



Adverse impacts of off-road vehicles on coastal dune vegetation are widespread, substantial, and long-lasting: Evidence from a global meta-analysis of sandy beach-dune systems

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ABSTRACT

1: Ocean shores are among the most spectacular and sought-after sites for leisure activities, including 'nature and wilderness experiences'. Some of these activities can involve the use of off-road vehicles (ORVs) driven across extensive stretches of sandy coastlines. Yet, this recreation mode can be controversial because of environmental,

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cultural, social, and ethical concerns. However, ORV users often question the putative impacts, especially the ecological aspects.

2: Here, we review the available published data about the ecological impacts of vehicles on coastal plants. We focus on vegetation because of its critical role in coastal resilience and its foundational role in the structure and function of dune-beach systems. The principal type of evidence is a formal meta-analysis of effect sizes that can be unambiguously linked to ORV use.

3: The evidence of serious ecological harm caused by ORVs to plants of beach-dune habitats is geographically widespread, extensive in taxonomic coverage (253 species, 174 genera, and 64 families), sizeable in the magnitude of reported impacts (443 records) and statistically robust (significant negative departures from zero responses).

4: Vegetation stressed by ORVs typically has substantially reduced abundance, cover, biomass, area, occurrence, diversity, and productivity. ORVs also significantly alter the composition and structure of assemblages.

5: Degradation occurs rapidly, with the first few vehicle passes causing most of the damage. Thresholds of impact can be exceptionally low (one or two cars separated by weeks), implying that in many cases, dunes and the back-shore of beaches have extremely limited resilience to repeat traffic by off-road vehicles: No 'safe threshold' of use may exist.

6: Recovery after closure to off-road vehicles is highly variable, depending on species traits (slower for woody shrubs) and habitat conditions (slower for back-dunes). It can be protracted, with some assemblages typically taking around a decade or more to recover.

7: The exceptionally low tolerance of many coastal plant species and habitats translates into policies to phase out ORV use on ocean shores and dunes. Spatial closures and strict controls should be the mainstay of management interventions, supplemented by novel approaches seeking to identify where and when environmentally safe and benign practices may exist and whether these can be culturally and ethically acceptable.

1. Introduction

Sandy shores are highly valued environments that underpin coastal tourism and recreation globally (Schlacher et al., 2022). Demands for 'beach leisure' opportunities can be intense and encompass a broad spectrum of activities and land uses, ranging from coastal cities featuring urban beach cultures to wilderness areas providing for nature-based experiences (Provost et al., 2021). In urban settings, the mode of mobility on beaches is mostly by walking, bicycle, or similar non-motorised devices. By contrast, a desire 'to experience nature' and 'get away from it all' encourages using off-road vehicles (ORVs) to access wilderness and rural areas, remote beaches and dunes, and National Parks and similar conservation areas (Petch et al., 2018).

People drive ORVs on ocean shores and in coastal dunes for a variety of recreational reasons, mostly to access fishing spots, engage in vehicle-based activities such as touring, 'four-wheel driving' and camping, while much fewer vehicles are used in search and rescue operations, patrolling, utility maintenance, and access for people with mobility impairments (Godfrey and Godfrey, 1980; Hockings and Twyford, 1997). Whilst the use of ORVs for essential services (e.g. emergency responses) is ethically justifiable and uncontested, the recreational use of ORVs on ocean shores is controversial on environmental, social, cultural, and moral grounds (Godfrey and Godfrey, 1980; Vivian and Schlacher, 2015; Maslo et al., 2016; Schlacher et al., 2016).

Adverse environmental impacts attributed to ORVs in beach-dune ecosystems span a broad range of responses, ranging from depletions of invertebrate populations, declines in animal diversity, disturbance and mortality of birds (including their nests/eggs), crushing of sea turtle hatchlings, enhanced erosion, and harmful impacts on coastal vegetation (Godfrey et al., 1980; Schlacher et al., 2008, 2013; Schlacher et al., 2008a,b; Meager et al., 2012; Schlacher et al., 2013a,b). In particular, the harmful impacts on the plants of the backshore and dunes are not trivial for two main reasons. First, because vegetation is critical for the capacity of dunes to build dune landforms (Martínez et al., 2013) and to buffer the extremes of waves and storm surges (Feagin et al., 2005, 2010), loss of plants can propagate to loss of essential ecosystem services (Orchard and Schiel, 2021). Secondly, vegetation forms the structural backbone of habitat complexity and heterogeneity that are essential for a diversity of animals reliant on vegetated dunes and backshores, including rare and threatened species (Howe et al., 2010; Koyama and Ide, 2020). In short, the loss of coastal vegetation often leads to broader biodiversity declines.

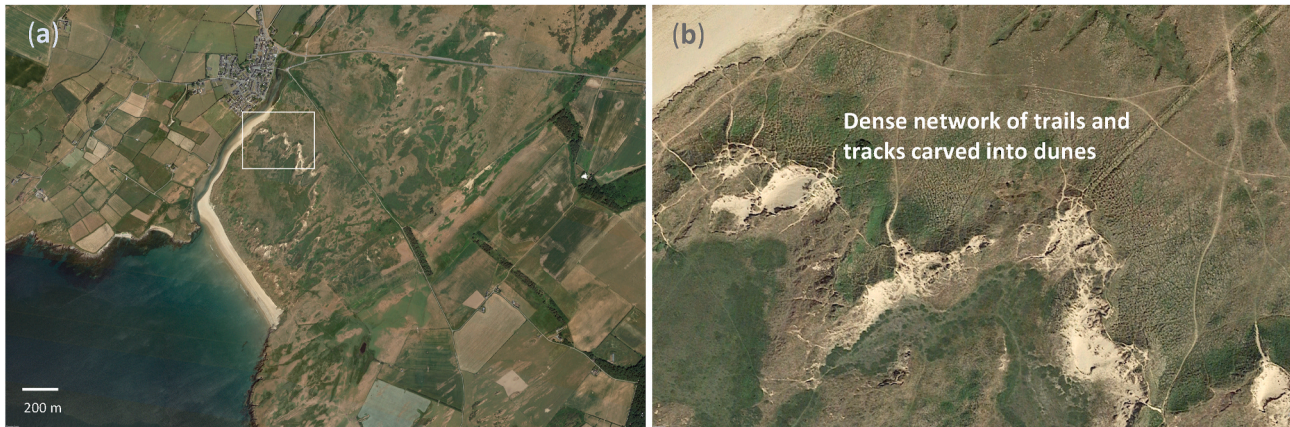
The physical scars caused by recreational off-road traffic on ocean shores can be stark and extensive (Fig. 1). Yet, the question of how much environmental harm, if any, is attributable to ORVs is contested (Wardell-Johnson et al., 2015). Given the convincing physical signs, this may seem surprising, but it can be linked to three interacting factors. First, value orientations, attitudes, belief systems, and norms amongst ORV users can result in limited awareness of consequences, dissociated personal responsibilities, and non-perceived environmental impacts (Hogan et al., 2021). Secondly, the recreational ORV lobby is powerful, vocal and supported by various media emphasising the 'outdoor experience that ORVs make possible', and the pervasive advertising by manufacturers and sellers of ORV vehicles, vehicle accessories, and fishing- and outdoor gear. Thirdly, the widespread and persistent notion that beaches are low-value biological deserts and can recover rapidly (e.g. *"the tides and winds sweep away the temporary signs of vehicles"*) (Schlacher et al., 2022). These factors suggest the need for improved information on the actual impacts of ORV use that could usefully inform the views of all stakeholders, and ultimately lead to workable solutions. Given the prevalence of red herrings and fallacies in this thematic space, the primary goal of the present study is to compile a dossier of factual evidence relating to environmental effects linked to off-road vehicles. We focus on the impacts on coastal vegetation because these effects are observable by most ORV drivers and because plants are the foundation of biological structures that shape these ecosystems at the edge of the sea.

