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Ecosystem integrity of active sand dunes: A case study to implement and test the SEEA-EA global standard, from Aotearoa New Zealand

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ABSTRACT

Biodiversity and ecosystem functions are deteriorating worldwide, and there is an urgent need to reverse these declines and set ecosystems on a path to recovery. Effective monitoring, including a fit for purpose indicator framework, is essential to track progress towards targets but, as yet there is no universal framework that delivers timely data on biodiversity and ecosystem change. Ecosystem integrity is a unifying concept that refers to the capacity of an ecosystem to be resilient to natural or anthropogenic perturbations, and to maintain characteristic species composition, structure, functioning and self-organisation over time within a natural range of variability. Using a case study which can be generalised to international contexts, we implement and test a new global standard for the assessment, monitoring and ranking of ecosystem integrity of active sand dunes in Aotearoa New Zealand.

1. Introduction

To halt the decline in global biodiversity (IPBES, 2019), 196 countries have committed to the United Nations (UN) Convention on Biological Diversity which requires reporting on the changing status of ecosystems (United Nations, 1992). Effective monitoring is essential to track progress towards targets, including a fit for purpose indicator framework (Nicholson et al., 2021, Tittensor et al., 2014), but, as yet there is no harmonized, universal framework that delivers timely data on biodiversity and ecosystem change (Hansen et al., 2021; Pereira et al., 2013).

Ecosystem integrity is a unifying concept, referring to the capacity of an ecosystem to be resilient to natural or anthropogenic perturbations, and to maintain characteristic composition, structure, functioning and self-organisation over time within a natural range of variability (Holling, 1973; Karr 1993; McGlone et al., 2020). Measures of integrity include characteristics of abiotic state (physical and chemical), biotic state (composition, structure and function), and landscape state (e.g., connectivity and fragmentation) in relation to a reference state (Andreasen et al., 2001; Czúcz et al., 2021; Keith et al., 2020; Noss, 1990). Another important measure is ecosystem areal extent which can reflect how many species an ecosystem can support (Bellingham et al., 2021; Cieraad et al., 2015; Dengler, 2009), and the rate of decline in extent can be used as an indicator of the trajectory towards ecosystem collapse (Bland et al., 2016).

The UN Statistics Division has developed the System of Environmental – Economic Accounting, Ecosystem Accounting (SEEA-EA) which assesses physical, chemical, biotic and landscape characteristics to quantify ecosystem condition (ecosystem integrity), as part of a new method to account for the provision of ecosystem services (United Nations, 2021). To quantify ecosystem integrity specifically, indicators are derived from a range of variables in relation to reference states (United Nations, 2021). Areal extent is also measured to compare temporal change (Keith, et al., 2020). The identification and monitoring of ecosystem integrity indicators is critical for monitoring all ecosystems, especially ones that are highly dynamic whether due to natural or human-caused perturbations.

Coastal active dune ecosystems occur globally, and are dynamic sand dune systems where the physical, ecological and landscape characteristics result from continuously moving aeolian sands (Hesp and Walker, 2021; Psuty, 2008). They are highly mobile with bare to sparse, scattered vegetation (Hesp and Walker, 2021; Hilton et al., 2000). Active sand dunes also provide vital ecosystem services such as acting as natural barriers to storm surge and protection from coastal erosion and sea

Abbreviations: SEEA-EA, System of Environmental - Economic Accounting – Ecosystem Accounting; UN, United Nations.

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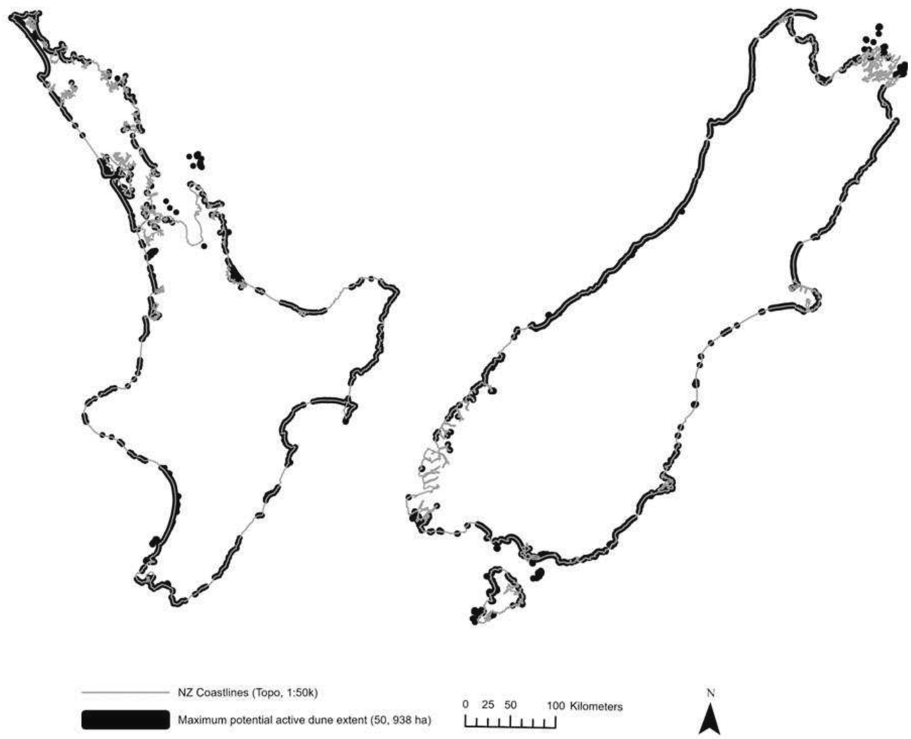

Fig. 1. Maximum potential extent of active sand dunes in Aotearoa. Input datasets include an overlay of surface lithology types that could potentially form active dunes from the New Zealand Land Resource Inventory, third edition (Landcare Research/Manaaki Whenua, 2021; Appendix A1), with land cover types that could also potentially form active dunes from the New Zealand Land Cover Database v5.0 (Landcare Research/Manaaki Whenua, 2020, Appendices A2); and the most recent digitised extent of active dunes by Hilton et. al (2000), derived from 1990s aerial photography.

level rise (Walker et al., 2013). They are a habitat for indigenous biodiversity, sustain culturally important practices and provide opportunities for recreation and tourism (Bergin, 2011; Hare et al., 2019; Hesp, 2000; Martínez et al., 2013, Nordstrom and Jackson, 2021). Despite their economic, ecological, cultural and social importance, coastal dune systems remain among the most threatened ecosystems in the world (Muñoz-Vallés and Cambrollé, 2014), largely because of human activities.

Globally, the drivers of active dune ecosystem integrity are relatively ubiquitous. The key factors for contemporary dune system formation and development are an available supply of sandy sediment, sufficiently high wind speeds to mobilise the sediment, the presence of coloniser, sand-binding vegetation, and adequate space inland from the shoreline to accommodate coastal processes (Delgado-Fernandez and Davidson-Arnott, 2011; Gao et al., 2020; Hesp, 2011; Psuty and Silveira, 2010). Storms also affect dune mobility through shifts in sediment supply and impacts on plant community dynamics (Miller et al., 2010). Changes in these factors over time create a continuum of dune mobility from highly active dunes comprised completely of bare sand, to entirely vegetated or 'stable' dunes (Gao et al, 2020; Levin et al., 2008; Tsoar, 2005). Gao et al. (2020) presented a global trend towards stabilisation of active dunes in the last century largely due to land use change, practices such as afforestation, overgrazing, urbanisation, and intentional stabilisation projects, and sediment supply decline due to hydrological works and human made sea defences (Gao et al., 2020).

As a large island nation in the South Pacific, Aotearoa has c.15,000 km of coastline (Bell and Gibb, 1996) that contain a subset of active sand dunes with a wide variability of ages and morphological diversity, creating a range of habitat types (Hilton et al., 2000). Active dunes in Aotearoa are characterised by a high frequency of natural disturbance and, therefore, sparse, low growing herbaceous vegetation (Hilton et al., 2000). Pioneer sand binding plants such as native pīngao (*Ficinia spiralis* (A.Rich.) Muasya et de Lange) and spinifex (*Spinifex sericeus* R.Br.), are adapted to the stressful conditions of coastal dunes in Aotearoa and act as ecosystem engineers (Hesp, 2000). Pīngao and spinifex cause accretion, building foredunes and other geomorphic habitats for other species (Hesp, 2000; Maun, 2009), increasing their ecological diversity and resilience (Nordstrom, 2008; Walker et al., 2013). Remnant populations of native species, for example pīngao and spinifex, also provide greater genetic diversity and resilience (Eriksson, 2000; Hoban et al., 2021; Polley et al., 2005; United Nations, 2021), compared to planted populations and/or non-native populations (Polley et al., 2005). The presence of exotic woody species represents a change in active dune vegetation structure to a more stable state (Gadgil & Ede, 1998; Gao et al., 2020; Pegman & Rapson, 2005), with lower geomorphic and ecological diversity (Hugenholtz et al., 2012; Nordstrom, 2008; Walker et al., 2013). The presence of exotic forbs and graminoids also increases the stability of active dunes to varying extents, depending on the species (Provoost et al., 2011; Pegman & Rapson, 2005). However, the presence of woody species is an indicator of increased moisture and accumulated organic matter, and that the ecosystem is more stable than active dunes (Maun, 2009).

