 1981), vehicle use of New Zealand sandy beaches may impact on this element of the biota.

Gastropods

In New Zealand there appear to be no larger gastropods intertidally on exposed sandy beaches, although several species can occur on moderately sheltered and sheltered beaches, including *Amalda australis* (Olividae), *Cominella adspersa* and *C. glandiformis* (Cominellidae). A study of vehicle impacts on the beach whelk *Bullia rhodostoma* in South Africa indicated this species would be safe from damage by vehicles provided they were buried (the normal situation when the tide is out) and the sand was reasonably compact. Individuals of *Bullia* were robust enough to withstand being run over even if placed on the surface of the beach (van der Merwe & van der Merwe 1991). *Amalda australis* and the *Cominella* species have shells of similar size and robustness to *Bullia rhodostoma* and like the latter they remain buried in the sand at low tide. It would appear *Amalda australis*, *Cominella adspersa* and *C. glandiformis* are unlikely to be damaged by vehicles.

Bivalves

The principal suspension-feeding bivalves found in the intertidal and subtidal on sandy beaches in New Zealand are species belonging to the genus *Paphies.* The tuatuas (*P. subtriangulata* and *P. donacina*) and the toheroa (*P. ventricosa*) are found on exposed beaches, and the pipi (*P. australis*) on more sheltered sites.

Based on experimental studies of the impact of off-road vehicles on two intertidal species of *Donax* in South Africa (van der Merwe & van der Merwe 1991) larger specimens of tuatua and toheroa would appear to be safe from damage by vehicles, even at relatively high traffic intensities, provided they are buried (the normal situation when the tide is out) and the sand is reasonably compact. However, specimens stranded on the surface would be easily crushed. The pipi rests in the sand with its long axis vertical so that the posterior part of its shell just protrudes above the surface (Wood 1968). As a consequence pipi could be more vulnerable to damage by vehicles than the other species, but this needs to be tested experimentally.

The South African experiments included individuals <20 mm in length, but the lower limit was not specified, so there could be a question over the vulnerability of juvenile *Paphies* in the first few weeks after they come ashore, especially since their shells have very little calcification at that time. Juvenile *Paphies* initially move up and down the beach with the swash and a study on Bay of Plenty beaches in December 1994 found them distributed across the beach from the drift line to the swash zone at low tide with the maximum densities just above the groundwater table outcrop, that is, in the area most likely to be driven on by vehicles (Stephenson unpubl. data).

Observations on some New Zealand sandy beaches indicate that vehicles may have an important indirect effect on toheroa related to the position they occupy on the shore. Redfearn (1974) noted that heavy vehicular traffic semi-liquified the sand, and toheroa were floated upwards towards the sand surface, forming small hummocks. However, Brunton (1978) considered the elevation of the animals was an active response; possibly the pressure of the vehicle imitating the cue normally provided by advancing bores of the rising tide for the animals to emerge to feed or move across the beach face. Since toheroa which have raised themselves in response to this cue can only burrow down again if the sand is saturated with water (or remains semi-liquified as a result of continued vibration), they become more vulnerable to predation, particularly by southern black-backed gulls (*Larus dominicanus*), which have been observed digging into and removing toheroa from hummocks after vehicles had passed over a bed (Brunton 1978). Gulls and oystercatchers are important predators of toheroa (Street 1971; Brunton 1978) and vehicle use on sandy beaches thus could increase the mortality of toheroa related to these predators. It is also relevant to note that food scraps and litter left behind by human visitors attract and help maintain larger populations of scavengers such as southern black-backed gulls than might otherwise be present.

In the intertidal of sheltered sandy beaches two other species of bivalves may be present; the thin wedge shell (*Macomona liliana*) and the cockle (*Austrovenus stutchburyi*). The thin wedge shell lies on its side in the sand at a depth of 5–10 cm (Wood 1968) while the cockle is usually buried just beneath the surface of the sand, so both species may be vulnerable to being crushed by vehicles. This needs to be tested experimentally.

Copepods

Copepods are prominent members of the interstitial meiofauna of sandy beaches. Little is known of the copepod fauna of New Zealand sandy beaches and no research results are available to enable an assessment of the possible impact of vehicles on them. Any such assessment may prove difficult: attempts to determine whether off-road vehicles had an impact on meiofauna populations in the intertidal zone at Cape Cod National Seashore, Massachusetts, USA, were unsuccessful as the high variability within the sample areas masked any correlation with vehicle damage (Leatherman & Godfrey 1979).

Cumaceans

Cumaceans have been reported from the lower intertidal of New Zealand sandy beaches (Fincham 1974, 1977). While they appear to tolerate a wide range of exposure, they tend to be more abundant in sheltered situations. No research results are available to enable an assessment of the possible impact of vehicles on the cumacean fauna of New Zealand sandy beaches.

Amphipods

The talitrid *Talorchestia quoyana* is found on the backshore of New Zealand sandy beaches, while the phoxocephalids *Diogodias littoralis*, *Waitangi brevirostris* and *W. chelatus*, and the oedicerotids *Patuki breviuropodus* and *P. roperi*, inhabit the intertidal, especially of exposed beaches (Fincham 1974, 1977). No research results are available to enable an assessment of the possible impact of vehicles on the amphipod fauna of New Zealand sandy beaches. However, even in the absence of any direct impact, the pulverising and dispersion of drift material by vehicles would have adverse effects on populations of *Talorchestia quoyana*, which are dependent on this drift for food.