2. Methods

2.1. Sources and data extraction

We conducted an exhaustive search of the literature on vehicle impacts using four complementary approaches and sources: a) library databases (Scopus, Web of Science), b) cited paper searches of papers published on the topic, c) bibliographies published in hard copy in the 1980s (held by the authors), and d) reference lists of papers obtained in the first three steps. We purposefully cast the net very wide initially to ensure all papers that contain information on some form of 'vehicle' in natural environments were included, using the following search string [(vehicle OR off-road OR ORV OR car OR truck OR all-terrain OR ATV OR bus OR traffic OR off-highway OR four-wheel OR 4WD OR OHV) AND (coast* OR dune* OR beach* OR shore) AND (vegetation OR plant*)], in the fields 'Title' OR 'Abstract' OR 'Key-Words'. This exhaustive search

Aberffraw, Wales, UK; LAT 53.19° LONG -4.46°; 28 June 2018
(Liddle & Grieg-Smith P (1975) *J. Appl. Ecology*. 12:909-930)



Race Point Beach, Cape Cod, USA; LAT 42.08° LONG -70.22°; 24 Oct 2021
(Brodhead & Godfrey PJ (1977) *Intern. J. Biomet.* 21: 299-306)



Hatches Harbour, Cape Cod, USA; LAT 42.06° LONG -70.24°; 24 Oct 2021;
(Brodhead, 1978, *UM-NPSCRU Report 40 Univ. Massachusetts*)

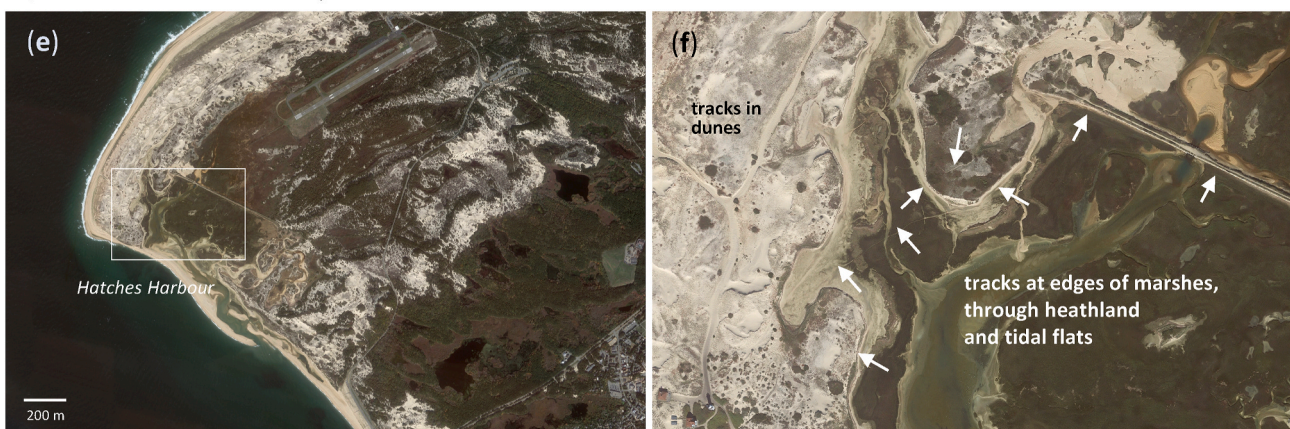


Fig. 1A. (Panel 1 of 4).

strategy resulted in >800 articles which we screened. The primary criterion for inclusion in the meta-analysis was that a publication must contain at least the mean value of a biological metric measured in a treatment group/habitat area/time directly affected by off-road vehicles and a corresponding mean value for controls/reference conditions or times without ORV stress. It also must examine the vegetation of ocean

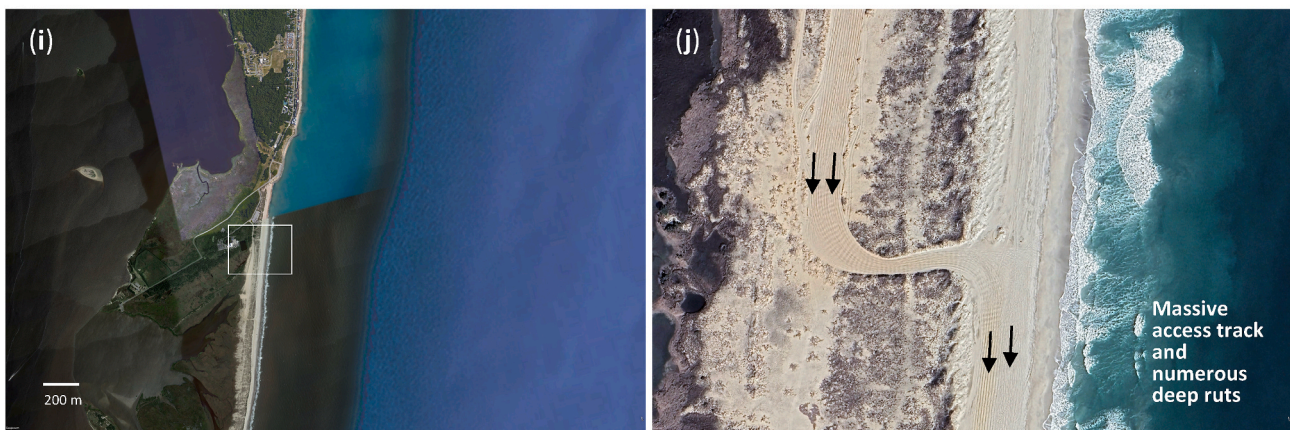
shores, primarily at the strandline, in the sandy dunes and in functionally linked upland coastal habitats in similar seascape settings.

For papers containing mean values, but which did not report sample sizes or a measure of dispersion, we indexed the size and direction of effects attributed to off-road vehicles as the Response Ratio, $L = \ln(X_{ORV-impacted} + 1) - \ln(X_{reference} + 1)$, where $X_{ORV-impacted}$ is the mean

Nueces County Park, North Padre Island, TX, USA; LAT 27.59° LONG -97.22°; 19 June 2023

(McAtee & Drawe, 1980, *Environmental Management*. 4:527-538)

Fort Fisher Beach, Cape Fear Islands, NC, USA; LAT 34.00° LONG -77.90°; 02 June 2023

(Hosier & Eaton, 1980, *J. Applied Ecology*. 17:173-182)