Despite their widespread importance for coastline protection, recreation and cultural value to the indigenous Māori people of Aotearoa (Coastal Restoration Trust, 2011), there have been relatively few attempts to systematically assess the ecosystem integrity of active dunes. The only national survey, published as Johnson (1992) and Partridge (1992), ranked nearly all dune systems in Aotearoa (Hilton et al., 2000) and is now 30 years old. It ranks sand dune sites along a gradient of conservation values, with the main aim of identifying priority areas for conservation protection. The authors ranked 606 sites in all 25 local government regions by assessing a mix of state and pressure factors using qualitative field surveys. They used a scoring matrix comprising four criteria: "diversity of vegetation communities and diversity of dune landforms; the number or proportion of native sand species, or good representation of characteristic or rare dune species; the degree of invasion by weed species; and the degree of modification from human or animal interference" (Johnson, 1992; Partridge, 1992, page 12). In addition, Shepherd and Hesp (2003) provide a geomorphologic overview of large scale sandy barriers and coastal dune systems of Aotearoa, which are mapped nationally at a high level, alongside detailed descriptions and mapping for a handful of sites.

A few active dune surveys exist for local government regions in Aotearoa. Uys and Crisp (2019) used field survey methods to quantify

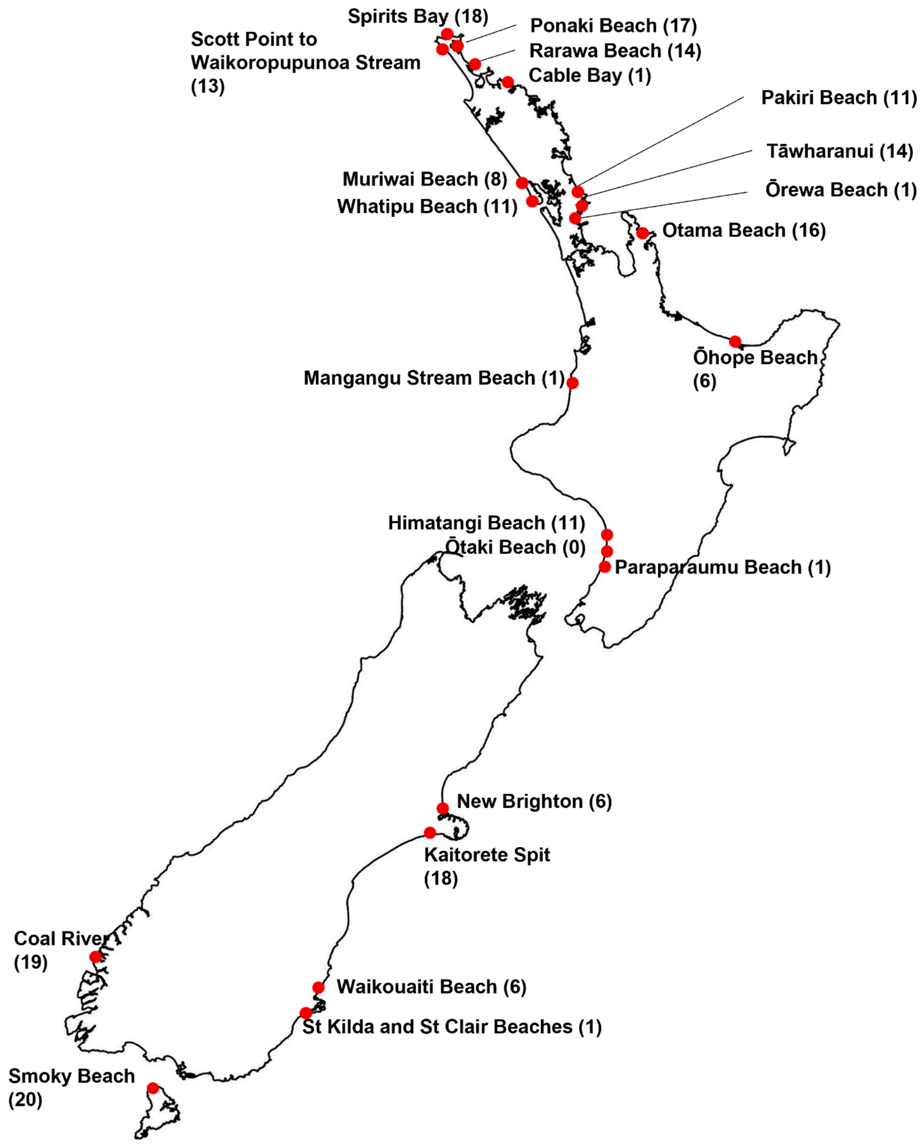

Fig. 2. Sites selected as a representative sample of active dunes in Aotearoa (n = 22). Dune integrity rank scores from Partridge (1992) and Johnson (1992) out of 20, given in parentheses. Higher scores indicate dune sites with greater integrity.

several variables for the Greater Wellington Region, including indigenous dominance, species richness, areal cover, proportion of bare ground, canopy height of vegetation, alongside a number of pressures such as rabbit browse and human traffic. Wildlands (2008) used a field survey to map sand dunes in the Tauranga Ecological District based on Atkinson (1985), which is standardized physiognomic method for describing vegetation that incorporates both compositional and structural information. Their method also included scoring for both positive and negative impacts of humans and pest animals. Between 1980 and 2000, a handful of regional Protected Natural Area Programme surveys (Bellingham, 2001), which are used to assess and prioritise areas for conservation protection, have described active dune ecosystem integrity at local and regional scales (Hilton et al., 2000).

As a key indicator of ecosystem integrity, extent has been estimated three times for Aotearoa's active sand dunes in the last 35 years. Newsome et al. (1987) identified potential active dunes from the New Zealand Land Resource Inventory at a scale of 1:1,000,000 based on aerial imagery from the 1960s and 1970s, but because of the low resolution of the maps significant dunelands were omitted (Hilton et al., 2000). Active dune extent was mapped by hand from regional aerial imagery from the 1950s, 70s, 80s and 90s by Hilton et al. (2000). In 2008, the New Zealand Department of Conservation assessed extent from moderate resolution satellite imagery and lithology maps (Stats New Zealand, 2015), and estimated active dunes extent has decreased 80.5%, to 25,208 ha, from their predicted pre-human extent of 129,402 ha (Stats New Zealand, 2015). Given the highly dynamic nature of active sand dunes, and the spread and intensification of human development around Aotearoa, these estimates are likely to be out of date. The current extent of active dune ecosystems is therefore unknown.

In sum, the information about the ecosystem integrity and extent of active dunes in Aotearoa is sparse, disparate, and in need of updating. Notably, a recent attempt to register active dunes in Aotearoa as a Red List Ecosystem was not successful due to data deficiencies (Holdaway, R. pers. comm, 2020). Similarly, an attempt to use the International Union for the Conservation of Nature (IUCN) Green List framework to assess the impact of conservation efforts on the threatened species pīngao was also deemed data deficient (Grace et al., 2021). Clearly, the dearth of up-to-date, quantitative information about the integrity and extent of active dunes in Aotearoa means there is no reliable indication of how, and how far, these ecosystems have diverged from their baseline extent, or their capacity to adequately provide critical conservation and ecosystem service values. Thus, there is a clear need for an up-to-date assessment of