Isopods

Tylos is a genus of large, semi-terrestrial isopods found on backshores and coastal dunes. Species of the genus studied to date display well-marked tidal rhythms of activity and are essentially nocturnal in habit. The genus is circumglobal from the tropics to cold-temperate latitudes and one species, the endemic *T. neozelanicus*, is found in New Zealand. It is restricted to the North Island and is associated with dunes carrying pingao, silvery sand grass or marram, but has declined in abundance since European settlement as a result of habitat destruction and competition with introduced species, in particular *Porcellio scaber*. Based on the results of a study of vehicle impacts on the South African species *Tylos capensis* (van der Merwe & van der Merwe 1991), it is probable that *T. neozelanicus* populations would be affected by vehicle use on New Zealand sandy beaches and coastal dunes.

Scyphax ornatus is another large isopod which lives on New Zealand sandy beaches. Adults of this species spend the day in burrows near the high water mark and make nightly foraging excursions on the uncovered intertidal beach down to the edge of the swash (Quilter 1987). The demonstrated vulnerability of *Tylos* to vehicle impacts suggests the extent to which the burrows of *Scyphax* provide protection from vehicles in daylight hours remains equivocal. These isopods would be crushed if run over by a vehicle when on the surface at night.

Actaecia euchroa is a very small isopod which makes shallow burrows in the supralittoral zone. The species may be active during the day on damp sand (MacIntyre 1963) and if disturbed rolls itself up into a ball. In view of the demonstrated impact of vehicles on the much larger and deeper burrowing *Tylos* the amount of protection afforded this species by its burrow remains equivocal; while on the surface *Actaecia euchroa* would be crushed if run over by a vehicle.

Several other small species of isopods also have been recorded on the backshore of New Zealand sandy beaches (Hurley 1961; Stephenson unpubl. data). Like *Actaecia euchroa*, these probably are vulnerable to vehicle impact.

Cirolanid isopods are often a numerically dominant component of the middle and upper intertidal on New Zealand exposed sandy beaches (Fincham 1977, Stephenson unpubl. data). There are three endemic genera and at least six species. Other isopods reported on New Zealand sandy beaches include the idotheid *Macrochiridothea uncinata* from the lower intertidal of exposed beaches (Hurley & Murray 1968; Fincham 1974, 1977, Stephenson unpubl. data) and the sphaeromatid *Isocladus armatus* from the upper intertidal of moderately sheltered and sheltered beaches (Morgans 1967a, 1967b; Wood 1968; Fincham 1974, 1977). All of these species remain buried in the sand at low tide, and emerge to forage over the beach face, as the tide rises. No research results are available to enable an assessment of the possible impact of vehicles on these components of the isopod fauna of New Zealand sandy beaches.

Shrimps and crabs

Species of burrowing shrimp live on sandy shores where the sand is stable enough to allow semi-permanent burrows to exist. The genus *Callianassa* is virtually cosmopolitan and one species, *C. filholi*, occurs in the lower intertidal on some New Zealand sandy beaches. The burrows of *Callianassa filholi* may be up to 45 cm deep, often have multiple openings, and larger burrows usually contain several animals (Devine 1966). The animals have a very fragile exoskeleton, but rarely emerge from their burrows even when covered by the tide. No research results are available to enable an assessment of the possible impact of vehicles on *Callianassa filholi*.

Ovalipes is a genus of carnivorous swimming crabs inhabiting subtropical and temperate waters around the world, with one species occurring as far south as New Zealand. *Ovalipes catharus* is essentially subtidal, but individuals may follow the rising tide up the beach and also remain buried in the sand, usually below the groundwater table outcrop, at low tide. In this situation the carapace is barely covered with sand and the animal would probably be crushed if run over by a vehicle.

Centipedes

One species of centipede is found on the backshore of sandy beaches throughout New Zealand (MacIntyre 1963). It also occurs on coastal dunes. No research results are available to enable an assessment of the impact of vehicles on centipedes.

Spiders

Several species of wolf spiders (Lycosidae) are present on the backshore of New Zealand sandy beaches. These spiders do not burrow or spin webs, but hunt on the surface of the sand. The katipo spider (*Latrodectus katipo*) may also occur on the backshore, where it constructs webs under driftwood (Forster & Forster 1973). All these spiders would be crushed if run over by a vehicle.

Insects

In New Zealand the orders Diptera (flies) and Coleoptera (beetles) are the main groups of insects represented on the backshore of sandy beaches. Larvae of kelp-flies (*Coelopa* spp.) burrow in and digest decaying seaweed before descending into the sand to pupate. Vermiform larvae of the therevid fly *Anabarhynchus bilineatus* burrow in the sand and probably feed on the larvae and pupae of other insects. The beetle fauna is diverse and includes species confined to the backshore (e.g. *Cafius litoreus*, *Chaerodes trachyscelides*, *Eutornus littoralis*, *Pericoptus truncatus*, *Thelyphassa limbata*) as well as species which also occur on coastal dunes (e.g. *Actizeta albata*, *Lagrioida brouni*, *Phycosecis atomaria*, *Reichardtia pedator*). *Chaerodes trachyscelides* adults are nocturnal and feed on decaying algae, as do the subterranean larvae. Adult *Actizeta albata* and both adult and larval *Phycosecis atomaria* run over the surface of the sand during the day feeding on carrion and invertebrate corpses (Harris 1970a, 1970b). The larva of *Actizeta*, on the other hand, is a typical 'false wireworm' and seldom runs on the sand surface (Harris 1970b). *Pericoptus truncatus* larvae, pupae and adults occur under any part of the surface, regardless of the presence of organic matter, but they are most common among the roots of foredune plants and occur in high concentrations under and within well-anchored driftwood. During the day all stages are deeply buried in the sand. Adults emerge at night and nocturnal surface migrations of the larvae between the backshore and the foredune are a feature of larval habits (Dale 1963).