South Padre Island, TX, USA; LAT 26.23° LONG -97.19°; 25 March 2022

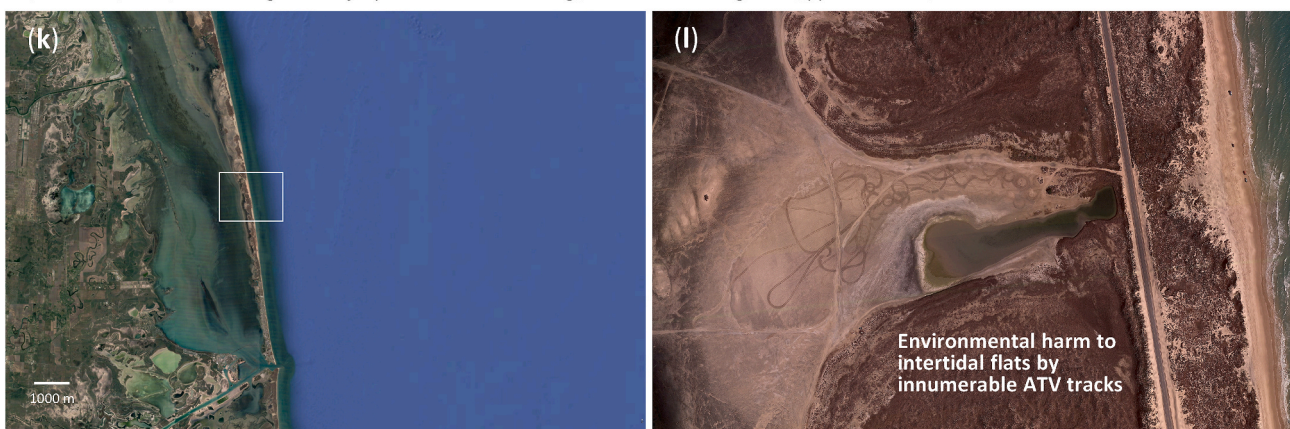
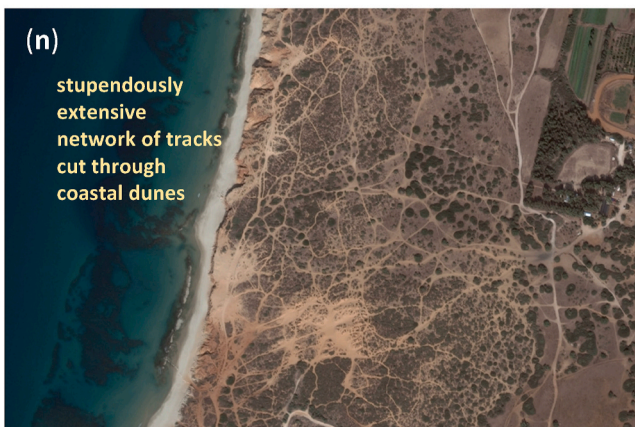
(Judd et al, 1989, *Proceedings Sixth Symp. Coast. Ocean Manag.; Am. Soc. Civil Engineers*, pp 4634-4645)

Fig. 1B. (Panel 2 of 4).

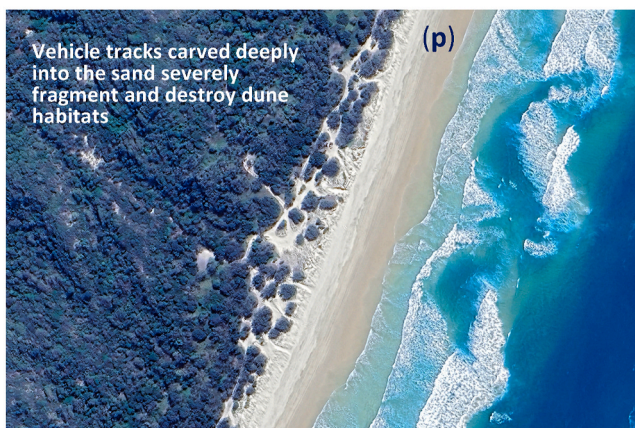
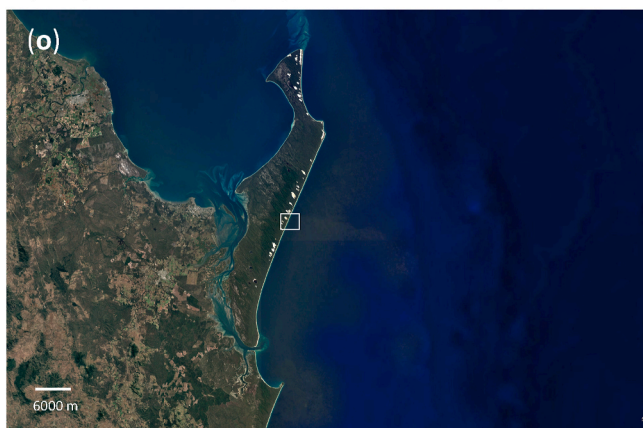
outcome for the group being stressed/affected/impacted by off-road vehicles, and $X_{reference}$ the mean value for the control group without vehicle traffic (Hedges et al., 1999; Lin and Aloe, 2021). For papers reporting means, sample sizes, and variance or standard deviation or standard error, we calculated standardised effect sizes, expressed as Hedge's $g = (x_1 - x_2) / (((n_1 - 1) * s_1^2 + (n_2 - 1) * s_2^2) / (n_1 + n_2 - 2))^{0.5}$, where a)

x_1, x_2 : the sample 1 mean and sample 2 mean, respectively, b) n_1, n_2 : The sample 1 size and sample 2 size, respectively, and c) s_1^2, s_2^2 : The sample 1 variance and sample 2 variance, respectively (Hedges, 1981; Lin and Aloe, 2021).

Sharon Park, Israel; LAT 32.42° LONG 34.88°; 25 Nov 2016;
(Kutiel, 1999, *Enviro. Manag.* 23: 401-408)



K'gari (Fraser Island), Queensland, Australia, LAT -25.45° LONG 153.15°; 02 May 2023
(Thompson & Schlacher, 2008, *J. Coast. Cons.* 12:67-82).



Island Beach State Park, New Jersey, USA; LAT 39.78° LONG -74.09°; 29 June 2021
(Kelly, 2014, *J. Coastal Cons.* 18: 383-398)

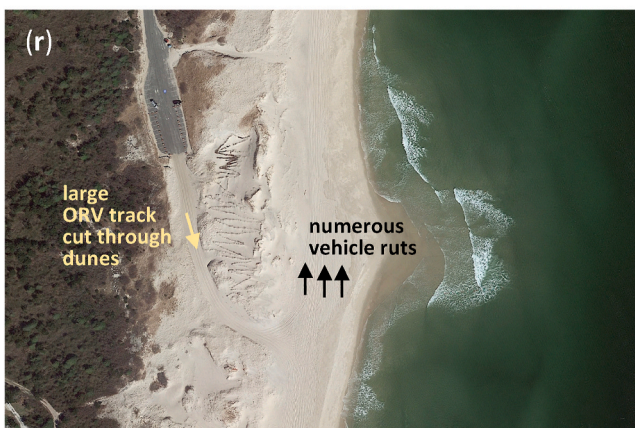
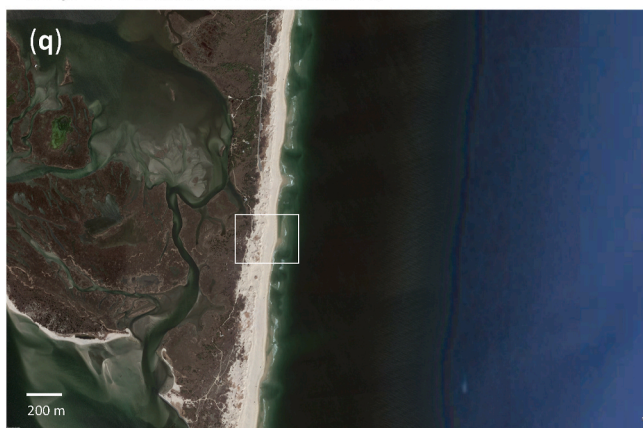
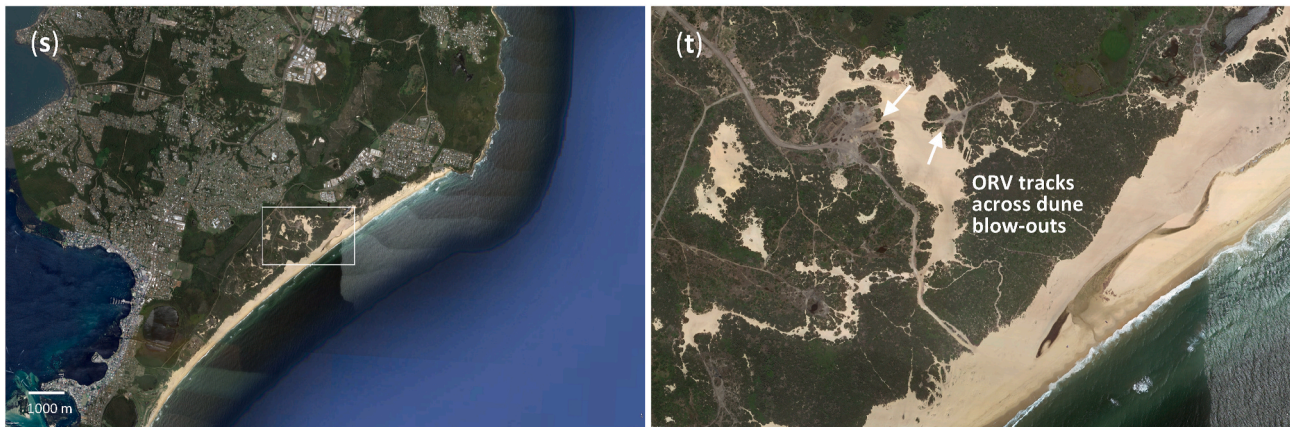