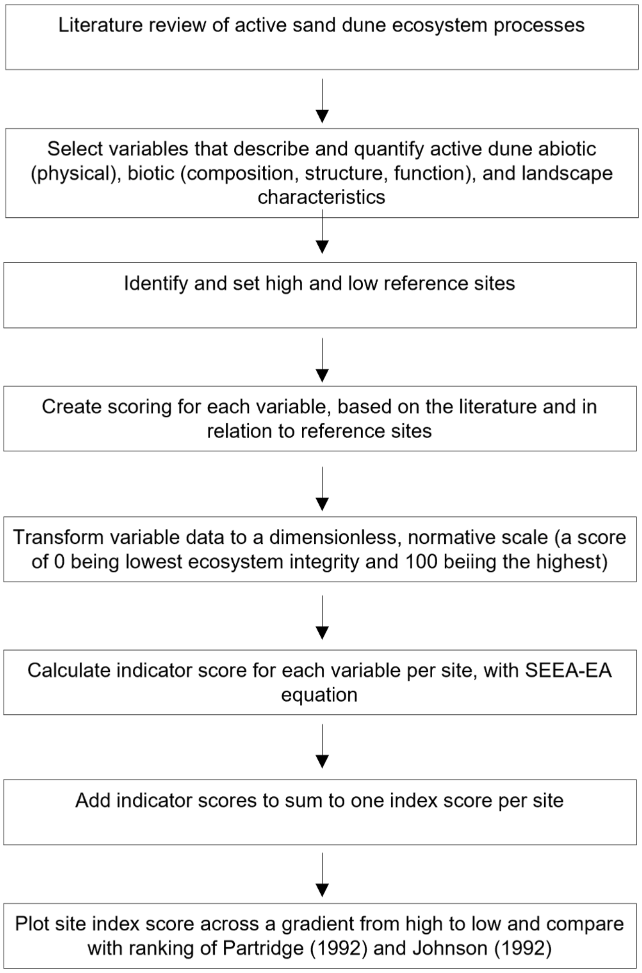

Fig.3. Indicator development process for actives dune ecosystem integrity based on SEEA-EA process (U.N, 2021).

integrity and extent across Aotearoa's active sand dune ecosystems using a standard methodology that incorporates mapped extent and all the characteristics of ecosystem integrity: physical, chemical, biotic (plant community composition, structure and function), and landscape configuration. Moreover, the assessment should be repeatable, to enable comparison of the extent and ecological integrity of dunelands today with future states, and compatible with national and international environmental monitoring frameworks.

The aim of this study is to implement and test the UN SEEA-EA method to assess and rank ecosystem integrity and extent, using active dune systems in Aotearoa as a case study. Specifically, this study: (1) Assesses the change in areal extent of a representative sample of active sand dunes since the first mapped inventory (2) Identifies indicators and a method to assess and compare and rank active dune ecosystem integrity.

2. Methods

2.1. Estimating the change in areal extent of active dunes

A representative sample of active dunes was identified by firstly assessing the maximum potential areal extent of active dunes in Aotearoa, then applying a filter of location and condition. Maximum potential extent was defined here as potential areas where active sand dunes could form based on lithology and cover types. This was estimated by following a two-step process adapted from a method used by the New Zealand Department of Conservation to estimate active dune extent in

Table 1
Characteristics, variables and rationale used to assess the ecosystem integrity of active dunes in Aotearoa.

Characteristics and variable description	Scoring rationale	Aotearoa data source
Abiotic characteristics		
Physical: Geomorphic alignment of shoreline	Greater exposure to incoming swell wave energy enables greater transport of sediment for dune building phases in normal weather conditions (Hesp, 2011; Miller et al., 2010).	Coastal Sensitivity Index (Goodhue et al., 2012, for NZ National Institute of Water and Air (NIWA))
Physical: Number of extreme wave events (greater than 4 m and longer than 12 h).	Greater numbers of days exposed to extreme wave events means more disturbance, sediment transport and restarting of vegetation succession sequences. This creates the characteristic early-stage vegetation of active dunes (Hesp, 2011; Miller et al. 2010; Pegman & Rapson, 2005).	Extreme wave events (Gorman, 2016, for the NZ Ministry for the Environment, MfE)
Chemical	Data deficient at scale of active dunes. However, organic carbon and pH are strongly linked to biotic value and can serve as a proxy here.	Newsome et al. (2008).
Biotic characteristics		
Composition: Proportion of native species to exotic plant species	Greater proportion of native species represents lower ecological degradation (Lee et al., 2005).	National datasets for plant community composition of active dunes are deficient in Aotearoa but can be gathered from site specific data in the grey literature, consultancy reports and peer reviewed papers and datasets (Appendix Table A1).
Vegetation structure: Presence of exotic woody species	The presence of exotic woody species is interpreted here as an increase in biomass at a site, since sites of high ecosystem integrity will have no or very few native woody species, therefore the presence of exotic woody species is used as a proxy for increased biomass given the lack data about cover type or density at the requisite scale. Woody species represent a change in ecosystem structure from a mobile to more stable state with less geomorphic and ecological diversity (Maun, 2009; Nordstrom, 2008; Walker et al., 2013 Pegman & Rapson, 2005)	
Function (characteristic flora): Presence of remnant and/or planted populations of native sand binders (treated as two separate indicators).	Native pīngao and spinifex populations increase ecological diversity and resilience (Hesp, 2000; Nordstrom, 2008; Walker et al., 2013). Remnant populations of native species provide genetic diversity and resilience (Eriksson, 2000; Hoban et al., 2021; Polley et al.,	

(*continued on next page*)

Table 1 (*continued*)

Characteristics and variable description	Scoring rationale	Aotearoa data source
	2005; United Nations, 2021)	
Landscape characteristics		
Fragmentation: Distance from roads	Road networks can cause habitat fragmentation and loss (Bennett, 2017; Gao et al., 2020). Increasing distance from road networks reduces negative impacts on ecosystems (Bennett, 2017; Benítez-López et al., 2010).	Land Information New Zealand (2021). NZ Roads Addressing

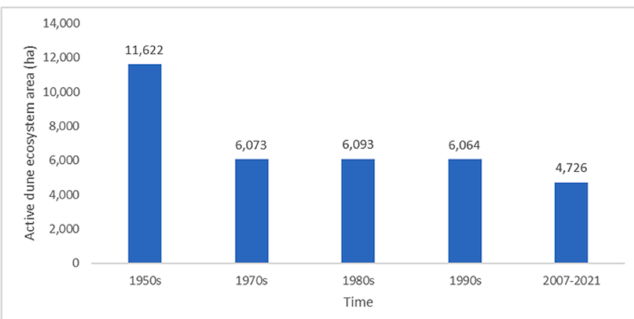

Fig. 4. Total estimated active sand dune ecosystem extent in hectares for all sample sites in this study over the last 70 years, excluding Mangangu Stream Beach and Ōrewa Beach, which were not mapped by Hilton et al. (2000). Sample sites were identified from polygon map datasets by Hilton et al. (2000), and ecosystem extent was calculated per site using ArcGIS Pro v. 2.8 (Esri, 2020) and summed for the 1950s, 70s, 80s, and 90s. Extent for sites 2007 – 2021 was identified and hand digitised in ArcGIS Pro, v. 2.8 (Esri, 2020) from aerial imagery, comprising the most recent and publicly available, high resolution, orthorectified aerial imagery from Land Information New Zealand (LINZ) Data Service under a Creative Commons open licence (CC BY 4.0). Snapshot imagery was taken by local and regional councils over the period 2007–2021 and comprised red, green and blue colour bands. The original resolution ranged from 0.075 m to 7.5 m and came in New Zealand Transverse Mercator projection. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2008 (Burlace, D. and Brown, D., personal communication, 2020). First, surface lithology types on which active dunes could potentially form were identified from a classification provided as part of the New Zealand Land Resource Inventory (LRI) third edition dataset (Newsome et al., 1987; Newsome et al. 2008, Appendix A1). This polygon dataset delineates physiographic areas of relatively homogenous surface and near-surface lithology (Newsome et al., 2008) and is derived from stereo aerial photograph interpretation, field verification and measurement at the 1:50,000 scale carried out over the 1970s and 1980s (Newsome et al., 2008). Lithology types identified as potentially forming active dunes were: 'Wind blown sand', 'Unconsolidated sand', 'Estuary', 'River', 'Alluvium' and 'Towns'. The lithology type 'Towns', which often occur on duneland at the coast, was included so that the impact of towns on the natural processes of active dunes could be quantified and recorded.

Second, selected lithologies were overlaid in ArcGIS Pro, verison 2.8 (Esri Inc, 2020), with land cover types that could also potentially form active dunes from the New Zealand Land Cover Database v 5.0 (Landcare Research/Manaaki Whenua, 2020), which is a 1: 50,000 scale digital map and multi-temporal thematic classification of Aotearoa's land cover derived from satellite imagery (Appendix A2). Land cover types that were identified as potentially forming active dunes were: 'Coastal Sand and Gravel', 'Herbaceous Saline Vegetation', 'Low Producing Grassland' and 'Urban Parkland/Open Space'. The cover type 'Urban Parkland/Open Space', which often occurs on duneland at the coast was also included because it is useful to assess the impact of this cover type on active dune processes.