No research results are available to enable an assessment of the possible impact of vehicles on New Zealand's beach-inhabiting insects. However, it should be noted that there are species of insects active on the surface day and night and therefore vulnerable to being crushed if run over by a vehicle. Even in the absence of any direct impact the pulverising and dispersion of drift material by vehicles would have adverse effects on populations of those species of insects which are dependent on this drift for shelter and/or food.

3.1.3 Birds

Birds which nest on the backshore of New Zealand sandy beaches include variable oystercatcher (*Haematopus unicolor*), New Zealand dotterel (*Charadrius obscurus*), banded dotterel (*Charadrius bicinctus*) and caspian tern (*Sterna caspia*). Overseas research has demonstrated that vehicle use on sandy beaches reduces the reproductive potential of shore-nesting birds, and although Walsby (1996) indicated predators are the main cause of nest failure for New Zealand species, vehicle use of beaches is likely to be contributing to the failure rate. These species all have inconspicuous nests and highly camouflaged eggs, making them vulnerable to being inadvertently run over by vehicles. Food scraps and litter left behind by human visitors attract and help maintain larger populations of scavengers such as southern black-backed gulls than might otherwise be present, thereby increasing predation pressure on eggs and chicks. Vehicle use of beaches has permitted these impacts to extend even to remote areas of the coast.

3.2 VEHICLE IMPACTS ON THE BIOTA OF COASTAL DUNES

3.2.1 Vegetation

In New Zealand the seaward face of the foredune is usually occupied by one or more of three rhizomatous sand-binding plants—the native sedge pingao (*Desmoschoenus spiralis*), silvery sand grass (*Spinifex sericeus*), and the introduced marram grass (*Ammophila arenaria*). Each species builds dunes that differ in slope and height (Esler 1978). The cosmopolitan sand convolvulus (*Calystegia soldanella*) also occurs in this habitat and sometimes persists landwards into denser vegetation, while the tussock-forming *Austrofestuca littoralis* grows on the lower part of the foredune in a few localities. To landward of the foredune crest sprawling woody shrubs such as sand coprosma (*Coprosma acerosa*) and sand pimelea (*Pimelea arenaria*) occur on exposed sites, and are joined, in more sheltered places, by upright shrubs such as tauhinu (*Ozothamnus leptophyllus*), *Olearia solandri*, *Coprosma propinqua* and manuka (*Leptospermum scoparium*), and the lianes pohuehue (*Muehlenbeckia complexa*) and New Zealand spinach (*Tetragonia trigyna*). However, the introduced tree lupin (*Lupinus arboreus*) is now the main shrubby pioneer on coastal sands in many areas of New Zealand. Wet hollows behind the foredune contain herbaceous native plants such as *Selliera* *radicans*, sand buttercup (*Ranunculus acaulis*), sand gunnera (*Gunnera arenaria*), sand sedge (*Carex pumila*), jointed rush (*Leptocarpus similis*), sand iris (*Libertia peregrinans*), flax (*Phormium tenax*), and *Scirpoides nodosa*, this last species also extending to drier sites on the foredune. The hollows may also support a variety of adventive species, including harestail grass (*Lagurus ovatus*), catsear (*Hypochoeris radicata*), hawkbit (*Leontodon taraxacoides*), and sheep's sorrel (*Rumex acetosella*). Several rhizomatous grasses colonise unstable, unweathered coastal sand through invading from stable areas, or keep pace with sand which is burying established vegetation. These include the adventive species Indian doab (*Cynodon dactylon*), kikuyu grass (*Pennisetum clandestinum*), and buffalo grass (*Stenotaphrum secundatum*), and the native *Poa pusilla* and *Zoysia* spp. (Wardle 1991).

The New Zealand flora has evolved in isolation for a long period and about 85% of the native vascular plant species are endemic (Wardle 1991). However, the principal environmental factors operating upon sand dune plants—too-rapid accretion or deflation, abrasion, unweathered substrates with few nutrients, high surface temperatures, summer droughting of shallow-rooted plants, and influx of salt—are the same world-wide and the adaptations which have appeared in New Zealand native dune plants in response to these factors are similar to those found in other floras. In addition, a proportion of the present-day New Zealand dune flora is made up of adventive species derived from dune habitats in other countries, where a broad range of sand dune plant communities and species have been shown to be damaged by vehicles. These facts suggest that the response of New Zealand dune vegetation to vehicle impacts will mirror that observed elsewhere: namely, reduction in height and cover, reduction (or an initial increase followed by a reduction) in the number of plant species where vehicle impact is prolonged, and changes in species composition.

The plants of the New Zealand foredune provide an example. Silvery sand grass grows by means of surface runners which later become buried under the sand accumulated by its foliage, and as a result these would be particularly vulnerable to the shearing effects of vehicle wheels. This is confirmed by the observations of Gilbertson (1977) in South Australia, who noted that the species was unable to spread into areas used by vehicles. The sensitivity of marram grass to trampling has been documented in England (Boorman & Fuller 1977), as has the negative response of a related species to vehicle impacts in the USA (e.g. Brodhead & Godfrey 1977). Pingao has stout underground rhizomes which may be more resistant to damage by vehicles, but like most pioneer species it requires active accumulation of fresh sand for optimum growth, so even in situations where damage to rhizomes was minimal, any vehicle-induced deflation could result in the roots being exposed and the plants dying.