Fig. 1C. (Panel 3 of 4).

Belmont Beach, NSW, Australia; LAT -33.04° LONG 151.68°; 01 Oct 2016
(Cooke et al. 2020, *Science Total Env.* 724:138115)



Miscou Island, New Brunswick, Canada; LAT 47.93° LONG -64.59°; 22 May 2023
(Hogan & Brown, 2021, *Applied Vegetation Science*. Vol 24, e12549)

Fig. 1D. (panel 4 of 4)

Fig. 1 Satellite imagery of coastal environments degraded by off-road vehicles. The examples included here are sites covered by publications in the formal meta-analysis (cf. Fig. 2). In many cases, damage to landscapes and vegetation remains severe and widespread, several decades after studies suggested management interventions to limit serious ecological harm. Left-hand panels indicate the broader seascape setting, whilst right-hand panels illustrate the types and damage caused by vehicles. Studies included are (Liddle and Grieg-Smith, 1975; Brodhead and Godfrey, 1977; Brodhead, 1978; Hosier and Eaton, 1980; McAtee and Drawe, 1980; Judd et al., 1989; Kutiel, 1999; Kutiel et al. 2000, 2001; Thompson and Schlacher, 2008; Kelly, 2014; Cooke et al., 2020; Hogan and Brown, 2021). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2.2. Data coverage

Publications that included numerical data on effect sizes attributable to off-road vehicles encompassed a sizeable number of taxa: 253 species, 174 genera, and 64 families (Table 1). Grasses (Fam. Poaceae) were the most speciose ($n = 54$), followed by asters (Fam. Asteraceae – 35 species), legumes (Fam. Fabaceae – 24 species), sedges (Fam. Cyperaceae – 11 species), amaranths (Fam. Amaranthaceae – 8 species), carnations (Fam. Caryophyllaceae – 7 species), spurge (Fam. Euphorbiaceae – 6 species), rushes (Fam. Juncaceae – 5 species), and plantains (Fam. Plantaginaceae – 5 species) - these 11 families comprise 61 % of all species covered; the remainder of families ($n = 53$) each contained fewer than five species (Table SU-1). In addition to the broad taxonomic ambit, our data also cover a variety of growth forms, dominated by forbs (134 species), followed by grasses (55 species), shrubs (23 species), mosses (18 species), sedges (10 species), liverworts (5 species) rushes (5 species), and lichens (5 species). The geographic data coverage primarily reflects coasts where the practice of driving vehicles on beaches and in dunes for

recreation is popular (Table SU-2). Half of all ($n = 15$) studies come from the USA, the rest from Israel and South Africa (13 % each), as well as Australia, Canada and the UK (7% each). The data span 87° of latitude (min. -34° , max. 54°) and 249° longitude (min. -97° , max. 152°), encompassing the coasts of the Atlantic, the Indian Ocean, the South Pacific and the Mediterranean. Nearly half a century of evidence is available, with publication years ranging from 1975 to 2021 (mean 1993, SE = 4 years).

3. Results

3.1. The magnitude and types of adverse impacts

Effect sizes across all biological response types were strongly negative, signifying that off-road vehicles damage coastal vegetation (Table 1, Fig. 2 & SU-1). Harmful impacts are clearly evident as lower biomass, sparser ground cover, shorter plants, fewer species, lower frequency of occurrence, less diverse assemblages, smaller vegetated

Table 1

Summary values of response metrics for plants stressed by off-road vehicles in coastal areas. The magnitude and direction of responses were quantified using two complementary indices of effect sizes commonly used in meta-analysis: a) the response ratio (L), and b) standardised effect size (Hedge's g). Negative values for either index denote adverse impacts, where biological entities are smaller in vegetation stressed by vehicles compared with plants under reference conditions without vehicles (e.g. fewer species, smaller biomass, lower productivity. etc.).

A – Response Ratios (L) ^a				
Response Type/Metric	n	mean	se	(Confidence Interval, 95%)
1 – Abundance	367	−0.67	0.04	(−0.75 to −0.59)
1.1 - cover (vegetation/ foliage)	120	−0.46	0.04	(−0.53 to −0.39)
1.2 - biomass	27	−2.10	0.36	(−2.80 to −1.30)
1.3 - height	88	−0.45	0.05	(−0.54 to −0.36)
1.4 - spatial extent	3	−1.20	0.45	(−3.10 - 0.75)
1.5 - occurrence (frequency)	129	−0.71	0.05	(−0.80 to −0.62)
2 – Diversity	52	−0.41	0.07	(−0.55 to −0.27)
2.1 - species richness	32	−0.51	0.10	(−0.71 to −0.30)
2.2 - diversity index	20	−0.27	0.07	(−0.41 to −0.12)
3 – Productivity	24	−0.56	0.11	(−0.79 to −0.32)
ALL	443	−0.63	0.04	(−0.70 to −0.56)
B – Standardised Effect Size (Hedge's g) ^b				
Response Type/Metric	n	mean	se	(Confidence Interval, 95%)
1 – Abundance	118	−0.98	0.11	(−1.20 - 0.76)
1.1 - cover (vegetation/ foliage)	16	−1.60	0.22	(−2.00 - 1.10)
1.2 - biomass	10	−2.70	0.43	(−3.70 - 1.70)
1.3 - height	88	−0.64	0.11	(−0.86 - 0.42)
1.4 - spatial extent	3	−2.40	0.71	(−5.50 - 0.64)
1.5 - occurrence (frequency)	1	−0.55	na	(na - na)
2 – Diversity	6	−0.93	0.43	(−2.00 - 0.18)
2.1 - species richness	6	−0.93	0.43	(−2.00 - 0.18)
2.2 - diversity index	0	na	na	(na - na)
3 – Productivity	0	na	na	(na - na)
ALL	124	−0.98	0.11	(−1.20 to −0.76)

^a **Response Ratio**, $L = \ln(X_{ORV-impacted} + 1) - \ln(X_{reference} + 1)$, where $X_{ORV-impacted}$ is the mean outcome for the group being stressed/affected/impacted by off-road vehicles, and $X_{reference}$ the mean value for the control group without vehicle traffic (Hedges et al., 1999; Lin and Aloe, 2021).