To identify areas where both suitable lithology types and land cover types occurred, as well as the 'Towns' and 'Urban Parkland/Open Space' areas that were likely to occur on active dunes, the layers of suitable lithology and cover types were overlaid with the most recent digitised extent of active dunes by Hilton et al. (2000). It is important to note that this inventory of 'active' dunes' is therefore ~30 years old, and may not truly reflect current (2023) conditions. The Hilton et al. (2000) layers were derived from 1990s aerial photography, at a scale of between 1:10,000 and 1:63,000. This overlay result offers a coarse approximation of maximum potential sand dune extent, returning a total area of 50,938 ha on the mainland islands and Rakiura/Stewart Island (Fig. 1). An overlap of more than 15% between the selected landcover (Manaaki Whenua/Landcare Research, 2020) and lithology types (Newsome et al., 2008) and the 1990s mapped extent of active dunes was taken as a strong indication that the dune system still existed but may have been modified by natural or human processes (Burlace, D., Brown, D. personal communication, 2021).

2.2. Site selection

Sites from the maximum potential extent were stratified by the two main coastlines (east and west), and then by different levels of condition from the most recent national survey of active dune condition (Johnson, 1992; Partridge, 1992) in three steps. The first step was to filter the Partridge (1992) and Johnson (1992) sites (n = 606) based on their condition scores, into three groups for each of the 25 regions used in their study: Highest, mid - range (based on the median, not the mean) and lowest, but where these sites also had sandy substrate, and where characteristic, native sand binding species pīngao and/or spinifex were present on the highest and mid - range scoring sites; these species were rarely recorded as occurring on the lowest scoring sites. This provided a total of 75 locations for further consideration as study sites. Second, the filtered sites were plotted on a map including geographic coordinates of sand dunes given in Johnson (1992) and Partridge (1992). Where the 75 sites occurred on an area that was also part of the maximum potential extent, it was assumed that these sites still existed and, therefore, they were retained on the list (n = 18). The eighteen sites retained occurred on both the east and west coasts, and four more sites were added from the Auckland Region due to availability of additional imagery, totalling 22 sites that were used for the analysis presented in this paper (Fig. 2).

Finally, the ecosystem extent of the 22 selected sites was visually identified from aerial imagery and hand mapped in ArcGIS Pro, verison 2.8 (Esri Inc, 2020). Aerial imagery comprised the most recent and publicly available, high resolution, orthorectified aerial imagery covering sample sites, and was acquired from Land Information New Zealand (LINZ) Data Service under a Creative Commons open licence (CC BY 4.0). Snapshot imagery was taken by local and regional councils over the period 2007–2021 and comprised red, green and blue colour bands. The original resolution ranged from 0.075 m to 7.5 m and came in New Zealand Transverse Mercator projection.

2.3. Indicator development process to assess variation in ecosystem integrity

Indicators for ecosystem integrity were developed following the process described in the United Nations' SEEA-EA framework (Fig. 3; United Nations, 2021): Seven characteristics of active dune ecological processes were identified from the literature, incorporating abiotic (physical), biotic (composition, structure, function), and landscape characteristics (Table 1) and following SEEA-EA guidelines (Czúcz et al.,

Table 2
Change in ecosystem extent for sampled sites, 1950s-2021. Area (ha) was derived from hand digitised maps from aerial imagery in different decades. DD indicates a lack of data for that site (data deficient).

	Data from Hilton et al. (2000)				Hand drawn (this research)	
Beach	1950s area (ha)	1970s area (ha)	1980s area (ha)	1990s area (ha)	2007/2021 area (ha)	% change since 1950 s
Muriwai Beach	2798	779	779	779	137	−95
Pakiri Beach	1703	241	241	241	88	−95
Waikouaiti Beach	80	37	37	31	17	−78
Cable Bay	3	3	3	3	1	−76
Himatangi Beach	3648	1476	1476	1477	919	−75
Paraparaumu Beach	73	73	94	94	21	−72
Otaki Beach	49	14	14	14	15	−70
New Brighton	200	48	48	48	73	−64
St Kilda and St Clair Beaches	13	13	13	13	5	−62
Rarawa Beach	47	47	47	47	20	−58
Otama Beach	17	18	18	18	12	−28
Spirits Bay	100	100	100	100	76	−24
Smoky Beach	62	62	62	51	50	−18
Scott Point to Waikoropupunoa Stream	1895	1894	1894	1880	1929	2
Tāwharanui	25	25	25	25	25	0
Coal River	14	14	14	14	16	14
Ponaki Beach	152	152	152	152	181	19
Kaitorete Spit	535	535	535	535	682	28
Whatipu Beach	200	499	499	499	414	107
Ōhope Beach*	DD	32	32	32	37	DD
Mangangu Stream Beach	DD	DD	DD	DD	11	DD
Ōrewa Beach	DD	DD	DD	DD	2	DD
Total area (ha)	**11,619**	**6073**	**6093**	**6064**	**4739**	**−59**

*Data for Ōhope Beach in the 1950s was not used because not all of the active area was mapped at that time. This discrepancy meant that, at this site, the change in extent between the 1960 s and 2007–2021 was an increase of 17%.

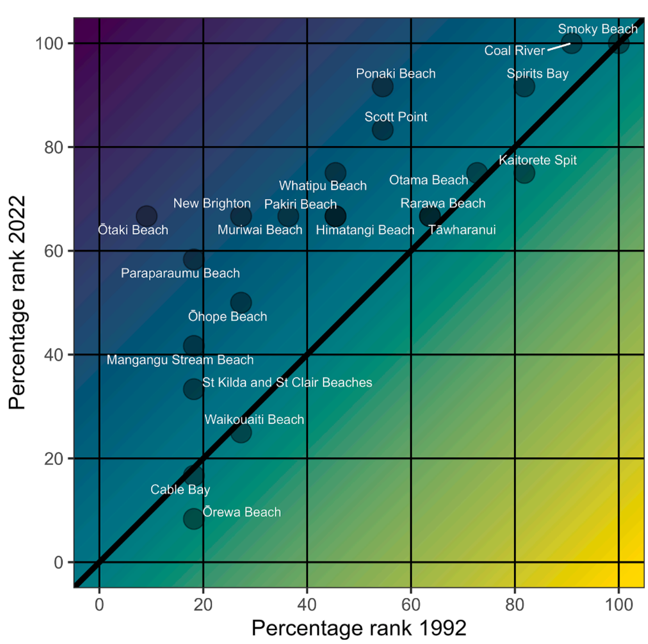

Fig. 5. Comparison of two gradients of active dune ecosystem integrity using 22 selected active sand dune sites selected to represent a range of active dune condition and geographic representation of sites around Aotearoa. The thick, black line is the 1:1 relationship; points above this line were ranked relatively higher on the new gradient presented in this paper compared to the ranking by Johnson (1992) and Partridge (1992). The background colour scale represents the relative degree of match (teal) or mismatch, as either improved rank over time (blue) or decreased rank over time (yellow). Two pairs of points completely overlap: Rarawa Beach and Tāwharanui, and Himatangi Beach and Pakiri Beach. 'Scott Point' represents the site 'Scott Point to Waikoropupunoa Stream'. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2021; United Nations, 2021). Specific variables that quantified these characteristics were selected and scoring rationale for each variable was compiled based on information gleaned from peer reviewed and grey literature regarding how ecosystem integrity was putatively related to changing levels of each variable (Table 1 and Table S2). Variable data were then transformed into a common, dimensionless scale by allocating a score along a scale of zero to 100%, with 100% representing with the highest ecosystem integrity. Reference sites were identified and set from the 22 sample sites. The purpose of these sites was to reflect the highest and lowest quality active duneland sites and provide normative data to compare other sites against. The top scoring site from Partridge (1992) and Johnson (1992) was Smoky Beach on Rakiura, Stewart Island. Smoky Beach was selected to use as the highest quality reference site since it remains largely unmodified since the last survey in 1987 (Department of Conservation, 2012; Hilton and Konlechner, 2021). However, the bottom scoring site from 1992, Ōtaki Beach, had improved due to natural accretion and restoration activities (Todd et al., 2022), so the next lowest scoring site (Ōrewa Beach) was assessed and used as the low reference site. This site was selected due to ongoing erosion from natural processes, relatively sheltered geomorphology, extensive modification from sand mining, extensive sea defences, residential development and lack of established native vegetation over much of the beach (Mead et al., 2009; Roberts et al., 2020). Transformed data were then converted to ecosystem indicators calculated by a linear transformation function using the formula:

$$I = (V - VL)/(VH - VL),$$

where I is the value of the indicator, V is the value of the variable, VH is the high integrity score and VL is the low integrity score (United Nations, 2021). Note that the VH score is required to be higher than the VL score. Indicator scores for each characteristic are then summed to give one score per site, which allows for comparison between sites (see Supplementary, Table S1 for a worked example). Finally, site index scores were converted to a percent rank and plotted on a gradient from low to high and compared with the percent score ranking of Partridge (1992) and Johnson (1992).