3.2.2 Invertebrates

The invertebrate fauna of New Zealand coastal dunes is poorly documented from both a taxonomic and an ecological perspective. As a result it is not possible, at a national level, to quantify the diversity of the dune invertebrate fauna, describe any faunal relationships with coastal dune vegetation and environmental gradients, or comment on dune invertebrate biogeography. Pilgrim (1969) gave a brief account of the invertebrate fauna of the Canterbury dunes and Harris (1970a) described the composition and zonation of the beetle fauna in sand dunes of the Wanganui–Manawatu region. However, there have been few detailed surveys, and while there is undoubtedly some information on dune invertebrates available in taxonomic papers and other sources, it has yet to be collated into regional summaries, or a national inventory, as has been done for the dune flora (e.g. Esler 1978; Johnson 1992; Partridge 1992). Some species of invertebrates are known to be restricted to New Zealand coastal dunes, such as the amphipods *Talorchestia spadix* (Hurley 1961; Stephenson & Hurley 1992), *T. tumida* and *T. kirki* (MacIntyre 1963), and the beetles *Cecyropa jucunda*, *Odontria cassiniae*, *Pericoptus punctatus*, and *Xyloteles griseus* (Harris 1970a). There are also numerous elements of the invertebrate fauna of coastal dunes which are not confined to life there, but are common elsewhere (Pilgrim 1969). This is particularly true of species whose distributions extend from inland on to the coast; for example, the native blowflies (*Calliphora* spp.), the tiger beetle *Cicindela tuberculata*, and the introduced woodlouse *Porcellio scaber*.

The limited research results available from overseas indicate that reductions in both the abundance and number of species of soil surface and subsurface invertebrates can be expected to accompany the use of vehicles on New Zealand coastal dunes. Crushing by vehicle wheels, destruction of the surface litter layer (where present), and the changes in soil properties and microclimate which accompany track creation or the overall reduction in plant cover will contribute to the negative response of these elements of the fauna. Invertebrates associated with the above-ground portions of plants also can be expected to exhibit reductions in abundance and number of species as a consequence of vehicle impacts on the vegetation and microclimate of the dunes. Species which are host-specific, or which have a narrow tolerance for some other environmental factor, will tend to be the most vulnerable to any disturbance.

3.2.3 Birds

Shore birds which nest on New Zealand's coastal dunes include variable oystercatcher (*Haematopus unicolor*), New Zealand dotterel (*Charadrius obscurus*), banded dotterel (*Charadrius bicinctus*), pied stilt (*Himantopus leucocephalus*), caspian tern (*Hydroprogne caspia*) and, in Northland, fairy tern (*Sterna nereis*). Coastal dunes also are among the variety of nesting sites utilised by white-fronted tern (*Sterna striata*) and southern black-backed gull (*Larus dominicanus*). Land birds which may be resident on coastal dunes include New Zealand pipit (*Anthus novaeseelandiae*), hedge sparrow (*Prunella modularis*), and skylark (*Alauda arvensis*), while other introduced species such as redpoll (*Carduelis flammea*), yellowhammer (*Emberiza citrinella*), and starling (*Sturnus vulgaris*) are regular visitors.

Overseas research has demonstrated that vehicle use of sandy beaches reduces the reproductive potential of beach-nesting shore birds, and a similar response could be expected from dune-nesting shore birds in situations of direct conflict with vehicles since the impacts would be similar. For land birds the influence of vehicles on reproductive potential is likely to be more subtle and relate to changes in food supplies and availability of suitable nest sites consequent upon vehicle impacts on the vegetative cover, soils and microclimate of the dunes.

3.2.4 Reptiles

In the North Island as far south as Auckland on the west coast and Gisborne on the east coast, the shore skink (*Oligosoma smithi*) occurs among low vegetation on coastal dunes. In the southern North Island, South Island and Stewart Island it is replaced in this habitat by the common skink (*Oligosoma nigriplantare*) (Gill & Whitaker 1996). Both the widespread common gecko (*Hoplodactylus maculatus*) and, in Nelson and eastern areas from Hawkes Bay to Southland and Stewart Island, the spotted skink (*Oligosoma lineoocellatum*), also may be found on coastal dunes. As Luckenbach & Bury (1983) have demonstrated in California, USA, that vehicle use of dunes can depress lizard population densities and lead to a decline in the number of species, it seems probable that vehicles would have adverse effects on lizards if used on New Zealand coastal dunes.

3.2.5 Mammals

Ship rat (*Rattus rattus*), house mouse (*Mus musculus*), wild cat (*Felis catus*), hedgehog (*Erinaceus europaeus*), rabbit (*Oryctolagus cuniculus*), hare (*Lepus europaeus*), stoat (*Mustela erminea*), and ferret (*Mustela putorius*) can occur on New Zealand coastal dunes. All of these species are introduced and have detrimental effects on the native flora and fauna, so the overseas observations that vehicle use of dunes reduces the population density and diversity of dune mammals indicates such use could have a positive impact in a New Zealand context.

