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Extending the DPSIR framework to analyse Driver-Pressure-State-Impact-Response of sand dune management in Manawatu-Whanganui (New Zealand) since the 19th century

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A R T I C L E I N F O

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A B S T R A C T

Coastal sand dunes are multifunctional landscapes with rich biodiversity. In New Zealand, with the establishment of European settlement around 1840, dunes in the Manawatu-Whanganui region were affected due to the removal of their vegetation cover by human activities and animal grazing. As a result, sand drifted further inland affecting villages, infrastructure and agricultural areas. The main response was to introduce marram grass (*Ammophila arenaria*) used in Europe to stabilize dunes. This solution caused significant environmental impacts as marram grass turned invasive and native habitats of fauna and flora significantly decreased.

This paper focused on the long-term analysis of aspects related to sand dune management in the region during two-time frames: 1) from the 19th to the late 20th century and 2) from then on to the early 21st century, using the innovative spiral DPSIR (Driver-Pressure-State-Impact-Response) framework. Data for this study comes from historical records, scientific literature and present management reports.

The integrated spiral framework allows for establishing the connections between historical and future management initiatives for mitigating and adapting to environmental impacts due to socio-economic drivers and their pressures. The study reinforces the paradigm shift from dune stabilization before the late 20th century to the restoration of stabilized dunes to make them active for enhancing native biodiversity should be again assessed in the context of sea-level rise during this century. Coastal managers should adopt an optimized solution between these two extreme solutions adopted from the 19th century to the present, by considering long-term and interdisciplinary analysis to better understand the systems' evolution and the full consequences of human actions.

1. Introduction

Coastal sand dune migration was viewed as an environmental issue affecting settlements and infrastructure, a problem that occurred for centuries in different places. The policy-makers and scientists focused on sustainable sand dune management as part of integrated coastal zone management. The socioeconomic and environmental sustainability goals are assessed using different kinds of methods including the Drivers-Pressures-States-Impacts-Responses (DPSIR) framework. The DPSIR framework was proposed by the European Environmental Agency (EEA, 1999) as an integrated environmental assessment tool for decision-making to achieve sustainable development (OECD, 2003). Years before, the Organization of Economic Cooperation and Development (OECD, 1993) had established the Stress-Response (SR) framework, which was also used by the United Nations Environmental Program (UNEP 1994). The SR approach was extended as the Pressure-State-Response (PSR) framework by the EEA and the European Statistical Office (1999). As a further extended version of the SR and PSR approaches, the DPSIR framework conceptualizes the cause-and-effect relationships among diagnostic variables, identifying the connections between the environment and various anthropogenic activities (Song and Frostell, 2012).

Abbreviations: DPSIR, (Driver-Pressure-State-Impact-Response).

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1.1. Definition of the components of the DPSIR framework

According to Borja et al. (2006) and Song and Frostell (2012), drivers are the human activities that cause environmental pressures. State indicates a qualitative or quantitative measure of the present situation of the environment or else, environmental parameters that can change due to the pressures. Changes in the state parameters can generate socio-economic and environmental losses, which are termed impacts. The responses represent the societal actions aimed at minimizing or eliminating those losses. Gari et al. (2015) and Semeoshenkova et al. (2017) also give similar definitions for each component of the DPSIR framework. Accordingly, drivers are functions through social, demographic and economic developments in societies and associated human activities that exert pressures on the system. Pressures affect the State of the environment and the state reflects the changes in the environment and shows the level and trends of degradation. It is related to the status of the environment and ecosystem that determines the ability to support demands placed on it and to deliver sustainable ecosystem services to humans. Impacts are the changes in the quality and functioning of the ecosystem that have an impact on the welfare or well-being of humans and society. The response is the management measures to prevent, compensate, or adapt to changes in the environment by seeking to 1) control drivers or pressures through regulation, prevention or mitigation; 2) directly maintain or restore the state of the environment; or 3) deliberately "do nothing". Elliott et al. (2017), extended the DPSIR framework to a DAPSI(W)R(M) in which a new component (Activities) was introduced. Drivers of basic human needs require Activities that lead to Pressures; the Pressures are the mechanisms of State change in the natural systems, which cause Impacts (on human Welfare) that require Responses (as Measures). In this definition, there is a differentiation between human or societal needs and human activities.

1.2. Improving the DPSIR framework for long-term management purposes

Analysing each indicator of the DPSIR framework for several periods is important for long-term management planning. The classical DPSIR framework shows the links from the Response to Drivers, Pressures, State and Impacts. However, if the DPSIR framework is applied for analysing a long-term problem, such links do not represent correctly because such response may not result in the same drivers, pressures, states or impacts. In a different period, a particular response may result in new drivers, pressures, states and impacts. Therefore, for the next period, the possible links of management responses to the other four components should be represented with a new cycle but connected to the previous response. Thus, it can be represented in a new spiral DPSIR framework. Such an integrated framework represents the continuous influence of the previous and new components of a DPSIR analysis. Thus, the objective of this paper is to establish this innovative framework in terms of a case study of the sand dune management in the Manawatu-Whanganui region, in New Zealand from the 19th to the second decade of the 21st century.

2. Study Area

The sandy littoral is an important geomorphologic feature of the Manawatu-Whanganui region (Fig. 1), in particular, due to its continuous low-lying plains with extensive dune fields. The Manawatu dune field, extending from Patea to Paekakariki, is the largest in the country (Hesp, 2001). The geomorphology of the region is characterized by aggrading flood plains (Clement et al., 2010), incised valleys, estuaries, and prograding coastal segments with transgressive or parabolic dune fields (Hesp, 2001). The sand can be blown over 3 km inland (Esler, 1970). Wind data for Ohakea Air Base shows that West to North-West winds account for about 50% of frequencies and are stronger in the spring-summer (Esler, 1970). The average wind speed is 17 km/h and gusty winds can have 96 km/h and may sustain for over 6 days (NZMS, 1983). The west coast and the Manawatu region are one of the three main areas that have been affected by wind erosion in the North Island due to poor vegetation cover and degraded soils due to continuous maize cropping (Basher and Painter, 1997; Sparling et al., 2000).

As shown in Fig. 2, the Manawatu region is subject to a temperate maritime climate, with rainfall increasing from 800 mm at the coast to more than 5000 mm along with the inland ranges (Clement et al., 2010) without any significant seasonal variability (Heerdegen and Shepherd, 1992). The annual rainfall in Himatangi Beach, which is the driest area, is 812 mm and it is less than 76 mm in the windy months from October to December (see Fig. 2c and d) (Esler, 1970; Chappell, 2015).