The process was then iterated to ensure balance between abiotic,

Fig.6. Selection of sites and their ranking (high, mid - range or low) from the new 2022 ranking (this study). From left to right and top to bottom: a.) Smoky Beach, high (Alistair Hay); b.) Spirits Bay, high (Thomas Buckley), c.) Pakiri Beach, mid - range (Cate Ryan), d.) Whatipu Beach, mid - range (Graham Hinchliffe), e.). New Brighton, low (Cate Ryan), f.). Ōrewa Beach, low (Graham Hinchliffe – unpublished data).

biotic and landscape characteristics, yet remain sensitive to environmental changes. For example, iterations of functional characteristics tested the sensitivity of different treatments of the two main species of sand binders, pīngao and spinifex. Initially, the presence or absence of pīngao and spinifex were treated separately, however, because there is a latitudinal limit to spinifex distribution (Coastal Restoration Trust NZ, 2011), the gradient was loaded in favour of functional state characteristics, given pīngao has a nationwide extent. Therefore, both species were then incorporated under one indicator. This indicator was then further refined to reflect the importance of remnant populations of these two species, as remnants (i.e., un-planted sites) have more value due to their genetic diversity and resilience (Eriksson, 2000; Hoban et al., 2021; Polley et al., 2005; United Nations, 2021). The final variable included a scenario where, if only remnant populations occurred at a site, it was scored equally with planted populations to ensure remnant populations did not falsely score poorly or with null values due to divisions by zero, should no planted populations occur at the *VH* reference site.

3. Results

3.1. Change in extent of active dunes in Aotearoa

The combined total extent for the 22 sample beaches (i.e., the extent of active dune ecosystems) reduced by 59% between the 1950s and 2021. Eighty percent of this reduction occurred between the 1950s and 1970s - equating to 52% of the 1950s area (Fig. 4). Over the 1970s, 80s and 90s, active dune extent remained largely constant, but then decreased a further 20% of the1950s area, between the 1990s and the current assessment (Fig. 4). The average annual rate of decline in active dune ecosystem extent since the 1950s is 85 ha per year.

Of the 22 active sand dune sites, 14 individual sites had decreased in extent between 1950 and 2021, seven had increased, and three were data deficient (Table 2). On average, individual sites decreased by 33% between the 1950s and 2021.The largest decreases were at Muriwai Beach and Pakiri Beach (95%) and the largest increase was at Whatipu Beach (107%).

3.2. Gradient of active dune ecosystem integrity

Most sites (n = 17) had relatively higher rankings on the new gradient compared to the Johnson and Partridge gradient. Differences in rank between the two gradients represents change in the status of sites over time and / or the difference between the two ranking systems. Better condition sites with high rankings on both gradients were more similar in their rankings (Figs. 5 and 6). At the lower end of the Partridge (1992) and Johnson (1992) gradient, there was little distinction among sites; in contrast, these same sites were well distinguished on the new gradient (Figs. 5 and 6). Conversely, sites with mid - range scores, between 60 and 80 percent rank on the 2022 gradient, were spread across a wider range of values on the 1992 gradient (Figs. 5 and 6).

4. Discussion

Using a case study of active sand dunes in Aotearoa, the UN SEEA-EA method has been successfully implemented and tested to create a

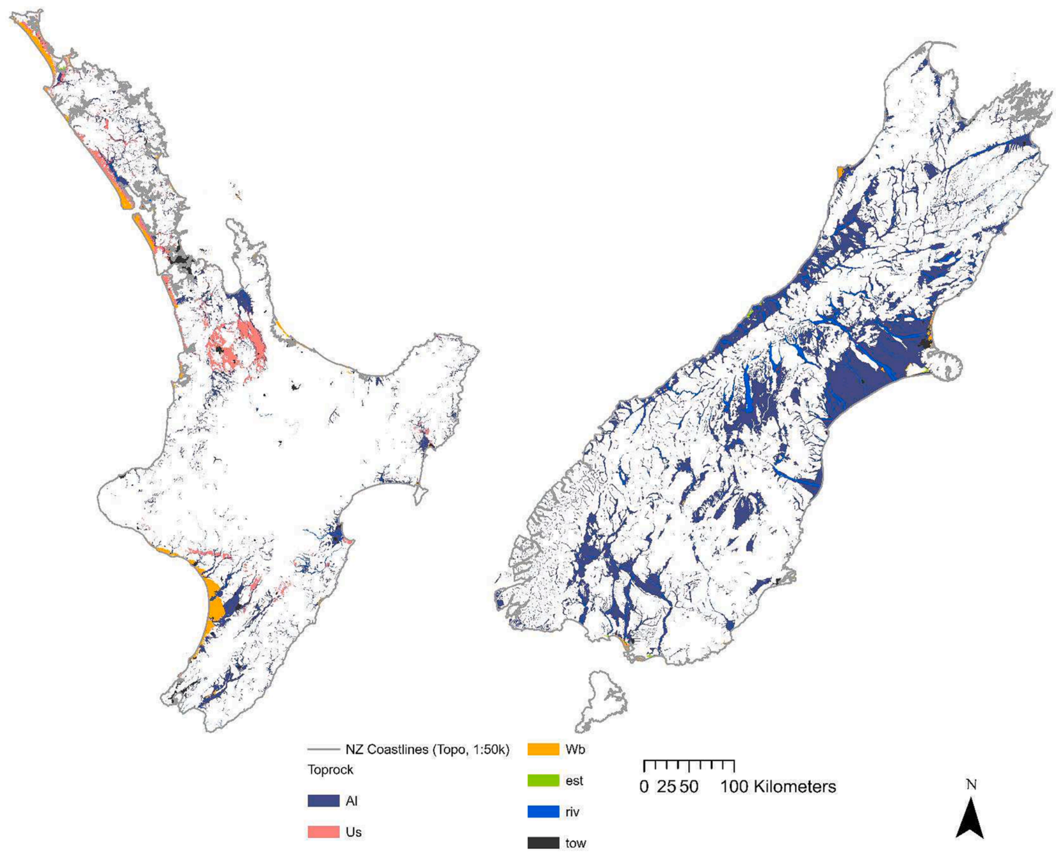

Fig. A1. Selected LRI surface lithology types that could potentially form active dunes, from the New Zealand Land Resource Inventory, third edition (Newsome et al., 1987; Newsome et al. 2008). Types include: 'Wb' = Wind blown sand, 'Us' = Unconsolidated sand, 'est' = Estuary, 'riv' = River, 'tow' = Town, 'Al' = Aluvium.

narrative of the state of ecosystem integrity nationally. Given the ubiquity of the drivers of active dune condition globally, it is possible the method could also be successfully used on active sand dune ecosystems in other countries. Our research shows that dune extent in Aotearoa continues to decline, in line with trends globally (Gao et al., 2020; Jackson et al., 2019). The new factors incorporated to assess ecosystem integrity correctly identify sites at the high end of the gradient, produces finer scale scoring for sites at the lower end of the gradient, but mid-range sites are less well distinguished. Reasons for discrepancies in results with previous studies are most likely due to the long interval between surveys, given active sand dunes are dynamic systems subject to both natural processes and human impacts. Despite data gaps and constraints (described in the next sections), the assessment of ecosystem extent and this gradient of ecosystem integrity is both feasible and highly useful in building a narrative on the state of active sand dunes in Aotearoa, which can be of use for coastal management. Moreover, the method can be repeated to show how these systems are changing.