^b **Hedge's g** = $(x_1 - x_2) / (((n_1 - 1)s_1^2 + (n_2 - 1)s_2^2) / (n_1 + n_2 - 2))^{0.5}$, where a) x_1 , x_2 : the sample 1 mean and sample 2 mean, respectively, b) n_1 , n_2 : The sample 1 size and sample 2 size, respectively, and c) s_1^2 , s_2^2 : The sample 1 variance and sample 2 variance, respectively. (Hedges, 1981; Lin and Aloe, 2021).

areas, and lower productivity (Table 1, Fig. 2 & SU-1). On average, vegetation exposed to ORVs had only 25–50% of the abundance, biomass, spatial extent, or biodiversity compared with control areas. The mean and median values of calculated effects with sample sizes of five or more were all significantly ($P < 0.001$) more negative than a hypothetical zero value (Fig. 2 & SU-1). Significant damage across the entire range of measured vegetation attributes is equally manifest when indexed by response ratios (Fig. 2) or standardised effect sizes (Fig. SU-1).

Off-road vehicles create extensive and dense 'scar networks' in beach- and dune seascapes, thereby fundamentally fragmenting and depleting the vegetation (Fig. 1 & SU-2). These tracks represent a series of sharp boundaries between low biomass and low diversity trails and abutting remnant stands (Fig. SU-2). The vast majority of vehicle-stressed species are markedly less common in tracks (Fig. SU-3). Harmful ORV effects are manifest in all life forms, including smaller and somewhat inconspicuous forms (e.g. mosses, lichens, liverworts) that are rarely included in standard vegetation impact surveys (Fig. SU-4). Most responses are reported as injurious changes in terms of declines in 'amounts' (i.e. biomass, 'counts', 'numbers', 'cover' etc.). However,

plants can react to ORVs in more subtle ways, such as changing metabolic investments among growth modes (Fig. SU-5). Vehicles can also fundamentally alter the composition and structure of entire plant assemblages (Fig. SU-6).

3.2. Dose-response relationships

The severity of adverse impacts is typically related to traffic volume. Such 'dose' (aka the number of vehicle passes) vs 'response' (aka damage to plants) relationships are, however, rarely linear (Fig. SU-7), and can depend on the characteristics of the affected plants and the types and intensity of the stressor (Fig. SU-8). In many cases, it is the first few passes of a vehicle that cause most of the damage (Fig. SU-9). Consequently, no safe level of ORV traffic exists, as even a single pass has been shown to cause considerable harm (Fig. SU-9). Similarly, spacing out vehicle travels over sizeable time intervals (weeks) does not reduce damage, with harmful effects measurable at exceedingly sparse and infrequent traffic (single car making 16 passes over 80 weeks, Fig. SU-9) – dune vegetation does not accommodate traffic. Thus, it seems to matter little whether traffic stressors occur as a pulse disturbance or are spread out over time, both deplete the dune vegetation (Fig. SU-10). In addition, environmentally insensitive driver behaviour can magnify damage, with turning vehicles causing more harm than those driving along straight paths (Fig. SU-10).

3.3. Post impact – recovery

After vehicle traffic ceases, most vegetation has the capacity to grow back and revert the damage caused by ORVs. However, the recovery rate and the shape of the recovery trajectories vary greatly (Figs. SU-11, DSU-12). Even when considering sites in the same beach-dune setting, there are marked differences between species, habitats, and assemblage types (Fig. SU-11, SU12). Marshes and tidal flats located at the upland edge of the seascape have very low carrying capacity for vehicles, and recovery may be exceptionally protracted (Fig. SU-11). Of the vegetation growing on shifting sand, a few communities (mostly pioneer species at the seaward edge of the dunes) can have the capacity to recover within a year or two, whilst shrubs on back-dunes can take more than four years to re-grow (Figs. SU-12, SU-13). Recovery dynamics are very similar amongst complementary plant attributes measured (Fig. SU-14). Because recovery patterns are so variable, being the product of permutations of plant attributes, sand/soil characteristics, habitat types, life forms, and initial stressors, it is challenging to generalise about the time needed to recover (Fig. 3A). However, predictions can be made for individual situations, and these predictions averaged to arrive at broad generalisations (Fig. 3B). In some cases it is possible to measure, on average, $\pm 50\%$ re-growth within one month to half a year, but these estimates also include many situations of zero recoveries (Fig. 3B). Beyond the first year post-impact, recovery slows and plateaus at $\pm 70\%$; there is no indication in our data that several communities can re-grow within four years. Overall, impacts on dune vegetation can be remarkably long-lasting, and recovery can be protracted (Fig. 3).

4. Discussion

4.1. Ecological harm to -beach-dune vegetation: part of a broader impacts to ocean shores

Our global meta-analysis unequivocally shows that off-road vehicles cause serious harm to the vegetation of ocean shores. Adverse impacts of ORVs are widespread, with declines evident for a range of metrics, including significantly lower density, cover, biomass, height, productivity, and diversity. It is often the first few vehicle passes that cause the most damage, and there is rarely, if ever, a 'benign' level of traffic intensity that does not cause harm. Instead, the evidence shows that a single vehicle pass can result in substantial degradation and that an