The mean wave height in Whanganui is 1.2 m and the storm wave height is 3.2 m. Wave means periods are 7.8 s (SHAND et al., 1999). As the wind angle at the Wanganui coast varies from 20 to 43° (SHAND et al., 1999), the westerly swell approaches the coast at an oblique angle resulting in a southward moving long-shore drift (Clement et al., 2010).

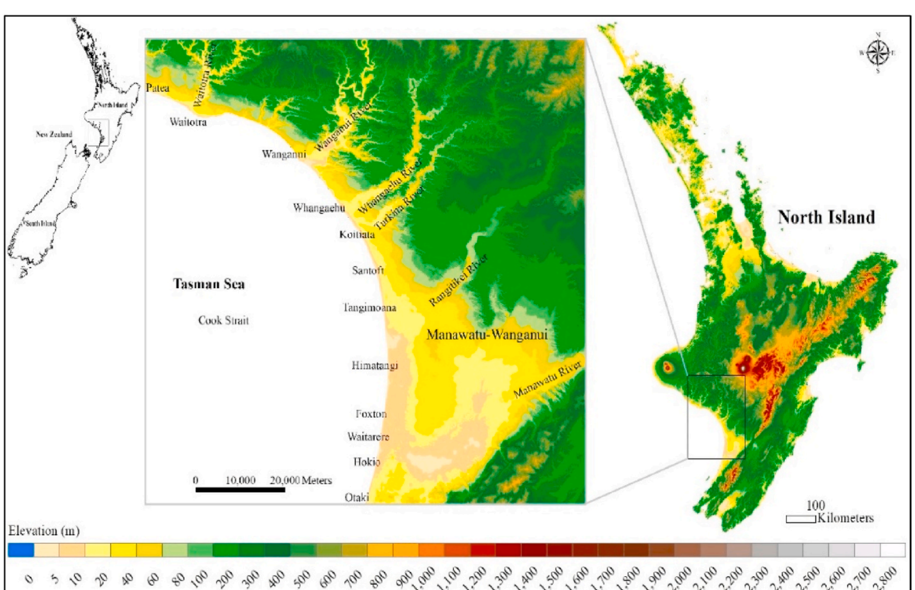

Fig. 1. Study area: A digital elevation model of the North Island and the Manawatu-Whanganui dune fields in New Zealand.

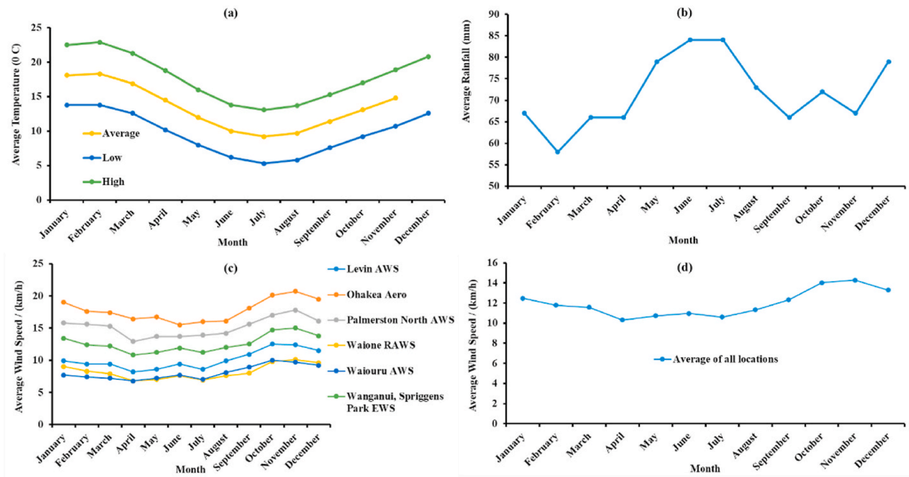

Fig. 2. Climate data of the Manawatu-Whanganui region: a) average monthly temperature, b) average monthly rainfall, average monthly wind speed of six locations and average monthly wind speed of all locations (Source: National Institute of Water and Atmospheric Research, Chappell, 2015).

The foreshore and nearshore sediment sizes vary from 0.4 to 0.23 mm and from 0.16 to 0.20 mm, respectively (SHAND et al., 1999). South of the Whanganui River, the present coastline is dominated by fine-grained sandy sediment derived from the Plio-Pleistocene Whanganui River Basin sediments and the greywacke axial ranges to the east (Clement et al., 2010).

The foredunes of the Manawatu beach accrete 20 m^3/m in width per year (Johnson 1987). They include well-vegetated stabilized foredunes, as well as poorly vegetated blown-outs (Hesp, 2001). Spinifex sericeus, and Desmoschoenus spiralis (Pingao) are the main indigenous, primary sand-colonizing, foredune species ((Hilton, 2006). Spinifex is green/-silvery in colour and it can be propagated from seed or by roots (Bergin, 2018). This grass is usually found on foredunes and it requires active sand accumulation (Rapson et al., 2016). Its long trailing runners and vigorous growth make it an ideal sand dune stabiliser (Bergin, 2018). It has a greater tolerance to seawater or salt spray (Esler, 1970). Desmoschoenus (Pingao) is a tussock-like perennial plant 30–90 cm tall found on active sand dunes (Bergin, 2018). It thrives on accumulating sand, in particular, on foredune slopes as its rhizomes keep submerged (Esler, 1970). Its distribution may be sparse or patchy within larger dune systems (Hilton, 2006). According to Esler (1970), the foredune slope and height vary according to the vegetation type. The seaward slope of a foredune colonized by Spinifex, for instance, has between 14 and 16° and up to a height of 6 m. The foreshore slope of a foredune with *Desmoschoenus* can have between 8 and 14° and be as low as 3 m. On the other hand, the foreshore slope of a foredune with marram grass can reach 24–28°. This way, dunes with marram grass can be much higher than the ones with a native vegetation cover (Esler 1970).