4. Conclusions and recommendations

When examined from a New Zealand perspective, previous research into vehicle impacts on the biota of sandy beaches and coastal dunes provides limited data that are directly relevant to the local situation. The research does, however, provide clear guidelines on the general strategies required to manage vehicle impacts on these resources. The use of vehicles on coastal dunes has been demonstrated to be highly destructive to both flora and fauna, often with the first vehicle passage causing the most damage. The conclusion has been that coastal dunes have a nil ‘carrying capacity’ for vehicles and that vehicle use of these areas should be banned altogether. Where vehicle access to the beach is required for emergency services or some other activity, such as boat launching, carefully designed roadways should be provided to cross the dune system.

The use of vehicles on the backshore of sandy beaches has been demonstrated to be highly destructive to both flora and fauna, while the impact of vehicles on the biota of the intertidal beach has appeared to be minimal, at least when the vehicle use occurred during the day. (However, in reality the impact of vehicles on the biota of the intertidal beach has not been adequately quantified and requires further research.) The conclusion has been that vehicle use of sandy beaches should be restricted to periods of low tide, to the area seaward of the drift line, and to daylight hours (i.e. from one hour before sunrise to one hour after sunset).

On the basis of the information currently available on the biota of New Zealand's sandy beaches and coastal dunes, these overseas management strategies could be applied here, but decision-making processes within the Department of Conservation would benefit from the availability of results from local research. Consideration should be given to funding, and/or promoting and supporting applications to other funding agencies, for the following research:

1. An experimental investigation of the vulnerability to vehicle impacts of key intertidal and supralittoral invertebrates on New Zealand sandy beaches.

Commentary

Although there has been some experimental investigation of vehicle impacts on sandy beach fauna elsewhere, representatives of only a few of the major groups found on sandy beaches have been studied, and very few are from groups represented on New Zealand sandy beaches. Some quantitative information regarding vehicle impacts on key intertidal and supralittoral invertebrates on New Zealand sandy beaches would assist in the decision-making process regarding management of beach resources. Taxa which should be considered for investigation include the polychaetes *Euzonus otagoensis* and *Hemipodus simplex*, the bivalves *Chione stutchburyi*, *Paphies australis*, and the juveniles of other *Paphies* spp., the amphipods *Talorchestia quoyana* and *Waitangi brevirostris*, the isopods *Pseudaega tertia* and *Scyphax ornatus*, and the beetle *Chaerodes trachyscelides*.

2. An investigation of the impact of vehicles on the fauna of coastal dunes in an area currently used for recreation.

Commentary

There have been very few investigations into the impact of vehicles on coastal dune fauna elsewhere. Some quantitative information on the scale of such impacts in New Zealand would assist in the decision-making process regarding management of dune resources. This information could be derived by comparing the abundance and diversity of the fauna of adjoining impacted and non-impacted sites in an area currently used for recreation. Separate comparisons should be made for the different successional stages of dune vegetation within the area.

3. Investigations into the biodiversity of sandy beaches.

Commentary

A variety of descriptive and autecological studies have been carried out on New Zealand's sandy beach biota. However, quantitative synecological studies are few (Wood 1963; Morgans 1967a, 1967b; Morton & Miller 1968; Wood 1968) and although all the studies have used transects as the basis for sampling, other details of the methods have varied considerably. A more representative and consistent data set is a primary prerequisite both for deriving a meaningful overview of the biodiversity of New Zealand's sandy beaches and for assessing the impact of recreational activities on these resources at regional and national levels.

Recently Stephenson & McLachlan have been studying the responses of the macrofauna to physical factors on some wave-exposed sandy beaches in the northern North Island. Standardised qualitative and quantitative sampling techniques were used and a byproduct of the study has been a considerable amount of new faunal, ecological and biogeographical information. This work needs to be extended to exposed sandy beaches in the southern North Island, South Island, Stewart Island, and Chatham Island, and to sandy beaches in more sheltered situations.

4. Investigations into the diversity and abundance of coastal dune fauna, leading towards the compilation of a national database of these resources.

Commentary

A considerable amount of plant community description and floristic study has been carried out on coastal dunes in New Zealand (see bibliography in Johnson 1992), culminating in a national inventory of sand dune and beach vegetation (Partridge 1992; Johnson 1992). In contrast, there have been few comprehensive studies of the fauna of coastal dunes and the available information is dispersed. This situation needs to be rectified in order to identify important areas for maintaining the biodiversity of New Zealand's coastal dune fauna and to permit assessments of the impact of recreational activities on these resources at regional and national levels.

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6. Glossary

adventive: of a species that is not native to a country, but which human agency has brought in by accident, or which has escaped into the wild after being brought in by design.

aeolian: pertaining to the action or the effect of the wind.

annual: a plant which completes its life-cycle and dies within a year.

autecology: the study of the relationship between a species and its environment.

backshore: that part of a beach between the spring high water level and the dune margin.

biogeography: the science concerned with the geographical distribution of organisms.

biomass: the total weight of living organisms per unit area at a given time. The term can be applied to a community or an individual species.

climax: vegetation considered to have a reached a steady-state condition.

community: the plants and/or animals living together in an area (of any size).

cover: the proportion of the ground surface covered by the leaves or crowns of a plant species, or by one or more layers (storeys, tiers) of vegetation, when projected vertically downwards.

creeper: a plant which spreads along the surface of the ground or attaches itself to some other body.

dicotyledon: Dicotyledoneae, a class of flowering plants distinguished by the presence of two seed-leaves (cotyledons) in the embryo and by other structural features; hence the adjective dicotyledonous.