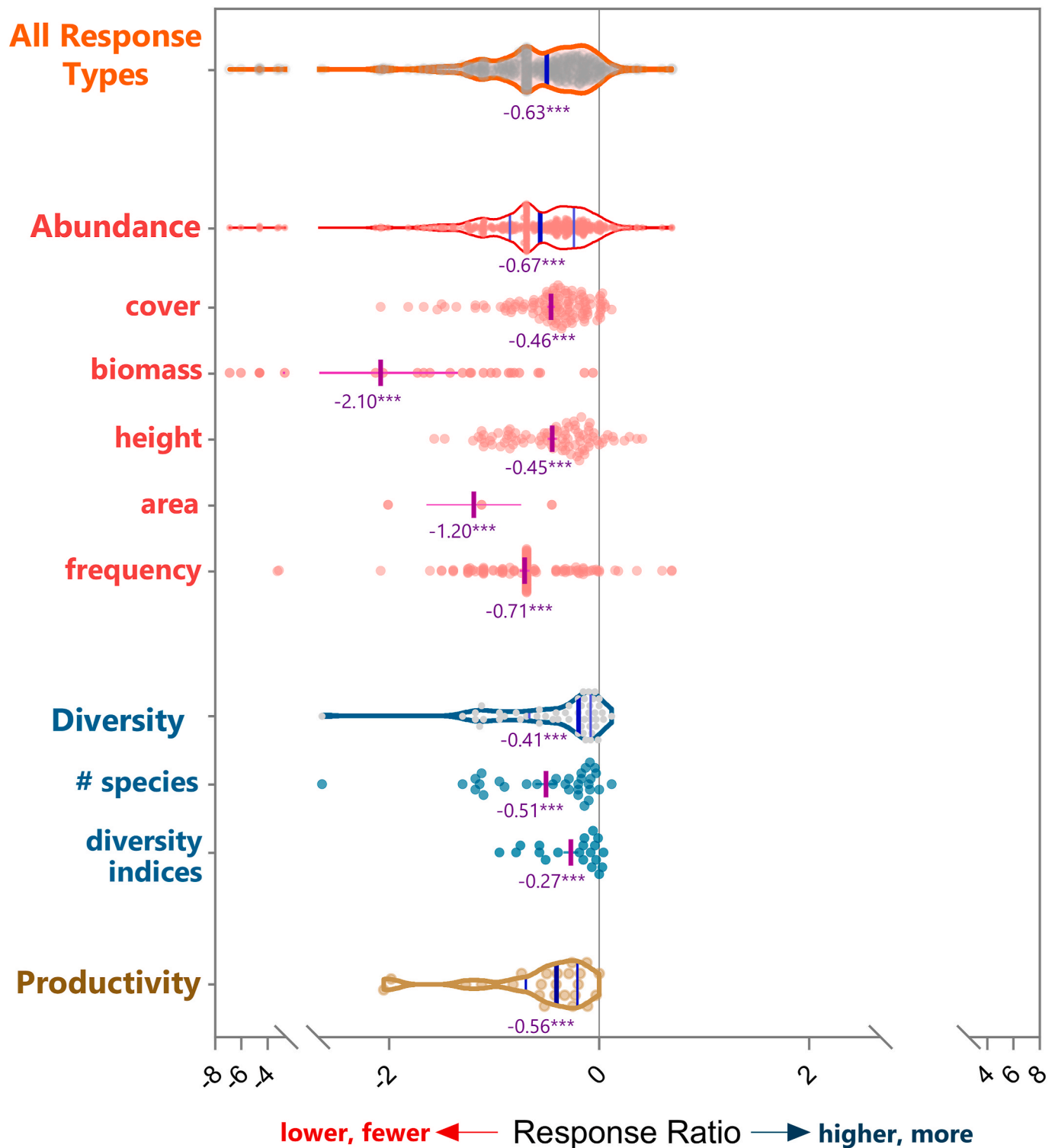


Fig. 2. Biological responses ($n = 443$) of coastal vegetation impacted by off-road vehicles. Effect sizes are calculated as response ratios, $L^{\#}$. Negative values of the response ratio (left side of the panel) denote that vegetation stressed by vehicles had biological attributes typically associated with ecological harm (e.g. fewer individuals, lower biomass, less diverse assemblages, decreased productivity, etc.). Vertical lines in violin plots for aggregate metrics show medians, quartiles, and mean values ($\pm$ one SE) in scatterplots for individual response variables. (Mean values of L are plotted for each metric, with *** denoting $P < 0.001$ for t-tests contrasting mean response ratios with a hypothetical mean value of zero that would indicate no distinct response). Violin plots illustrate compound metrics (e.g. abundance, diversity) whilst specific metrics nested within compound variables are shown as dot plots.

$^{\#}$ **Response Ratio**, $L = \ln(X_{ORV-impacted} + 1) - \ln(X_{reference} + 1)$, where $X_{ORV-impacted}$ is the mean outcome for the group being stressed/affected/impacted by off-road vehicles, and $X_{reference}$ the mean value for the control group without vehicle traffic (Hedges et al., 1999; Lin and Aloe, 2021).

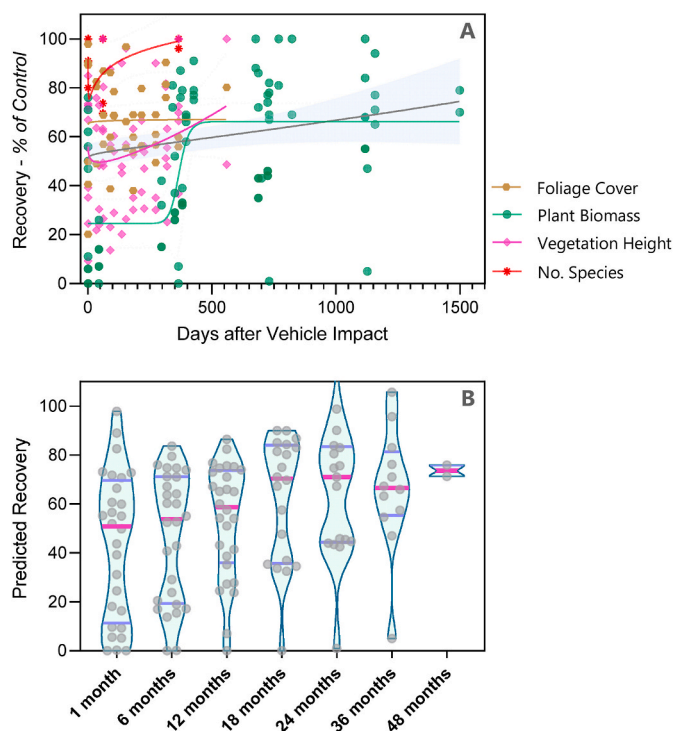


Fig. 3. Time course of changes in vegetation after vehicle impacts (A – top panel) and predictions of recovery at several time points that may be considered in a management context (B – bottom panel). Data are pooled from several studies that contain sufficient information to analyse temporal changes. The level and type of plant responses vary enormously between species, habitats, and measured attributes (top panel). However, for each permutation of species $\times$ habitat $\times$ attributes, one can fit non-linear regression models (cf. Fig. SU-11) to predict recovery at particular periods after traffic had ceased. The bottom panel graphically summarises predictions from these models (purple lines show medians, blue lines show quartiles). Principal data sources include (Rickard, McLachlan et al. 1994; Avis, 1992; Brodhead, 1978; Brodhead, 1979; Judd et al., 1989). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

accumulation of adverse effects from new tracks is likely. Recovery is highly variable and can take years, requiring active restoration intervention in many cases.

Whilst the above catalogue of ORV damage to plants is clear, the consequences of changes to vegetation that are attributable to vehicles extend well beyond the greenery. Plants in beach-dune ecosystems have multiple functions, but two cardinal attributes stand out: Firstly, dunes protect coastal assets and upland ecosystems from storms; typically, this critically important ecosystem service of erosion mitigation is firmly dependant on intact and diverse vegetation at the land-sea boundary (Feagin et al. 2005, 2010, 2019). It follows, that dunes with depleted vegetation will generally be less effective in buffering high waves and storm surges. This is clearly illustrated at local scales where vehicle tracks in the dunes create erosion hotspots (Thompson and Schlacher, 2008). The second cardinal attribute is that vegetation in beach-dune systems forms habitat structure and heterogeneity, thereby creating a milieu favourable for a diversity of animals, including rare and threatened species (Rocha et al., 2009; Howe et al., 2010; Koyama and Ide, 2020; Smith et al., 2021). Loss of vegetation can also increase the likelihood of nest failures in beach-nesting birds and turtles (Maslo et al., 2016; Costa et al., 2023). It follows that the degradation of plant communities will translate into adverse effects on animal populations and assemblages (Schlacher et al. 2006, 2011).

Although the impacts of ORVs on beach-dune vegetation are clear,

they are just one part of a broader spectrum of anthropogenic impacts on ocean shores (Schlacher et al. 2006, 2007; Jones et al., 2017; Costa and Zalmon, 2021). Amongst the potpourri of human activities that adversely affect the habitat values of beaches and dunes, massive physical change associated with urbanisation, armouring, nourishment, and grooming are some of the more ubiquitous and severe stressors (Walker et al., 2008; Dugan and Hubbard, 2010; Lucrezi et al., 2010; Dugan et al., 2011; Gilburn, 2012; de Schipper et al., 2021; Aguilera et al., 2022). These stressors can act concurrently and synergistically with ORVs on some urbanised coastlines. In other cases, however, ORV traffic is much more intense outside urban settings, often peaking in National Parks and wildlife conservation areas (Schlacher et al., 2013a, b; Weston et al., 2014). This ‘displacement’ of ORVs to natural areas, often into places of conservation importance, has created a paradoxical, yet dire and widespread, scenario in which beaches and dunes have become trapped between urban pressures along the more intensively developed shorelines and recreational ORV pressures in the supposedly more protected areas outside the urban shores – a superbly ironic case of ‘longshore coastal squeeze’ where most dune- and beach ecosystems are stressed by human activities over vast stretches of the coastline.