3. Methodology

3.1. Establishing spiral DPSIR framework

As the focus of this study is to introduce a new spiral framework for long-term DPSIR analysis, we used the classical DPSIR framework to illustrate the concept. The classical framework is more suited to this case

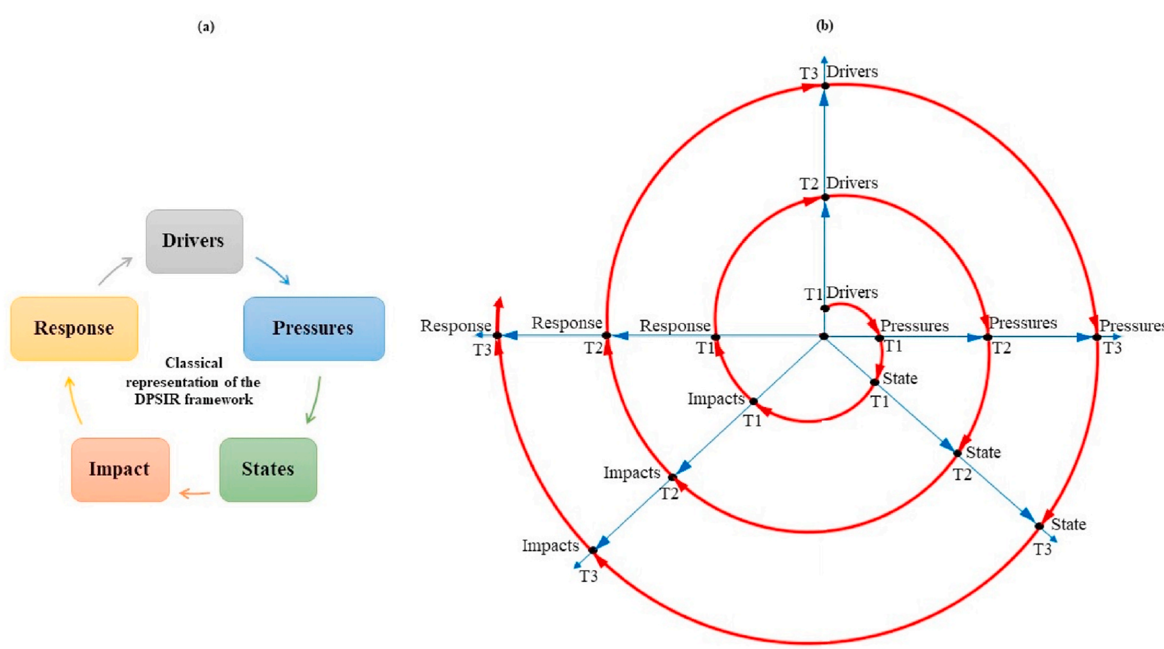

Fig. 3. a) classical cyclic representation of the DPSIR framework and b) proposed spiral representation of the DPSIR framework for long-term analysis.

because of the lack of quantitative data concerning the 19th century. Historical data on aeolian erosion and sand dune migration is not as accurate and consistent as present scientific measurements obtained through modern technologies. The definitions used in this paper to establish the spiral DPSIR framework (Fig. 3) follow the ones proposed by Gari et al. (2015) and Semeoshenkova et al. (2017). The components of the DPSIR approach reflect cyclic cause-effect relationships among the 5 categories (EEA, 1999). It depicts the feedback of management response on the other four components of the same cycle. In this paper, such connection is not elaborated on because such representation is inaccurate, as the feedback of management responses on drivers, pressures, state and impact on the same cycle would be different in time and space. There would be new drivers, pressures, states and impacts due to the initial human response to the environmental problem. The proposed framework represents both cause-effect relationships and the evolution of a particular component over time.

3.2. Data collection and analysis

A thorough literature review and analysis were carried out to identify drivers, pressures, states, impacts and responses related to the coastal sand dune management in the Manawatu-Whanganui region in New Zealand during two contrasting periods 1) from the 19th century to the late 20th century and 2) from the late 20th century to the 21st century. To maintain the quality of the literature up to the late 20th century, we mainly used scientific literature provided in Transactions and Proceedings of the Royal Society of New Zealand. Furthermore, we used the literature from the coastal dune ecosystem reference database, which has been collated by the Coastal Restoration Trust of New Zealand. We also used the government reports prepared by scientists and also the acts of the Government of New Zealand. In the early 20th century, there is a lack of scientific data, thus, some issues related to dune management in the region had been reported only in newspapers. However, such information was confirmed from reports in several newspapers. For the period from the late 20th century to the present, we used literature mainly in peer-reviewed journals as well as scientific reports and policy frameworks of the Government of New Zealand and the Horizon Regional Council which represents the Manawatu-Whanganui region. A few dissertations were used in the analysis, in case, there is a lack of peer-reviewed literature. Table 1 shows the classification of literature based on its source.

Drivers such as an increase in human population in the region and the country from the mid-19th century to the present were analysed using the data of the Statistics Department of New Zealand. However, there are no continuous data sets and also the population in coastal urban environments are given from the mid-20th century. The data on livestock and agriculture are not available for the region up to the late 20th century. This is mainly because the regional council were established only after 1989. Up to 1985, the demographic and other census data are given under the Wellington region. Therefore, it is not possible to find the data specifically for the Manawatu-Whanganui region before 1985. The livestock and agricultural data were analysed for five coastal territorial authorities (Horowhenua, Manawatu, Rangitikei, Whanganui and Palmerston city). Respective main urban areas are Levin, Fielding, Morton, Whanganui and Palmerston city. In addition, climatic data were obtained from the database of the National Institute of Water and Atmospheric Research of New Zealand.

The impact analysis was limited only to analysing the temporal and spatial variability of the vegetation cover on three selected coastal stretches in the region (Waitarere – 3 km, Foxton – 3 km and Whanganui – 3.5 km) (Fig. 4). These stretches include both urban and natural environments. Thus, the human impact and also natural variability of dune vegetation were assessed for the three stretches. The most seaward line of the solid forest or grass cover over the dunes was considered as a proxy for analysing the temporal and spatial distribution of the vegetation cover. The transects from 50 to 200 m were used to find the most seaward position of the dune vegetation cover on google earth images from 2003 to 2022.

Table 1
Classification of literature based on its source.

Type	Description	Number	Percentage/ (%)
1	National and International articles in journals, proceedings and books	39	58.2
2	Laws, regulations and policies of the New Zealand Government and the Regional Council	3	4.5
3	Scientific reports published by the New Zealand Government and the Regional Council	15	22.4
4	Databases	3	4.5
5	Doctoral and other dissertations	1	1.5
6	websites	1	1.5
7	Newspapers (All five referred to one reference)	5	7.5
Total		67	100

4. Results

4.1. DPSIR analysis for sand drifting from the 19th to late 20th century

4.1.1. Drivers

The main driver of dune destabilization in the Manawatu-Wanganui region during the 19th century were the intensive activities introduced by the European settlers after New Zealand become a British colony in 1840 (Table 2). The Maori were also responsible for clearing the vegetation in some coastal regions and hinterland. Nevertheless, the Whanganui's inland forest was not much affected by the Maori firing, as they burn less easily than the ones on the east coast due to higher rainfall (Sampath et al., 2021).