dominant: (1) the plant species with the greatest cover, basal area or biomass in a community. (2) the plant or animal species that chiefly affects the energy flow within a particular trophic level in a community.

drift line: a line of stranded debris along a beach face marking the point of maximum run-up during a previous high tide.

dune: a mound or ridge of unconsolidated granular material, usually of sand size and of durable composition (such as quartz), capable of movement by transfer of individual grains entrained by a moving fluid.

ecosystem: an open system of any size comprising organisms and non-living materials involved together in the flow of energy and the circulation of matter.

endemic: of a species whose natural distribution is restricted to a country.

epipsammic: of organisms which live attached to the surface of sand grains.

forb: a broad-leaved herb.

foreshore: that part of a beach between the spring low water level and the spring high water level.

groundwater table outcrop: the intersection of the beach face and the water table. The beach face surface seaward of the groundwater table outcrop is saturated with water, giving the ‘glassy layer’ effect commonly seen on a sandy beach.

heath: an open area with low shrubby vegetation, usually including heather.

hemicryptophyte: herb with perennating buds at the soil surface, protected by snow, litter, or by dry, dead portions of the plant.

herb: any vascular plant which is not woody; hence the adjective herbaceous.

intercalary: of a meristem (q.v.) situated between regions of permanent tissue, e.g., at the base of the leaves in many monocotyledons.

introduced: of a species that is not native to a country, but which human agency has brought in by design.

invertebrate: an animal which is not a vertebrate (q.v.).

liane: a woody climbing plant with roots in the ground.

macrofauna: multicellular animals greater than 1 mm in length.

meiofauna: multicellular animals less than 1 mm in length.

meristem: localised region of active cell-division in plants from which permanent tissue is derived.

monocotyledon: Monocotyledoneae, a class of flowering plants distinguished by the presence of one seed-leaf (cotyledon) in the embryo and by other structural features; hence the adjective monocotyledonous.

native: of a species not known to have been introduced by human agency.

perennial: a plant which lives for more than two years.

phenology: the study of the periodical phenomena of plants in relation to climate.

pioneer: an organism which is able to establish itself in a barren area and begin an ecological cycle.

population: the aggregate of all individuals of all ages of a particular species in a given area.

rhizome: an underground, usually creeping, stem.

rosette: a group of organs radiating from a centre, especially many overlapping leaves more or less flattened against the ground.

runner: a slender, ± prostrate lateral stem which roots at the nodes.

shrub: a woody plant of not very large size and lacking a distinct trunk.

stolon: a stem, ± horizontal or arched or running along the ground, rooting and capable of forming a new plant at its tip; hence the adjective stoloniferous.

succulent: a plant which accumulates reserves of water in the fleshy stems or leaves.

swash zone: that part of the intertidal zone which is periodically covered by water in response to tide excursions and wave run-up. The swash zone is located above the tide level and its position on the beach face varies with the tide.

synecology: the study of the relationship between groups of organisms (such as communities) and their environment.

tiller: a side shoot, as in grasses.

tussock: a grass-like plant with dense tufted habit.

vegetation: the cover of plants, above and below ground, commonly but not always differentiated into layers (storeys, tiers).

vertebrate: an animal having a skull which surrounds a well-developed brain, and a skeleton of cartilage or bone. Vertebrates include fish, amphibians, reptiles, birds, and mammals.

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Entries marked with * are repeated in Appendix 1 with annotations.

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Appendix 1

Annotated bibliography of research into vehicle impacts on the biota of sandy beaches and coastal dunes, 1988–1997

The following bibliography lists reports and journal articles containing original research into vehicle impacts on the biota of sandy beaches and coastal dunes published during the period 1988–1997. Literature reviews covering research published prior to 1988 can be found in Steiner & Leatherman (1979), Heath (1987), and van der Merwe (1988).

Buick, A.M.; Paton, D.C. 1989. Impact of off-road vehicles on the nesting success of Hooded Plovers *Charadrius rubricollis* in the Coorong region of South Australia. *Emu 89*: 159–172.

In the Coorong region of South Australia hooded plovers usually nested on the ocean beach above high tide mark and close to the base of the frontal dunes. There was a significant overlap in the areas of beach used by vehicles and by hooded plovers for nesting and the potential rate at which nests would be run over was estimated by deploying painted pigeon eggs in artificial nests. On average 6% of these nests were run over per day. This rate was equivalent to 81% of the nests on beaches being run over during the incubation period. Vehicles were found to cause little or no reduction in nest attentiveness of incubating birds when they passed at least 10 m away from the nests, but foot traffic or vehicles stopping nearby caused incubating birds to leave their nests on most occasions. Egg loss due to predation may be increased due to this disturbance and through rubbish left by visitors allowing the environment to support a larger population of scavenging predators. It is considered that the use of off-road vehicles on ocean beaches potentially reduced the reproductive output of hooded plovers in the Coorong region.

Carlson, L.H.; Godfrey, P.J. 1989. Human recreation management in a coastal recreation and natural area. *Biological Conservation 49*: 141–156.