Our estimated decline of 59% of active dune extent between the 1950s and 2021 differs to Hilton et al. (2000), who put the historical decline at 70% nationwide between the 1950s and the 1990s. Holdaway et al. (2012) put it at 50–80% since the 1750s (based on Hilton et al. 2000), and Stats New Zealand put the decline at 80.5% between the 1950s and 2008 (Stats New Zealand, 2015). The differing timescales between the studies is likely to be an important reason for the discrepancies, since the Hilton dataset would have been collected more than 20 years ago, and the Stats New Zealand dataset at least 14 years ago. Given active sand dunes are highly dynamic systems, we can expect significant variation in extent over time due to natural processes and human impacts. For example, extent at Muriwai Beach has decreased significantly since Hilton et al. (2000) recorded 779 ha in 1990, compared to the 137 ha in this study. Over that time there has been a natural reduction in sediment supply and erosion on this stretch of coast (McKelvey, 1999; Boyle, 2016) as well as extensive planting to stabilise the dunes with marram and the growing of Monterey Pine (*Pinus radiata* D. Don) as a commercial crop (McKelvey, 1999). Our estimated decline of 59% in Aotearoa's active dunelands is equivalent to a status of an 'Endangered Ecosystem' in the IUCN Red List Ecosystem Risk Assessment framework (IUCN, 2016), which concurs with the status given by Holdaway et al. (2012).

Different methods may also have a bearing on results; both Hilton et al. (2000) and the Stats NZ survey used spatially explicit methods to estimate extent compared to the representative sample used in this study. However, direct comparison is difficult since different approaches were used; Stats NZ analysed large scale GIS datasets and satellite imagery, whereas Hilton et al. (2000) hand mapped sites from aerial imagery, as in this study, albeit in the 1990s.

The new gradient of ecosystem integrity tended towards higher scores compared to the 1992 ranking; most sites (n = 17) scored higher (Fig. 5). This could be explained by the method used to generate the ranking comparison and ecological changes at the sites over time. The Partridge (1992) and Johnson (1992) sites were selected for this study using a stratified sample of high, mid - range and low scoring sites, and because many of the sites had the same score, when new scoring criteria was applied many sites were differentiated, this was especially true for the lower scoring 1992 sites. Ecological changes, caused by either natural or human processes, could further distinguish the sites. For example, Ōrewa, Cable Bay, St Kilda and St Clair Beaches, Paraparaumu Beach and Mangangu Stream Beach all scored equally in the 1992 rank, resulting in these sites occurring just below 20% on the 1992 *x*-axis, but these sites had a much wider spread on the corresponding 2022 *y*-axis (Fig. 5). These sites all scored very differently from each other across the new indicators for abiotic (physical: disturbance) and biotic (function:

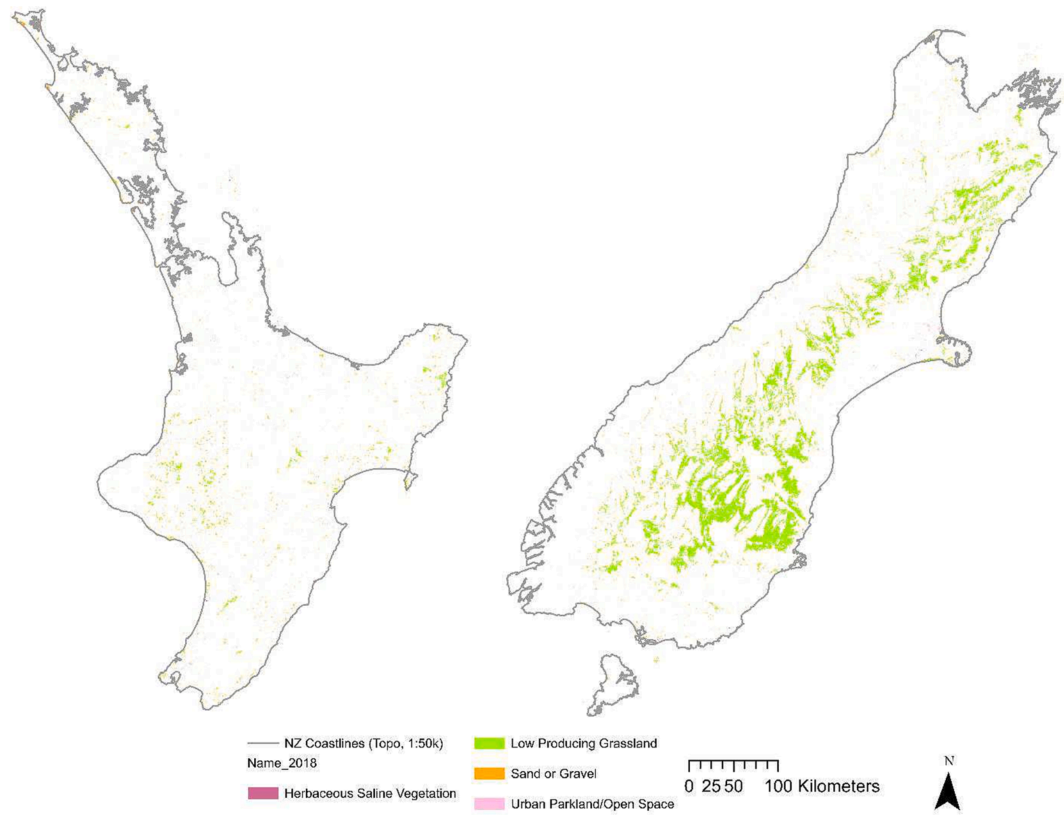

Fig. A2. Selected land cover types that could potentially form active dunes, from the New Zealand Land Cover Database v.5.0 (Landcare Research/Manaaki Whenua, 2020).

planted and remnant sand binders). Conversely, sites with a wide spread of low to mid - range scores on the 1992 axis, such as Himatangi Beach, Muriwai Beach, New Brighton, Ōtaki Beach, Pakiri Beach, Rarawa Beach, and Tāwharanui (Fig. 5), were spread across a narrower range of values in the 2022 gradient (between 60 and 80 percent rank). This result is likely due to these sites having the same score for vegetation structure (exotic woody vegetation) and function (planted and remnant sand binders), reflecting the limited, coarse data available at the requisite scale, whereas continuous, vegetation cover type data at site level could better draw out differences. Sites with high rankings on both gradients, such as Smoky Beach, Coal River and Spirits Bay were more similar in the new gradient (Fig. 5), this is likely due to criteria converging, for example in both gradients top scores go to sites with few or no exotics species and populations of native sand binders. Moreover, these sites, are unlikely to have changed much over time due to human impacts since they are in high conservation protection areas. Overall, the spread of scores in the new gradient suggests the new indicators are effective at identifying high quality sites, drawing out differences between sites at the lower end of the gradient, but it also suggests that data for structure and function characteristics is too coarse to clearly draw out the differences between mid - range sites.

A few sites decreased in score compared to the 1992 gradient. New indicators that had the most influence on these sites included species composition, vegetation structure and distances to the road (fragmentation). For example, Kaitorete Spit scored extremely high on the 1992 gradient but dropped several places on 2022 gradient due to a relatively high proportion of exotics to natives, presence of woody exotics and close proximity to roads. Moreover, the datasets available to use with this new gradient do not include abundance estimates, such as percent cover of characteristic plants, or botanical rarity. These are both likely to have heavily influenced the higher score awarded to Kaitorete Spit by Johnson (1992), since Kaitorete Spit has populations of rare endemic plants (*Carmichaelia appressa* G. Simpson), rare, vegetated dune deflation hollows, and the largest, most continuous population of pīngao in Aotearoa (Johnson, 1992).

The gradient could be refined since disparate datasets were aligned and overlayed in this research, but gaps in the data remain. A better understanding of the contribution of different species to ecosystem structure and function, and decline in ecosystem processes, can be obtained from estimates of the relative abundance of different vegetation types (Holdaway et al., 2012), through vegetation cover type analysis of remotely sensed imagery. It follows that, spatial patterns of different vegetation types could be identified, related to ecosystem integrity, and monitored for changes at a national scale. Other factors that could be relevant to include are the presence and abundance of characteristic native fauna, such as shore dwelling and nesting birds, lizards and invertebrates; the presence and abundance of rare plants; the presence and abundance of exotic fauna; and a more multi-faceted, finer-scale assessment of human impacts. Mātauranga Māori, or indigenous knowledge and perspectives, are highly relevant in the context of conservation ecology in Aotearoa (Bellingham et al., 2021; Lyver et al., 2018) and globally (IPBES, 2019). The inclusion of pīngao as an indicator, a species important in Māori culture and practices (Hare et al., 2019), can provide a starting point for the development of a cultural assessment of the condition of active dunes that is relevant and meaningful to Māori in Aotearoa (Lyver et al., 2018; Normyle et al., 2022). In addition, the linking and valuing the science of natural processes to human use and impacts is in its infancy in Aotearoa and the rest of world, and validation of assumptions, methods and results are required over a range of spatial and temporal scales.