According to the demographic data provided by the Statistical Department of New Zealand, the European population increased significantly since 1870 in Whanganui District and the area of the Palmerstone North City Council, while the population increased relatively slowly in Fielding, Levin and Foxton (Fig. 5). Due to the limitations such as high altitudes in the hinterland (Knight, 2013), Europeans concentrated on the low-lying coastal areas and introduced significant changes in land use during the early stages (Whitehead, 1964). They burnt and cut down a large area of forest and shrubs to convert them into farms. They introduced cattle, sheep, pigs, goats, rabbits, horses and sambar deers into the environment and the land was intensively utilised for grazing, crop production, settlements and development since the Crown started acquiring land in the 1870s (Hesp, 2001; Wendelken, 1974). A railway was constructed between Wellington and Manawatu and extended up to Whanganui for facilitating the transportation of production along the dune regions and the Railway Department had to initiate dune stabilization as the earliest management intervention (Whitehead, 1964).

4.1.2. Pressures

The sand dunes of the Manawatu-Whanganui region were rapidly set in motion because of the removal of the native sand-binding plants, such as Spinifex sericeus and, and Desmoschoenus spiralis (pingao), by both humans and animals (Whitehead, 1964). There were no measurements of drifting rates for the early periods, only for the last decades of the 20th century. The parabolic dunes migrated landward at an average rate of 20–25 m/yr while older parabolic dunes developed from 1990 to 1995 migrated 50–80 m/yr (Hesp, 2001).

4.1.3. State

The state of coastal sand dunes can be defined in terms of 1) Soil fertility, 2) Habitat quality, 3) River navigability, and 4) Landscape

Fig. 4. Three coastal stretches used for analysing the spatial and temporal distribution of the most seaward frontal line of the vegetation cover (either grassland or forest) over the sand dunes in a) Waitārere Beach, b) Foxton Beach and c) Whanganui Beach.

Table 2
From the 19th to the late 20th Century - Manawatū-Whanganui.

Drivers	Pressures	State	Impact	Response
Maori settlements	Less pressure due to the drivers such as the burning of fern land and agriculture by the Maori population	Habitat quality	Minimum or no impact on the environment or socio-economic aspects of the Maori population	No response
Intensive European settlements (burning shrubs, deforestation, grazing, agriculture, farming, mining, construction, infrastructure development) Introduction of non-native animals for stock production	Mobile sand dunes and sheets Sand dune blowouts	Soil fertility Habitat quality Landscape quality (Easthetic aspect for recreation purposes) Transportation River navigability	Agricultural lands into wastelands due to loss of fertility The creation of swamps as river mouths was closed by the deposition of moving sand Loss of landscape values Damages to buildings and infrastructure such as railroads Impact on river navigation	1903 and 1908 Sand Drift Acts Introduction of exotic vegetation (marram grass, radiata pinus, tree lupins) (at the beginning not successful, but repeatedly used) Native vegetation species plantation (at the beginning not successful) Artificial dune building with sand trapping fences

quality (aesthetic aspects mainly for recreational purposes). As the dunes are found in the coastal ecosystem, with their hydrodynamic and sedimentary processes and feedback human activities affected the natural functioning of the ecosystems, resulting in changes to the state of the entire coastal zone (Sampath et al., 2021).

4.1.4. *Impact*

Sand invaded roads and railway lines affecting transportation infrastructures (Wanganui Herald, 1874a, b; 1878a, b; *Manawatu Times*, 1878). Newspaper articles show timely issues for society. As the native vegetation was removed and exotic species become dominant, natural habitats disappeared, threatening the native biodiversity (Rapson et al., 2016). Soil erosion from hinterland and dune surfaces caused low fertility of the thin layer of surface soil (Saunders, 1968). In particular, when vegetation was removed from sandy dunes, the thin fertile humus layer could also be blown out (Smith et al., 1985). Furthermore, the deposition of blowout sand over agricultural areas caused barren lands since agriculture became less productive (Travers, 1881; Whitcombe, 1872). Moreover, sand transgressed into the rivers and streams creating swamps and wetlands and silting channels, imperilling riverine navigation (Whitcombe, 1872). Land-use changes in the coastal environment also affected the quality of the landscape and habitats.

4.1.5. *Response*

In Manawatu, Travers (1881) suggested planting grasses such as *Ammophila arenaria* and *Elymus arenarius* near the sea, *Pinus Maritima* in the lee of the dunes and growing vineyards upon the dunes on the west coast and in particular to the north of Rangitikei River. He was suggesting the adoption of the practices used in several European regions. Travers (1881) attributed the success of arresting the moving sand in France to the extensive support provided by the French government to the work of Nicolas Bremontier, who was responsible for the beginning of dune afforestation in Gascony. However, until the early 20th century, the sand dune issue drew little attention from the New Zealand Government (Hesp, 2001). As experts, politicians and landowners begin to campaign for sand-drifting prevention the Sand Drift Act (New Zealand

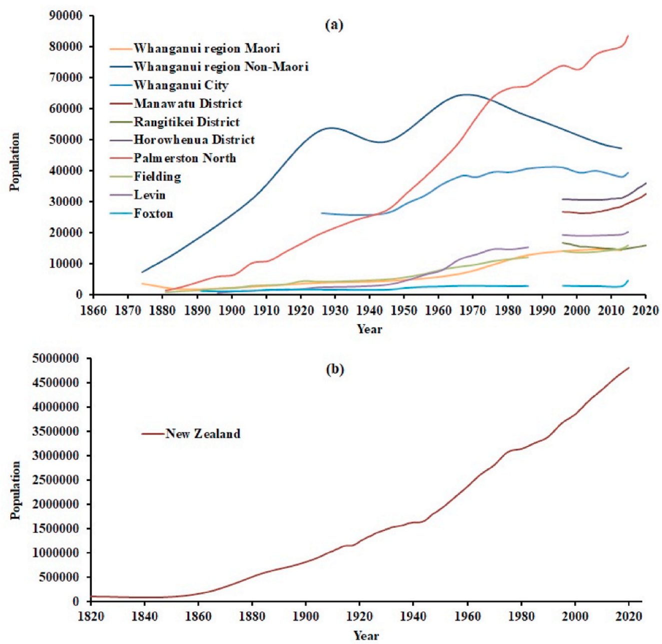

Fig. 5. Population trends a) in the Manawatu-Whanganui region and b) in New Zealand. (Data source: Statistical Department of New Zealand).