4.2. Recovery

A key finding of synthesising the available data on the recovery of coastal vegetation was the extraordinarily high variability of recovery velocities and trajectories – we conclude that it is well-nigh impossible to identify a ‘typical’ recovery pattern given the data available at present. This may well change in the future as more time series of vegetation recovery become available, which is a critical data gap at present. What we *can* generalise is that the initial intensity of the stressor (i.e. low vs high number of passes) does not necessarily translate consistently to correspondingly longer or shorter recovery times. By contrast, plant traits and habitat type are more important in predicting rehabilitation. Pioneer species growing as forbs and grasses around the seaward edge of the dunes have evolved in the most dynamic part of the beach-dune-upland sequence. As such, they can show faster recovery than their more upland floral chums (Brodhead, 1979; Rickard et al., 1994). However, the strandline and backshore are also habitats for rare plant species, for which loss of individuals may have much more severe population consequences, potentially leading to local extirpation rather than recovery (Kelly, 2013). Disturbance to natural vegetation can also increase the vulnerability of dune plant assemblages to invasion by non-native species, which can be further amplified by ORVs acting as vectors for the dispersal of weeds (Zarnetske et al., 2010; Burkitt and Wootton, 2011; Garbary et al., 2013; Moulton et al., 2019). Vegetation on the more mature back-dunes (rear dunes) is often more vulnerable to ORVs and is also much slower to recover (Brodhead, 1978); recovery can be especially protracted when the woody tissues of shrubs have been damaged by vehicles (Leatherman and Godfrey, 1979; Kuss, 1986; Avis, 1992; Rickard et al., 1994; Yorks et al., 1997). For example, vehicle tracks remained visible for at least eight years in the stabilised back dunes of Cape Cod (Leatherman and Godfrey, 1979).

The time required for full recovery may be a decade or more in many situations. Such protracted re-growth can result from severe initial damage to the habitat (e.g. soil compaction and altered water capacity) or is linked to prolonged ORV stress, even at low volume and extended return intervals (Avis, 1992). Repeated traffic not only damages remnant plants, but it can reduce their reproductive output (e.g. seed production), crush roots and horizontal runners, lower germination rates, and kill seedlings. The combined outcome will be stymied, or no recovery. In these situations, it will be necessary to intervene actively with restoration actions. However, for these investments to be successful requires a modern understanding of dune functioning (Maun, 2009; Bonito et al., 2017), the specific adaptations and growth requirements of dune plants (Hesp, 2012; Teixeira et al., 2016), and the ecological need to create heterogenous topographies and habitat diversity (Nordstrom,

2003; Nordstrom et al., 2011; Brunbjerg et al., 2014). Restoration can positively contribute to overall beach-dune habitat quality and coastal resilience (Maslo et al. 2018, 2019; Johnston et al., 2023; Walker et al., 2023).

4.3. Management & conservation

Reducing the extensive and harmful environmental footprint of recreational off-road driving is a wicked management challenge. It pervades all settings where vehicles are driven for leisure, including ocean shores, deserts, tundras, and mountain trails (Westhoff, 1966; Ploughe and Fraser, 2022). A unique feature of ORVs in beach- and dune settings is the narrow and linear shape of the environment, creating a narrow corridor in which traffic is concentrated (Godfrey, 1982). Channelling of vehicles by this distinct landscape geometry of beaches and dunes arguably magnifies the adverse impacts of vehicles, especially when traffic volumes are substantial (Schlacher et al., 2008a,b). Also important is the combined surface area of track networks that often crisscross the landscape and accumulate over time if uncontrolled and un-managed. This effect can be profound in open landscapes, as was seen graphically on New Zealand's east coast, where new beach areas created by uplift in the 2016 Kaikōura earthquake became extensively tracked over the summer (Orchard et al., 2022). Elsewhere, progressive

increases in the footprint of ORV impacts has been linked to the proliferation of access points; making these a key focus for management (Vallés et al., 2011). Aside from conservation issues, there is also the need to consider the potential for conflicts between ORV users and other beach visitors (Kelly, 2016). Thus, identifying the effective and efficient management interventions that can reduce ORV-associated threats to cultural-, environmental-, and social values, and the numerous services provided by beach systems, is a priority.

While there will always be some local adaptations and refinements due to site conditions and constraints, several fundamental principles of effective management interventions to lower ORV impacts can be identified; they will apply in most cases (Box 1). Above all, it must be recognised that ORV traffic is rarely – if ever – compatible with sustainable environmental use and protection that is underpinned by contemporary ethics (Vivian and Schlacher, 2015). Thus, the quintessential strategy is to phase out all non-essential off-road vehicle use on ocean shores and the upland dunes, heathlands, marshes, and tidal flats. Many of these ecosystems have zero tolerance for vehicles – the concepts of ‘carrying capacity’ and ‘acceptable thresholds’ are often fallacies in these environments (Godfrey and Godfrey, 1980).

From the perspective of protecting and restoring the vegetation of ocean shores, and their linked upland habitats, the basic management recommendations have been known for half a century and refined

BOX 1

Management Principles For Off-Road Vehicles in Dune-Beach Systems.

1. **Exclude all non-essential** motorised vehicles and craft from all dune-beach ecosystems. (Exceptions should be limited to providing access to cultural/spiritual sites for First Nations People, emergency responses (search & rescue), access for people with mobility impairments, law enforcement, and access by landholders and fishers with historical rights where alternative routes do not exist). In all cases, formed and designated access routes should be used where possible.
2. **Encourage** and incentivise recreationists to **walk** and cycle instead of driving in cars.
3. Create ‘**safe spaces**’ (i.e. free of traffic) for non-motorised users and wildlife.
4. To enable public access to beaches and dunes without private ORVs, consider **public transport options** where these do not conflict with environmental protection objectives.
5. In situations where the phasing out of existing recreational (non-essential) off-road vehicle use requires more time, the principal mechanisms that will yield environmental benefits are to: a) **limit the footprint** of vehicles (in space, time, and traffic volume) and b) **prevent particularly damaging behaviours**.
6. **Spatial closures** are typically more effective than controls on vehicle numbers because substantial damage is often caused by the first few passes of vehicles, even at very low frequencies (i.e. most beach-dune systems have zero carrying capacity for ORVs: there is typically no environmentally ‘safe’ level of ORV traffic in beach-dune systems).
7. Ideally, these spatial closures exclude vehicles from all beach-dune areas containing remnants of natural vegetation and fauna. If complete closure requires lead times, management interventions should target **partial closures** such as:
 - 7.1. A total and permanent ban of vehicles from shore sections that contain significant **cultural**, spiritual, historical, and **archaeological sites**;
 - 7.2. **Avoiding habitats** that have particularly low tolerance and **high sensitivity** to vehicles: a) the edge of the frontal dunes around the drift-line, b) strandline vegetation at the backshore and seaward fringe of dunes; c) back-dunes and the wetlands, heathlands and marshes upland of dunes; d) soft, dry sand of the upper beach.
 - 7.3. Protect sections of the coast that function as non-replaceable habitats and areas for rare plants and fauna, such as the nests and roosts of **birds and turtles**.
 - 7.4. **Prohibit** traffic from **narrow beaches** and beach sections that force vehicles into the particularly vulnerable upper beach fringe (backshore around drift and strandline).
 - 7.5. To avoid concentrations of traffic in a very narrow strip near the sensitive dune base, **prohibit** vehicle movement around times of **high tides** (e.g. ± 2 h on either side of predicted high-tide time) and at times of the year when exceptionally high tides occur regularly (e.g. equinoxes) or are expected during foul weather.
8. In settings where some sections of the shoreline have to remain open to non-essential traffic (for a limited time until leisure traffic is phased out), the **shore length of vehicle closure zones** should always be greater (i.e. $>50\%$) than the length of trafficked zones.
9. Regulations and law enforcement should **prohibit activities** and behaviours that often **cause serious environmental harm**, such as a) straying off established tracks, b) “dune busting” and similar activities that solely aim to test the capability of four-wheel drive vehicles, c) excessive speeds, d) targeting wildlife, e) excessive tyre pressures and vehicle weights. Regulatory agencies should ensure **compliance** with ORV regulations through appropriate resourcing of enforcement and **public transparency** in reporting compliance efforts and outcomes.
10. In addition to spatial closures, **route** all residual traffic to established, **formal tracks** and reduce the number of legal tracks, maintain their condition, avoid sharp turns, and re-orientate them to prevent blow-outs.