From a management perspective, an indexed rank of active dune ecosystem integrity and extent is useful to both prioritise areas for conservation protection and monitor sites for direction of dune recovery. In addition, the framework could be used to create a baseline for a joined-up view of active dune ecosystems through indicators, that can be applied to a range of issues such as biodiversity conservation and coastal

Table A1
List of sources from which plant community composition data was compiled.

Data for biotic indicators	
Cable Bay	Shaft, L. (2022). Coastcare Co-ordinator, Northland Regional Council -Te Kaunihera ā rohe o Te Taitokerau (personal correspondence – email, 31/05/2022).
Coal River	Johnson, P. (1992). The Sand Dune and Beach Inventory of News Zealand II. South Island and Stewart Island. pg 61 (Coal River). West, C. J. (n.d). Coal River Beach Weeds (B279). New Zealand Plant Conservation Network. Retrieved October 28th, 2022 from https://www.nzpcn.org.nz/publications/plant-lists/plant-lists-by-region/coal-river-beach-weeds-b279/
Himatangi Beach	Rapson, G.L., Smith, A., Murphy, A.L. (2016). Sand-dune vegetation of the Foxtangi Region, Manawatu Coast, New Zealand. Report to the Department of Conservation by the Ecology Group, Institute of Agriculture and Environment, Massey University, Palmerston North, New Zealand. Retrieved October 28th, 2022 from https://www.massey.ac.nz/massey/expertise/profile.cfm?stref = 361030 Milne, R., Sawyer, J. (2002). Coastal foredune vegetation in Wellington Conservancy, current status and future management. Published by Department of Conservation, Wellington Conservancy. Retrieved October 28th, 2022 from https://www.doc.govt.nz/about-us/science-publications/conservation-publications/native-plants/coastal-foredune-vegetation-in-wellington-conservancy/ Ogle, C.C., (2008). Vegetation and threatened and adventive plants of the Wanganui sand country. Paper presented to the Dune Restoration Trust, March 2008. Coastal Restoration Trust. Retrieved October 28th, 2022 from https://ref.coastalrestorationtrust.org.nz/site/assets/files/5987/weeds_and_indigenous_biodiversity_of_the_fed_northern_half_2008.pdf Manawatu District Council (2019). Coastal Reserves Management Plan. Manawatu District Council. Retrieved October 28th, 2022 from mdc.govt.nz/documents/plans/reserve-management-plans
Kaitorete Spit	Tordoni, E., Bacaro, G., Weigelt, P., Cameletti, M., Janssen, J. A. M., Acosta, A. T. R., … Kreft, H. (2021). Disentangling native and alien plant diversity in coastal sand dune ecosystems worldwide. Journal of Vegetation Science, 32 (1). [Dataset for New Zealand component, supplied by Hannah Buckley, collected 2010]. https://doi.org/10.1111/jvs.12961 Hoosen, S. (2017). Site Significance Statement, Kaitorete Spit. SES/E/2. In, Christchurch (N.Z.). City Council. (2017). Christchurch District Plan. [Appendix 9.1.6.1 Schedule of Sites of Ecological Significance, site SES/E/2]. Christchurch, New Zealand: The Council, 2017. Retrieved October 28th, 2022 from https://districtplan.ccc.govt.nz/pages/plan/book.aspx?exhibit = DistrictPlan Hetherington, J., & Bastow Wilson, J. (2014). Spatial associations between invasive tree lupin and populations of two katipo spiders at Kaitorete Spit, New Zealand. New Zealand Journal of Ecology, 38(2), 279–287. Case, B. S., Buckley, H. L., Fake, M., Bryan, S., & Bilkey, J. (2019). Assessing the use of UAV-collected data for characterising the distributions and frequencies of sand dune vegetation cover types at Kaitorete Spit, Canterbury. DOC Research & Development Series 359, 25. Retrieved October 28th, 2022 from https://www.doc.govt.nz/globalassets/documents/science-and-technical/doc-research-and-development-series/drds359entire.pdf Hutchison, M., Patrick, B. (2020). Canterbury Botanical Society report on Kaitorete Spit October field trip. Trilepidea, Newsletter of the New Zealand Plant Conservation Network. No.134, Jan 2015. Retrieved October 28th, 2022 from https://www.researchgate.net/publication/345753083_Canterbury_Botanical_Society_report_on_Kaitorete_Spit_October_field_trip New Zealand National Vegetation Survey Databank (2012). Birdlings Flat Gravel Beach Survey 2012 - Recce inventory (National Vegetation Survey). https://www.nvs.landcareresearch.co.nz.

Table A1 (*continued*)

Data for biotic indicators	
Mangangu Stream Beach	Partridge, T. R. (1992). The sand dune and beach vegetation inventory of New Zealand: 1. North Island. DSIR Land Resources scientific report (Vol. 15). Ryan, C. (2022). [Site visit]
Muriwai Beach	Partridge, T. R. (1992). The sand dune and beach vegetation inventory of New Zealand: 1. North Island. DSIR Land Resources scientific report (Vol. 15). Ryan, C. (2022). [Site visit]
New Brighton	Tordoni, E., Bacaro, G., Weigelt, P., Cameletti, M., Janssen, J. A. M., Acosta, A. T. R., … Kreft, H. (2021). Disentangling native and alien plant diversity in coastal sand dune ecosystems worldwide. Journal of Vegetation Science, 32 (1). [Dataset for New Zealand component, supplied by Hannah Buckley, collected 2010]. https://doi.org/10.1111/jvs.12961 Shadbolt, A. (2014). Site significance statement, Christchurch Coastal Strip, SES/LP/6. In, Christchurch (N. Z.). City Council. (2017). Christchurch District Plan. [Appendix 9.1.6.1 Schedule of Sites of Ecological Significance, site SES/LP/6]. Christchurch, New Zealand: The Council, 2017. Retrieved October 28th, 2022 from https://districtplan.ccc.govt.nz/pages/plan/book.aspx?exhibit = DistrictPlan Ryan, C. (2022). [Site visit]
Ōhope Beach	Wildlands (2008). Bay of Plenty region sand dune vegetation mapping and condition assessment methods for Tauranga Ecological District. Prepared for Environment Bay of Plenty, P.O Box 364, Whakatane. Retrieved October 28th, 2022 from https://cdn.boprc.govt.nz/media/32395/EnvReport-201002-SandDuneVegetationMapping.pdf Bay of Plenty Regional Council (2017). [Duneland Survey data sheets for 2017 and 2008, supplied by Bay of Plenty Regional Council]. Coastcare Bay of Plenty (n.d). Dune Management in Ōhope. Coastcare Bay of Plenty Retrieved October 28th, 2022 from https://cdn.boprc.govt.nz/media/30282/CoastCare-090527-RestorationOhope.pdf Ryan, C. (2022). [Site visit]
Ōrewa Beach	Bishop, C. (2022) [Site visit]
Ōtaki Beach	Tordoni, E., Bacaro, G., Weigelt, P., Cameletti, M., Janssen, J. A. M., Acosta, A. T. R., … Kreft, H. (2021). Disentangling native and alien plant diversity in coastal sand dune ecosystems worldwide. Journal of Vegetation Science, 32 (1). [Dataset for New Zealand component, supplied by Hannah Buckley, collected 2010]. https://doi.org/10.1111/jvs.12961 Milne, R., Sawyer, J. (2002). Coastal foredune vegetation in Wellington Conservancy, current status and future management. Published by Department of Conservation, Wellington Conservancy. Retrieved October 28th, 2022 from https://www.doc.govt.nz/about-us/science-publications/conservation-publications/native-plants/coastal-foredune-vegetation-in-wellington-conservancy/ Waiotahi Stream and Dune Care (n.d). Waiotahi Stream and Dune Care Ōtaki. Retrieved October 28th, 2022 from https://www.waitohudunecare.org/
Otama Beach	Auckland Botanical Society (2005). Field Trip: Coromandel Peninsula, Auckland Anniversary Weekend 28/01/05 to 1/02/05. Auckland Botanical Society. Retrieved October 28th, 2022 from https://bts.nzpcn.org.nz/articles/field-trip-coromandel-peninsula-auckland-anniversary-weekend-28–01-05-to-1–02-05/ Havel, D. (2017). Site assessment, Otama Beach Dunes. Megan Graeme (ecologist, personal communications - phone call, 03/03/2022). Otama Reserves Group (n.d). History of Otama. Retrieved October 28th, 2022 from https://www.otamareservesgroup.co.nz/history-of-otama/ Brown (2011). Coromandel Peninsula Landscape Assessment, draft. [see Landscape Unit 38, Otama Beach]. Prepared for the Thames Coromandel District Council. Retrieved October 28th, 2022 from https://www.tcdc.govt.nz/Global/1_Your%20Council/Council%20Projects/Current%20Projects/District%20Plan%20Review/Introduction.pdf