Government, 1903) and its consolidated act were passed in 1903 and 1908, respectively. Another management response to dune stabilization was to promote artificial foredunes through sand trapping fences, based on the model used in France (Cockayne, 1911). On this account, a series sand catching fences were built to safeguard areas with buildings and constructions. Cockayne endorsed the afforestation of dunes as the goal of sand reclamation and such activities increased after 1950 (Sampath et al., 2021).

4.2. DPSIR analysis of sand drifting from the late 20th century to present

4.2.1. Drivers

In the last 40 years, urbanization, deforestation, grazing, farming, construction, infrastructure development and recreational activities are the main drivers of dune destabilization in Manawatu-Whanganui (Table 3). For instance, Fig. 6 shows the total number of cattle, sheep and deers on farms in the region from the late 20th century to the early 21st century. Due to the changes in administrative boundaries of districts, it is not possible to compare all data in these statistical regions. However, if the whole region is considered, the number of animals (cattle, sheep, deer, pigs, goats, and horses) as well as the number of farms and the total agricultural area, do not significantly vary with time (Fig. 7). Thus, agricultural and livestock farming in the coastal district councils of the Manawatu-Whanganui region is still a significant economic driver that can create environmental pressures on dunes. At the same time, the planting of *Ammophila arenaria* become a driver due to its rapid spread causing habitat loss and a drastic reduction of biodiversity (Hilton, 2006). Dune restoration initiatives are now focused on removing exotic vegetation while planting native species such as pingao (Jenks, 2018). However, the native vegetation species do not support high dunes heights (Esler, 1970). Thus, dunes are also vulnerable to sea-level rise and coastal flooding due to storm surges. Therefore, human activities that result in global warming are considered drivers for developing sand dune management plans for the region.

4.2.2. Pressures

In contrast with previous times, dune destabilization is still a problem only in limited areas in the Manawatu-Whanganui region, (Hesp, 2001). The dune migration rates vary as per the type of leeward habitat. For instance, by 2007, the maximum advance rates through the forest were 1–10 m/yr, through low scrubs 70 m/yr and 400 m/yr through grasslands (Walrond, 2007). At present, however, the main pressure is the spread of invasive species and the loss of native biodiversity (Hilton, 2006). Sea-level rise driven by global climate change can also become an issue in the region. Due to the removal of marram grass (Jenks, 2018), the reduction of dune heights will be an environmental pressure during this century.

4.2.3. State

The biodiversity of dune habitats is the main parameter that defines the state of dunes in the context of the restoration of stabilized dunes. The availability and fragmentation of habitat can determine habitat quality. The extent of active dunes is important for the survival of native species (Poole, 2003). Landscapes with low biodiversity and dead or stabilized dunes do not appeal to the recreation or tourism industry (Gadgil, 2002). In addition, the mean sea level in the context of sea-level rise during this century and the availability of natural coastal defences to protect human activities from coastal flooding can be state variables that are important in coastal zone hazard management (Shand, 2008; Bell 2015).

4.2.4. Impacts

The region has lost much of its indigenous habitat due to more than a century of landscape modification while the remaining habitat continues to be threatened by land development and by pest species (Poole,

Table 3
From the late 20th century to the 21st century - Manawatū-Whanganui.

Drivers	Pressures	State	Impact	Response
Planting of marram grass to stabilize sand dunes until the late 20th century	Spread of invasive species (marram grass)	Biodiversity (flora and fauna Habitat quality	Loss of biodiversity Loss of habitats of native beach grasses	Removal of exotic vegetation (e.g. marram grass) Introduction of native vegetation species Enhance awareness Public participation
Urbanization Intensive settlements (deforestation, grazing, agriculture, farming, mining, construction, infrastructure development)	Mobile sand dunes Blowouts	Biodiversity Habitat quality Landscape quality	Loss of forest cover Loss of natural habitat for native fauna and flora Change of transgressive dunes to parabolic dunes	Resource Management Act 1991 (RMA) Integrated management "One Plan" The Consolidated Regional Policy Statement, Regional Plan and Regional Coastal Plan for the Manawatu-Wanganui Region prepared by the Horizons Regional Council
Industrial and human activities burning fossil fuel	Climate change: an increase of temperature resulting in sea-level rise	Mean sea-level	Coastal inundation and foredune erosion due to sea-level rise	Artificial dune building with sand trapping fences No special attention to the impacts of sea-level rise in One Plan
Removal of marram grass and planting of native species to achieve active nature of sand dunes from the late 20th century to the present	Reduction of dune heights	Natural flood defence	Coastal inundation due to the storm surges	No special attention to coastal flooding in the One Plan policy framework of the Horizon regional council of the Manawatū-Whanganui region

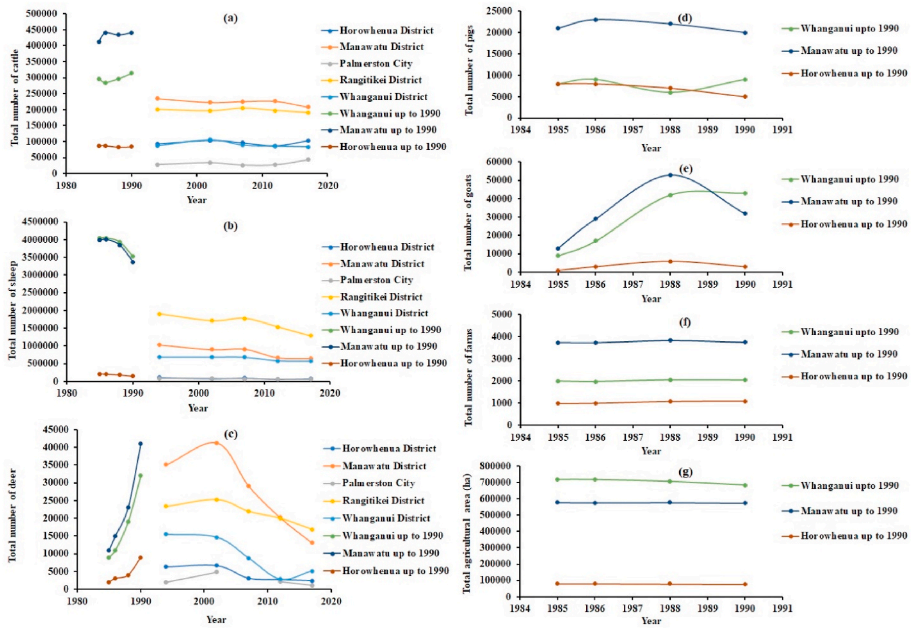

Fig. 6. Agricultural and livestock farming in the coastal district councils of the Manawatu-Whanganui region from the late 20th century to the early 21st century. Due to the changes in administrative boundaries of districts, it is not possible to compare data directly in these statistical regions. (Data source: Statistical Department of New Zealand).