subsequently (summarised in Box 1)(Godfrey and Godfrey, 1974; Godfrey, 1978). Recent remotely sensed imagery from the same study sites that were used to develop the first sets of conservation recommendations, shows that little (if any) progress towards better ORV management has been made in those areas – many environments show clear evidence of degradation directly linked to recreational vehicle use (Fig. 1). This suggests a fundamental disconnect between the known and effective management actions and their lack of uptake and enforcement by agencies charged with protecting beach- and dune ecosystems (Kelly, 2014; Orchard et al., 2022). It is a formidable complex problem, not least because the behaviour of drivers in the real world (and the damage they cause) is an equally complex composite of value orientations, norms, ethics, attitudes, belief systems and expectations (Priskin, 2003; Waight and Bath, 2014; Weston et al., 2014; Petch et al., 2018). It must also be recognised that ORVs create unacceptable risks to irreplaceable and fragile archaeological and spiritual sites that cannot be salvaged once destroyed and endanger the lives of non-motorised beach users. These issues create massive social inequalities by degrading the universal environmental heritage and displacing users without vehicles (Gilbertson, 1981; Collins and Kearns, 2013; Petch et al., 2018; Litster et al., 2020). Several of these issues will benefit from management interventions initially designed to conserve biological entities, but their protection must be explicitly spelt out and always woven into management strategies as non-negotiable actions (Box 1). Long-term and geographically widespread strategies are needed to limit the ecological harm caused by ORVs to beach ecosystems globally. One fundamental aspect is to shift people's perspective, effectively encouraging change towards people no longer perceiving driving ORVs on beaches as something 'enjoyable'. This is a wickedly complex ambition without clearly articulated actions and tactics at present. Creative solutions will need to come to the fore, such as collaborating with ORV manufacturers' lobbies to discourage the inclusion of beach driving in their advertisements, thereby contributing to a change in mentality over time.

Work that can narrow the divide between the theory and practice of environmental ORV management (i.e. 'what we know should happen versus what does not happen') is perhaps the most pressing challenge for coastal scientists and the government agencies legally required to prevent and reduce environmental harm on beaches and dunes. Suggesting that there is a 'single best solution' (or set of solutions) would be naïve. Nevertheless, we posit that progress can be made through a combination of multiple evidence-based approaches: 1.) Invest more in formally evaluating the performance of existing interventions (e.g. Kelly, 2014, Fig. SU-14) and learn from them in an adaptive management framework (Herbig, 2007); 2.) To shift value orientations, communicate (using attractive visuals, positive messaging and social media) the positive environmental outcomes when ORVs are removed from sections of beaches and dunes. 3.) Create and mainstream a new narrative of ocean shores as biodiverse and fragile ecosystems worthy of our protection, emphasising the unique and amazing wildlife and the ecosystem services they provide to humans ("beaches are cool"). 4.) Examine whether, where and when 'safe places' and 'safe practices' ('low impact options' sensu (Orchard et al., 2022)) can exist for recreational ORV use, including the conditions they need to operate under, to facilitate a constructive dialogue amongst diverse users and stakeholders.

5. Conclusions

1. **Serious harm** caused by off-road vehicles to the vegetation of ocean shores and their dunes is geographically widespread, often substantial in magnitude, and evident in a broad range of environmental settings and plant groups.
2. The **evidence** for adverse impacts directly attributable to off-road vehicles is **robust**, with reported effect sizes ($n = 443$ records) being significantly negative (i.e. statistically highly distinct from a neutral/zero response).
3. Vegetation damage often occurs **rapidly**: only a **few** passes of an off-road vehicle can be sufficient to cause severe ecological harm (i.e. most assemblages of dune vegetation have essentially zero tolerance to vehicle traffic).
4. Serious harm is caused by **pulses** in vehicle stressors, with the magnitude of adverse effects typically increasing at higher traffic volumes. Similarly, more 'diffuse' and sparse **traffic**, even at very low frequencies (i.e. intervals between ORV passages in the order of weeks) and after a single or two drives, can also cause sizeable impacts: it implies that there is **no evidence for safe traffic thresholds** below which environmental harm can be consistently avoided.
5. **Sustained** ORV traffic can lead to an expansion of vehicle tracks, increasing the **spatial footprint** of environmental harm.
6. There is no such thing as a typical **recovery pattern**: the shape of the re-growth trajectories varies enormously between species and environmental settings. **Recovery times** vary between localities and communities, often exceeding many months, or impacted communities not returning to reference conditions after several years: **adverse impacts can be long-lasting**.
7. Habitats and plants at the seaward edge (i.e. 'pioneers') can, in some instances, recover faster; by contrast, ecological features in more **mature dunes** are substantially more sensitive to vehicle stress and are considerably slower to recover.
8. Averaged across studies, re-growth can take months to a year in some cases but can be exceptionally protracted in many others, indicating that rehabilitating damaged sites may require **active restoration interventions**.
9. Despite the management interventions that can limit environmental damage being known for several decades, **satellite imagery reveals an ongoing, massive 'footprint' of ORVs** at the very same sites where seminal work was done – this suggests significant and widespread hurdles to translating environmental knowledge into tangible conservation strategies that work.
10. Progress in reducing the near-ubiquitous harm caused by off-road vehicles in beach-dune systems will primarily come from a combination of: a) visible and sustained **political will**, and courage by agency administrators to implement change and revert the social inequalities caused by ORV users; b) a transparent and thorough identification of '**safe places**' and '**safe practices**' - should they exist; and c) addressing hurdles to the uptake and **transition** to more **environmentally benign** modes of beach **recreation**, especially in National Parks and similar conservation areas.

CRedit authorship contribution statement

Thomas A. Schlacher: Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Michael A. Weston:** Writing – review & editing, Supervision, Project administration, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Shane Orchard:** Writing – review & editing, Conceptualization. **Brendan P. Kelaher:** Writing – review & editing, Conceptualization. **Brooke Maslo:** Writing – review & editing, Validation, Conceptualization. **Jenifer E. Dugan:** Writing – review & editing, Conceptualization. **David M. Hubbard:** Conceptualization. **Leonardo Costa:** Writing – review & editing, Conceptualization. **Melanie J. Bishop:** Writing – review & editing, Conceptualization. **Kristal N. Kostoglu:** Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ben L. Gilby:** Writing – review & editing. **Christofer J. Henderson:** Writing – review & editing. **Teresa Amaro:** Writing – review & editing, Conceptualization. **Serena Lucrezi:** Writing – review & editing, Conceptualization. **Christian Crosby:** Conceptualization. **Michael Elliott:** Conceptualization. **Kyle A. Emery:** Writing – review & editing, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ecss.2024.109038>.

based on the study authors' multi-decadal experiences and expertise as coastal scientists and numerous suggestions in the peer-reviewed literature such as, (Godfrey and Godfrey, 1974, 1980; Godfrey, 1978, 1982; Leatherman and Godfrey, 1979; Godfrey et al., 1980) (Gómez-Pina et al., 2002; Kelly, 2016; Petch et al., 2018; Hesp, 2002, Kelly, 2013, 2014, 2016, Blakely et al., 2022, Orchard et al., 2022; Rickard et al., 1994).

Data availability

Data will be made available on request.

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