Surveys were carried out at the R.T. Crane Jr Memorial Reservation, Massachusetts, U.S.A., in 1984 to quantify human impacts on the vegetation. A stratified random design was used in which 14 sites in the coastal dune community and 10 sites in the stabilised dune community were selected for study. At each coastal dune site, two randomly located transects were established perpendicular to the shoreline from seaward of the drift line to the crest of the foredune and sampled at 1 m intervals using a modified point quadrat method, with 25 points in a 0.25 m^2 quadrat. Stabilised dune sites were sampled using 0.25 m^2 quadrats every 0.5 m along two randomly located 5–25 m transects. These transects began and ended in apparently undisturbed areas, but were oriented to cross disturbed sites. Disturbance levels ranged from none to use by deer, humans, and off-road vehicles. Mean percentage vegetation cover was calculated for each transect using the quadrats as replicates. The mean percentage vegetation cover for each site was then computed using the two transect means. The mean number of plant species was determined for each site using the transects as replicates. Areas experiencing adverse effects from disturbance were identified by selecting a control site to which the results from other sites were compared. Following implementation of a management plan, nine coastal dune sites and eight stabilised dune sites were resurveyed three years later using the same methodology.

In 1984 the mean percentage vegetation cover and/or the mean numbers of plant species at some coastal dune sites were significantly lower than the control. At stabilised dune sites a significant reduction in mean percentage vegetation cover relative to the undisturbed control site was found at all sites with human disturbance, but not at sites used exclusively by deer. The severity of the reduction increased for deer, human, and off-road vehicle trails respectively.

In 1987 five of the coastal dune sites identified as significantly lower in mean percentage vegetation cover than the control in 1984 showed a significant increase in vegetation cover and the mean number of plant species also increased significantly at two of these sites. Neither vegetation cover or number of plant species decreased significantly at any resurveyed coastal dune site. At the stabilised dune sites there were no significant increases in vegetation cover or number of plant species at any resurveyed site.

It is concluded that the management plan, which included a vehicle ramp to the beach and restrictions on vehicle use, was reducing the impact of human activities on the vegetation of the Crane Reservation.

Rickard, C.A.; McLachlan, A.; Kerley, G.I.H. 1994. The effects of vehicular and pedestrian traffic on dune vegetation in South Africa. *Ocean and Coastal Management 23*: 225–247.

The effects of varying intensities of off-road vehicle and pedestrian traffic on vegetation height and percent-cover were investigated at two sites representing pioneer and climax dune shrubland communities in South African dune systems. The pioneer site was located in the Alexandria Dunefield, where the vegetation comprised predominantly *Arctotheca populifolia*, *Gazania rigens*, and *Sporobolus virginicus*. Plant cover ranged from 10–20% and species diversity was low, with less than a dozen species. The dune shrubland site was situated at Port Elizabeth, where the vegetation was a *Ficinia/Restiod* community containing shrubs such as *Metalasia muricata*, *Passerina rigida*, *Rhus crenata*, *Euclea racemosa*, *Myrica quercifolia*, and *Phylica ericoides*. The vegetation cover was 85–100%, and species diversity was high, with approximately 50 species.

After initial vegetation measurements, low (pioneer = 2 passes and shrub = 3 passes), medium (6, 15), and high treatments (100, 100) were applied to randomly assigned plots, each treatment being replicated and conducted for straight and turning vehicle passes. Vegetation measurements were repeated after the application of the treatments. The low- and medium-impact treatments were repeated five times at three-monthly intervals. A single-application high-intensity treatment was used to monitor vegetation recovery over a 10-month study period. Two randomly chosen plots served as controls. All treatments were applied to the pioneer and shrub study sites.

Neither the vegetation height nor cover of the control plots of either site changed significantly over the study period. On the impacted plots there was a negative trend in vegetation height and percent-cover following the application of the treatments, particularly for turning vehicles. The first application of the treatments showed significant reductions in these parameters for some of the treatments on the shrub site. The multiple repeats of the low and medium impacts had a cumulative effect of decreased vegetation height and cover. Measurements were significant for all vehicle treatments on the shrub site, but not on the pioneer site.

There were no significant differences in the magnitude of change in vegetation height and percent-cover between the different intensity treatments, although a trend of increasing impact on vegetation cover with increasing intensity treatments could be seen. Over the period of the study vegetation cover showed significant decreases on the shrub site for all treatments, but the final percent-cover on the pioneer site was similar in magnitude and not significantly different from the site's starting cover values, indicating a certain amount of recovery following treatments. In general, greater decreases in vegetation height and cover resulted from turning vehicle passes, though not with statistical significance. It was shown that to achieve the same level of damage to vegetation, the shrub site needed a greater number of vehicle passes than the pioneer site, indicating a greater tolerance of the impacts.

On the high-intensity treatment plots an initial decrease in vegetation height and percent-cover was followed by a further decrease which became evident at the next three-month vegetation measurement. Following this lag response to the impact, vegetation height and cover exhibited some sign of recovery, particularly at the shrub site, but was still lower than the starting values after 10 months. Both straight and turning high-intensity vehicle passes decreased vegetation cover immediately following the application of the treatment by similar percentages on the two sites. However, while vegetation cover on the pioneer site showed signs of recovery by the end of the study period, cover on the shrub site decreased significantly from starting cover values. Thus, despite its apparent greater tolerance of the impacts, the shrub site was actually more vulnerable in the long-term, owing to its poorer recuperative abilities.

Reasons for the differences in the responses of the pioneer and climax plant communities are discussed and the management implications of the results outlined.

van der Merwe, D.; van der Merwe, D. 1991. Effects of off-road vehicles on the macrofauna of a sandy beach. *South African Journal of Science 87*: 210–213.