2003). For instance, in Manawatu, there was an 81% decrease in active dunes from the 1950s to the 1990s, as dunes were covered with pastures, pine tree forests, gorse and other exotic species (Hilton, 2006). The dunes in the best natural condition occur in a strip of 9 km long, from the settlement of Foxton beach to the settlement of Himitangi (Rapson et al., 2016). Dune retreat rates in some parts of the Manawatu-Whanganui region are the largest in the world (Hesp, 2001). Fig. 8 shows the spatial and temporal distribution of the most seaward frontal line of the vegetation cover (either grassland or forest) over the sand dunes in a) Waitārere Beach, b) Foxton Beach and c) Whanganui Beach. According to this assessment, vegetation cover near the urban settlements and beyond the Waitārere beach is highly unstable. Foxton beach also shows high dune mobility with a large number of parabolic dunes and blowouts. A stable dune vegetation cover was present near the western margin of the Whanganui River while further beyond, dune vegetation cover is unstable and shows the characteristics of active dunes. In addition, coastal flooding and erosion due to sea-level rise and storm surges in Foxton and Himatangi are important management issues (Shand, 2008; Bell 2015).

4.2.5. Response

The main legal tool of coastal management in New Zealand is the Resource Management Act 1991 (RMA) (New Zealand Government, 1991). The practise of ecological restoration has become a panacea for enhancing the recovery of the ecosystems that were damaged by humans (Aronson et al., 2006). Policy item 1.1.2 of the New Zealand Coastal Policy Statement (New Zealand Government, 1994), Department of Conservation (1994) identified the protection and conservation of active dunes as a matter of national importance (Hilton et al., 2000). In the Manawatu-Whanganui region, natural resources management and the region's response to natural disasters are coordinated by the Horizon Regional Council, which prepared the Regional Policy Statement, the Regional Plan and the Regional Coastal Plan as an integrated plan, called the "One Plan, 2018". Two key issues identified in the One Plan have implications for dune management: unsustainable hill country land use and threatened indigenous biodiversity. Accordingly, limitations are enforced for vegetation clearance, land disturbance and cultivation adjacent to water bodies in the hinterland or coastal foredune areas. The Dune Restoration Trust, the Department of Conservation and the Council has started planting spinifex and pīngao with active public participation to restore sand dunes (Hilton et al., 2000). An increase in storminess and a subsequent increase in coastal flooding would have to be taken into consideration for future management plans (Pearce et al., 2016; IPCC 2021). The Horizon regional council assessed the impacts of coastal flooding and erosion due to sea-level rise and storm surges in Foxton and Himatangi (Shand, 2008; Bell 2015).

4.3. Integration of cyclic DPSIR frameworks into a spiral DPSIR framework

The main advantage of the integration of DPSIR cycles as the spiral framework is that it allows better visualization and a good understanding of mutual relationships between each component.

The analysis of dune management using the DPSIR cyclic framework for two periods separately is not an accurate representation because it is not possible to correctly link the management responses in the T1 period (from the 19th to the late 20th century) to the drivers of the T2 period (from the late 20th century to the 21st century). This issue was avoided by integrating two DPSIR cycles as a spiral framework (Fig. 9) while preserving the cause-effect relationships of each component. Furthermore, the introduced spiral representation shows the link between the predecessor and successor of the same component (for instance, the link between drivers of the T1 and T2 periods).

The impact of Maori settlements in the T1 period cannot be seen in the T2 period, however, activities related to urbanization and settlements have increased from T1 to T2 as indicated by the population increase in the Manawatu-Whanganui region (Fig. 5). As the number of animals and farms as well as the total agricultural area are almost constant their impact from the T1 to T2 period would not change significantly (Figs. 6 and 7). Industrial and human activities related to the burning of fossil fuels can be considered as a new driver relevant for the T2 period. The management responses of planting exotic plants over sand dunes in the 20th century (T1) became a new driver creating environmental pressures forcing their removal during the 21st century (T2). Such removal of exotic plants can result in new pressure in the T2 period as the effectiveness of dunes as natural defences against flooding

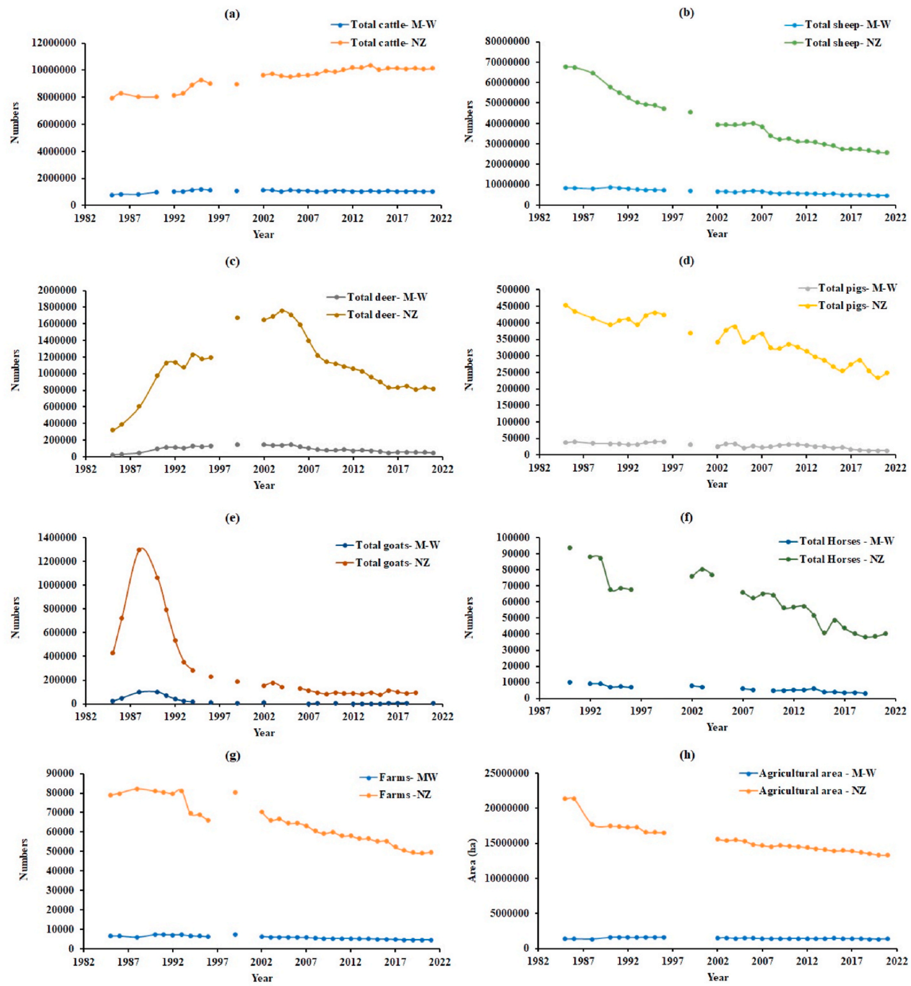

Fig. 7. Agricultural and livestock farming in the Manawatu-Whanganui region from the late 20th century to the early 21st century. (Data source: Statistical Department of New Zealand).

can be reduced. Biodiversity and habitat and landscape quality are important phenomena only in the T2 period because the loss of biodiversity and reduction of habitats for native fauna and flora are considered important with the paradigm shift in dune management.