(*continued on next page*)

Table A1 (*continued*)

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Pakiri Beach	Goldwater, N. (2013). The botanical treasures of Middle Pakiri Beach. Auckland Botanical Society, 2013. Retrieved October 28th, 2022 from https://bts.nzpcn.org.nz/articles/the-botanical-treasures-of-middle-pakiri-beach-farm-pakiri/ Shaft, L. (2022). Coastcare Co-ordinator, Northland Regional Council -Te Kaunihera ā rohe o Te Taitokerau (personal correspondence – email, 6 July 2022).
Paraparaumu Beach	Bergin (2005). Establishment of spinifex planting trial Paraparaumu Beach, Kapiti Coast. CSIRO and SCION, Ensis, Rotorua, New Zealand. Retrieved October 28th, 2022 from https://takutaikapiti.nz/wp-content/uploads/2020/11/Establishment-of-spinifex-planting-trial_Paraparaumu-Beach_Bergin_Ensis_2005.pdf New Zealand National Survey Databank (1991). Foxton Protected Natural Area Programme/National Vegetation Survey 1989 – 91. [Data sheets supplied by Landcare Research/Manaaki Whenua]. https://www.nvs.landcareresearch.co.nz) Kāpiti Coast District Council (n.d). Caring for Sand Dunes in Kāpiti. Retrieved October 28th, 2022 from https://waikawabeach.org.nz/wp-content/uploads/2019/02/1092-kap-dune-posterbrochure-reading-ff2-for-web.pdf
Ponaki Beach (Ngakengo Beach)	Lux, J., Holland, W., Rate, S., Beadel, S. (2009). Natural areas of Te Paki Ecological District: reconnaissance survey report for the Protected Natural Areas Programme, New Zealand Department of Conservation. [Ngakengo Beach, PNAP Survey no. N02/062]. Retrieved October 28th, 2022 from https://www.doc.govt.nz/about-us/science-publications/conservation-publications/land-and-freshwater/land/northland-conservancy-ecological-districts-survey-reports/natural-areas-of-te-paki-ecological-district/
Rarawa Beach	Jane, G., Donaghy, G. (2008). Rarawa Beach dunes (RARW). [plant species list]. New Zealand Plant Conservation Network. Retrieved October 28th, 2022 from https://www.nzpcn.org.nz/publications/plant-lists/plant-lists-by-region/rarawa-beach-dunes-rarw/ Northland Age (2021). Ngataki school kids restore Rarawa Beach dunes with pīngao. NZ Herald. Retrieved October 28th, 2022 from https://www.nzherald.co.nz/northland-age/news/ngataki-school-kids-restore-rarawa-beach-dunes-with-pingao/PWM7D4GMKKUM7ZS6GI77YL5JTY/
Scott Point to Waikoropupunoa Stream	Northland Regional Council (2014). Northland Regional Landscape Assessment. [Unit name - Twilight Beach/ Kahokawa Beach Dunefields, Wetlands and Bush]. Retrieved October 28th, 2022 from https://www.nrc.govt.nz/media/kiwe3v4y/twilightbeachkahokawabeachdunefieldandwetlands.pdf Lux, J., Holland, W., Rate, S., Beadel, S. (2009). Natural areas of Te Paki Ecological District: reconnaissance survey report for the Protected Natural Areas Programme, New Zealand Department of Conservation. Retrieved October 28th, 2022 from https://www.doc.govt.nz/about-us/science-publications/conservation-publications/land-and-freshwater/land/northland-conservancy-ecological-districts-survey-reports/natural-areas-of-te-paki-ecological-district/ Partridge, T. R. (1992). The sand dune and beach vegetation inventory of New Zealand: 1. North Island. DSIR Land Resources scientific report (Vol. 15).
Smoky Beach	Johnson, P. (1992). The Sand Dune and Beach Inventory of News Zealand II. South Island and Stewart Island. pg 61, Coal River. Rance, B. (personal communication, email, 25/03/2022) Department of Conservation (2012). Stewart Island/ Rakiura Conservation Management Strategy and Rakiura National Park Management Plan (pp. 1–316). New Zealand Department of Conservation. Retrieved October 28th, 2022 from https://www.doc.govt.nz/about-us/our-policies-and-plans/statutory-plans/statutory-plan-publications/conservation-management-strategies/stewart-island-rakiura/ Hilton, H., Konlechner, T. (2021). The Rakiura Dune Restoration Programme (1999–2021). Lessons Learned from 21 Years of Operations, Monitoring & Research. School of Geography, University of Otago, PO Box 56, Dunedin, New Zealand.
Spirits Bay	Lux, J., Holland, W., Rate, S., Beadel, S. (2009). Natural areas of Te Paki Ecological District: reconnaissance survey report for the Protected Natural Areas Programme, New Zealand Department of Conservation. [Site name Kapowairua, Survey no. N02/027]. Retrieved October 28th, 2022 from https://www.doc.govt.nz/about-us/science-publications/conservation-publications/land-and-freshwater/land/northland-conservancy-ecological-districts-survey-reports/natural-areas-of-te-paki-ecological-district/
St Kilda and Clair Beaches	Johnson, P. (1992). The Sand Dune and Beach Inventory of News Zealand II. South Island and Stewart Island.
Tāwharanui	Ryan, C. (2022). [Site visit] reviewed by Bishop, C. Tawharanui Open Sanctuary (n.d). What we do [revegetation]. Retrieved October 28th, 2022 from https://www.tossi.org.nz/?page_id = 73
Waikouaiti Beach	Johnson, P. (1992). The Sand Dune and Beach Inventory of News Zealand II. South Island and Stewart Island.
Whatipu Beach	Auckland Botanical Society (2013). A Visit to the Whatipu Sands, West Auckland. Auckland Botanical Society. Retrieved October 28th, 2022 from https://bts.nzpcn.org.nz/articles/a-visit-to-the-whatipu-sands-west-auckland/ Cameron, 1989: Vegetation of the Whatipu Sands, north Manukau Heads. Auckland Botanical Society Journal 44: 3–10. Retrieved October 28th, 2022 from https://bts.nzpcn.org.nz/articles/vegetation-of-the-whatipu-sands-north-manukau-heads/ Pegman, A.P. McK., Rapson, G.L. 2005: Plant succession and dune dynamics on actively prograding dunes, Whatipu Beach, northern New Zealand. New Zealand Journal of Botany 43: 223–24

hazard management. Due to the similarities between active dune system drivers globally (Gao et al., 2020; Jackson et al., 2019), and the ability to select characteristics to suit different contexts, this framework can be translated to active dune ecosystems around the world. Moreover, since it is grounded in the ecosystem integrity concept it is broadly compatible with national and international frameworks, such as the New Zealand Department of Conservation Biodiversity Assessment Framework (McGlone et al, 2020; Lee et al., 2005), the UN SEEA-EA accounts, Essential Biodiversity Variables, draft Goal A of the Post – 2020 Global Biodiversity Framework, and the Sustainable Development Goals (United Nations, 2021).

Long-term or nationally representative surveys of active dune extent and condition are rare globally (Schlacher et al., 2008; Holdaway et al., 2012). Our new gradient is the first since the 1990s to assess ecosystem extent and integrity at a site and national level. It has built on previous studies and improves our understanding of active dunes in Aotearoa. The challenges identified reflect those identified in similar studies attempting to implement the SEEA-EA and other frameworks that assess ecosystem extent and integrity around the world, namely, data gaps and lack of sufficiently regular temporal or spatial data (Holdaway et al., 2012; Farrell et al., 2021). Nonetheless, we conclude that this first attempt provides an important stepping stone in the development of an effective, globally relevant monitoring framework specific to active sand dunes, with ecosystem integrity at the core of its purpose. Our methods are repeatable, and the new gradient can be continued to be refined and improved over time with the incorporation of new data.

CRediT authorship contribution statement

Cate Ryan: Conceptualization, Data curation, Formal analysis, Methodology, Validation, Visualization, Writing – original draft, Editing. **Bradley S. Case:** Conceptualization, Funding acquisition, Methodology, Supervision, Validation, Reviewing. **Craig D. Bishop:** Conceptualization, Methodology, Supervision, Validation, Reviewing.

Hannah L. Buckley: Conceptualization, Funding acquisition, Methodology, Supervision, Validation, Visualization, Reviewing and editing.

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.

Data availability

Data will be made available on request.

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Appendix A

Fig. A1. Fig. A2.
Table 3.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2023.110172.

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