Effects of off-road vehicles on four intertidal macrofaunal species, the gastropod *Bullia rhodostoma*, the bivalves *Donax serra* and *D. sordidus*, and the benthic mysid *Gastrosaccus psammodytes*, and one supralittoral species, the isopod *Tylos capensis*, were investigated on Sundays River Beach, South Africa. Experimental animals were placed in sand-filled containers buried flush with the surface in areas where the animals in question were most likely to occur. Two size classes (large and small) were used where possible. Four replicates and two controls were conducted in each experiment, and the impact applied using a 4WD vehicle. The experiments were repeated for each species at different intensities of impact. The numbers of dead, injured and healthy animals were recorded 24 hours after the impact was applied.

For large *Bullia rhodostoma* (>25 mm) the mean percentage of damaged individuals at a low intensity of impact (5 passes) was 0.9%, at a high intensity of impact (50 passes) it was 0.6%. The corresponding figures for small individuals (<20 mm) were 12.3% and 3.1%. For *Donax serra* the mean percentage of damaged individuals at a high intensity of impact was 7.4% for large individuals and 6.3% for small individuals; for unspecified sizes of *D. sordidus* it was 2.9%. The response of *Gastrosaccus* was complicated by the surface sand in the containers becoming thixotropic, resulting in the animals migrating into the water column above the sand surface between vehicle passes and being crushed during subsequent runs. In an attempt to determine the impacts of off-road vehicles on this species under natural conditions samples were taken directly under vehicle wheels and next to the wheels (control). No significant differences were found and no animals were damaged. It is concluded that the intertidal animals examined in this study appeared to be safe from damage by vehicles, even at relatively high traffic intensities, provided they were buried and the sand was reasonably compact. Individuals of *Bullia* were robust enough to withstand being run over even if placed on the surface of the beach, but individuals of the other three species were easily crushed in this situation.

Tylos capensis was highly susceptible to vehicle impacts, the numbers of individuals crushed or damaged increasing as a function of the number of vehicle passes. No significant differences between large and small animals were found for any of the impact intensities. The relatively soft exoskeleton, their occurrence in soft, non-compacted sand, in which shearing and compression as a result of vehicle passage can extend to a depth of 20 cm or more, and their behavioural pattern of foraging on the surface at night, are considered to be the principal reasons for the vulnerability of this species.

It is suggested that vehicles be restricted to the area below the high water mark and that driving on beaches be permitted at low tide during daylight only.

Watson, J.J. 1992. Dune breeding birds and off-road vehicles. *The Naturalist 36 (3)*: 8–12.

A study of the impact of off-road vehicles on dune breeding birds in the Alexandria Dunefield, Algoa Bay, South Africa is summarised. The dunefield lies adjacent to a broad sandy beach which is heavily used by off-road vehicles. The beach and dunefield support breeding populations of the African black oystercatcher (*Haematopus moquini*), the white-fronted plover (*Charadrius marginatus*), and the endangered Damara tern (*Sterna balaenarum*).

African black oystercatchers built their nests on the berm just above the high water mark, where the eggs and chicks were exposed to being crushed under the wheels of passing vehicles. About 30 nests were monitored but no successful breeding was observed in the 1992/93 season even though all the birds laid eggs again after destruction of their initial clutches. White-fronted plovers nested landward of the high water mark and seemed to prefer areas where there was some vegetation. Hatching was observed, but chicks were led to the beach to feed and often sheltered in vehicle tracks where they were under threat of being crushed by off-road vehicles. Damara terns nested on open flat unvegetated areas >100 m from the high water mark and when nesting were probably only vulnerable to natural predators. However, juveniles moved to the beach a couple of days after hatching and evidence of their being crushed by vehicles was found.

Solutions are suggested to reduce the impact of off-road vehicles on these birds, including education of beach users about the presence of animals, restricting vehicle numbers during the breeding season, and fencing nesting areas.

Appendix 2

List of sources used to locate material

Three previous literature reviews include research into vehicle impacts on the biota of sandy beaches and coastal dunes carried out prior to 1988. These are:

Steiner, A.J.; Leatherman, S.P. 1979. An annotated bibliography of the effects of off- road vehicle and pedestrian traffic on coastal ecosystems. *University of Massachusetts/ National Parks Service Cooperative Research Unit Report No. 45*. 87 p.

Heath, R. 1987. Impact of trampling and recreational activities on the littoral active zone—a literature review. *Institute for Coastal Research Report No. 15*. 40 p. University of Port Elizabeth, South Africa.

van der Merwe, D. 1988. The effects of off-road vehicles (ORV's) on coastal ecosystems—a review. *Institute for Coastal Research Report No. 17*. ii + 64 p. University of Port Elizabeth, South Africa.

This last review has been used as the primary source for material produced prior to 1988 and the current search has concentrated on the period 1988–1997. Manual searches have been made of the following abstracting services and journals:

Biological Conservation 1988–1997
Coastal Management 1987–1997
Coastal Zone Management Journal 1980–1986
Ecological Abstracts 1989–1996
Geographical Abstracts Human Geography 1989–1996
Journal of Environmental Management 1988–1997
Ocean and Coastal Management 1988–1997
Shore and Beach 1977–1997

Searches also have been made of the following computerised databases:

Aquatic Science Abstracts 1979–1997/Oct.
Biosis Previews® 1985–1997/Oct.
CAB Abstracts 1972–1997/Sept.
Enviroline® 1975–1997/Sept.
Marine and Coastal Data Directory of Australia
(http://kaos.erin.gov.au/marine/mcdd/)