Coastal inundation would be an important management issue in the Manawatu and Horowhenua districts during the T2 period in the context of sea-level rise due to global warming. The Horizon Regional Council has undertaken some assessments of the impacts of sea-level rise, however, further studies are required to assess the impact of coastal flooding as the efficiency of natural defences would be reduced after the removal of marram grass.

5. Discussion

5.1. Sustainable coastal sand dune management in the 21st century

Coastal sand dunes are seen as complex, dynamic and sensitive landforms of coastal environments (Dahm, 2003; Hansom, 2001). It was been recognized that beaches and sand dunes significantly contribute to human welfare, providing many different valuable goods and services such as leisure and recreation, coastal defence, conservation, employment, cultural heritage and identity, nutrient cycling, and habitat for plants and animals (Marshall et al., 2014). Coastal sand dunes also exhibit a dual role as a sediment sink or source to maintain the long-term stability of a coastal system as long as the natural environmental functioning of such a system is not artificially constrained. For their sustainable management, processes and feedback related to natural dune evolution should be understood because anthropogenic influences on such processes result in the loss of the natural equilibrium of the ecosystem.

As in the Manawatu-Whanganui region, when there is a high sediment supply, climatic conditions (e.g., arid or semi-arid) and restricted plant cover, high wave and wind velocities above the threshold for entrainment may lead to the development of mobile dune fields (Hesp, 2001). Sand dune mobilization is also dependent on particle size, dryness of the sand, beach morphology and the degree of roughness elements, such as driftwood and vegetation (Sloss et al., 2012; Clarke and Rendell, 2011). Bordeaux in France (Clarke and Rendell, 2011), Oregon in the United States (Freitas, 2021), Cornwall in England (Polsue, 1868) and Manawatu-Whanganui in New Zealand (Sampath et al., 2021), are a few cases where dune drifting resulted due to natural and human activities such as removal of dune vegetation. To avoid the nuisance of sand dune migration and blowouts (Sherman and Nordstrom, 1994) sand dune stabilizations methods were adopted throughout the world. The main approach was to use sand binding grasses, such as *Ammophila arenaria*, which in some cases became invasive.

Even in the US, Non-native *Ammophila arenaria* (European beachgrass) and *Ammophila* breviligulata (American beachgrass) were widely used for stabilization from the early 20th century. Both species became invasive and these two species have produced hybrid species naturally (Mostow et al., 2021). As in Manawatu-Whanganui, the invasive spreading of American beachgrass resulted in low dune heights, which

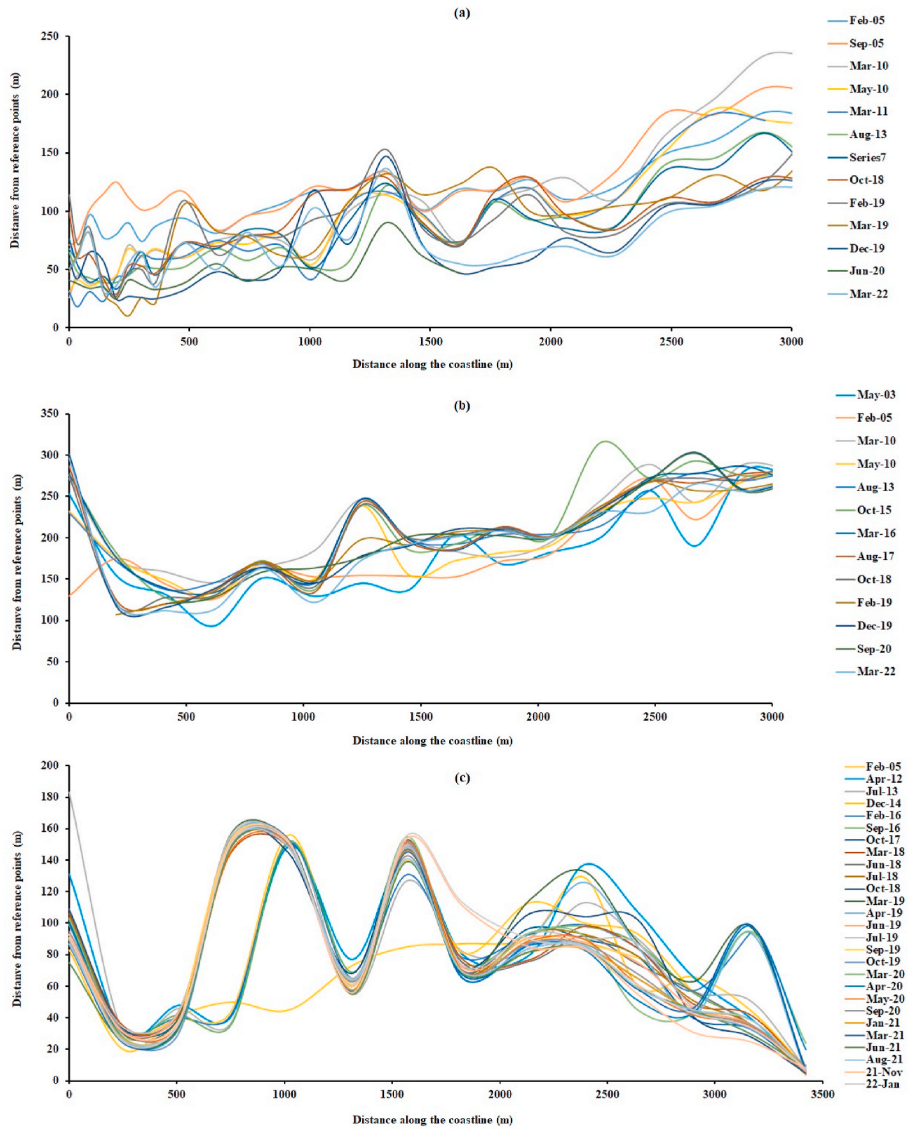

Fig. 8. The spatial and temporal distribution of the most seaward frontal line of the vegetation cover (either grassland or forest) over the sand dunes in a) Waitārere Beach, b) Foxton Beach and c) Whanganui Beach in New Zealand.

can compromise dunes' natural action as coastal defences against flooding during extreme events (Ruggiero et al., 2018). Thus, worldwide experience proves that responses to manage sand dunes resulted in new drivers and pressures with unexpected impacts on the environment and socio-economic activities during the 21st century. However, in the context of global warming and sea-level rise, marram grass promotes the development of large dune fields, which are valued as natural coastal protection from extreme sea-level rise events, for instance in Oregon (Ruggiero et al., 2018). Thus, as Delgado-Fernandez et al. (2019) suggested the paradigm shift from dune stabilization to the restoration of stabilized dunes should be again assessed so that coastal managers can find an optimized solution between these two extreme solutions adopted from the 19th century to the present.

5.2. Comparative analysis of spiral and different cyclic DPSIR frameworks

A holistic approach is needed to scientifically explore the links between socio-economic drivers and observed impacts of sand dune migration as well as the complex long-term environmental consequences of management responses to such hazards. Despite DPSIR being used for a long time, the management tool is still evolving by introducing new components and updating their definitions to illustrate the management responses accurately to environmental and socioeconomic pressures and impacts on human drivers. In this study, we addressed one of the main issues of the classical cyclic DPSIR framework as it does not allow the inclusion of new drivers though there is a cause and effect link between the Response to Drivers. The consequences of the management responses either in the form of new drivers or pressures may be visible after some time. The advantage of the spiral framework is that the spiral DPSIR framework can be further extended to any number of contrasting periods including future perceived drivers and their pressures, state, impacts and possible management initiatives. Thus, the proposed spiral DPSIR framework allows analysing of long-term coastal management strategies, which sometimes require a historical understanding of coastal system responses to past management initiatives. Therefore, the proposed spiral DPSIR framework may be used for the comprehensive planning of management strategies for coastal sand dunes.

Another advantage is that the spiral DPSIR framework can be further developed to accommodate the modifications. For instance, Carr et al. (2007); Song and Frostell (2012); Pinto et al. (2013); Elliott et al. (2017) made to the classical DPSIR framework. In the case of modification by

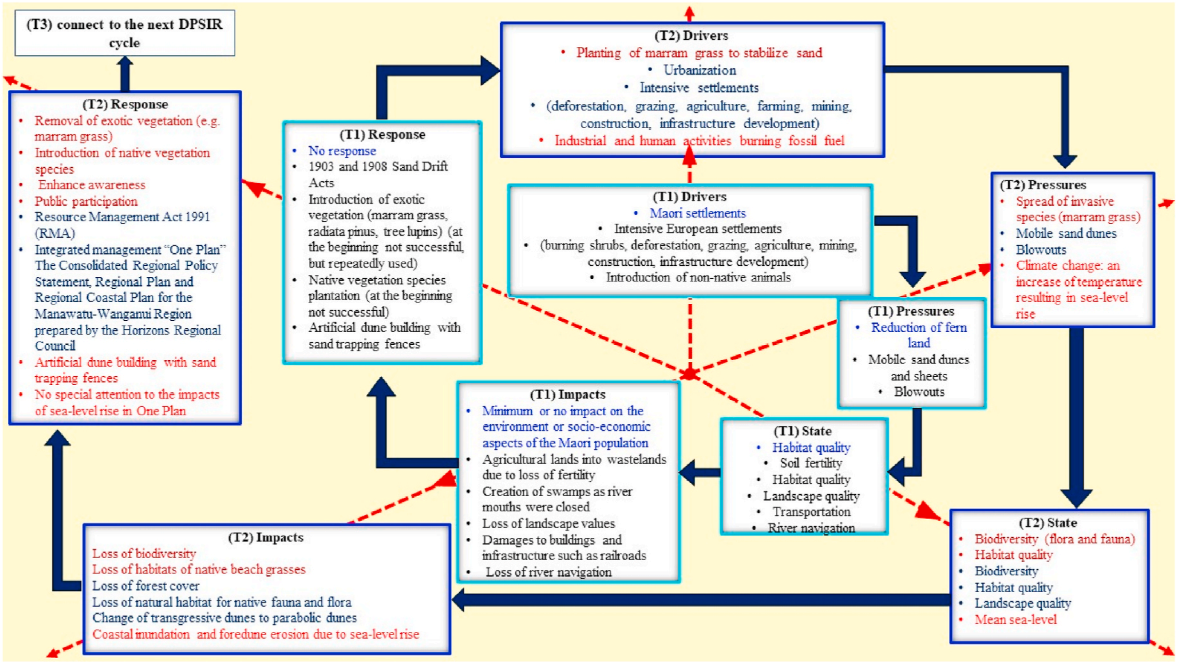

Fig. 9. DPSIR spiral framework analysis of dune management in Manawatu-Whanganui from the 19th to the 21st century. T1 is the first period (from the 19th to the late 20th century) and T2 is the second period (from the late 20th century to the 21st century).

Elliott et al. (2017), a new category (Activities) has to be included. The spiral DPSIR framework in this case study has three types of links. They are 1) cause and effect link within the same period; 2) Response in the initial period to Driver in the next period; and 3) the link between the same category from the initial to the next period). However, it may be required to represent additional links from Responses in the initial period to Pressures, State and Impacts in the next Period. Such a framework can be more complicated. Nevertheless, the proposed spiral DPSIR framework can be adopted not only for sand dune management but also for analysing other long-term environmental management issues.

6. Conclusion

This study focuses on establishing an innovative spiral DPSIR framework for analysing management responses adopted for the sand dunes in the Manawatu-Whanganui region in New Zealand from the 19th to the 21st century. Dune destabilization was initiated due to fire, grazing and agricultural practices by the Europeans who settled in New Zealand coastal areas after 1840. The main solution was to plant marram grass and to forest the dunes to stabilize them, by means of knowledge transfer from European countries, like France and Germany. However, the marram grass turned invasive, affecting the landscape and local habitats, which caused a decrease in fauna and flora, resulting in low native biodiversity. Thus, there was a paradigm shift from dune stabilization to the restoration of stabilized dunes to make them active and enhance native biodiversity. Dune restoration is achieved by removing marram grass and planting native species. However, dunes created by marram grass are higher than the ones created by native dune-building species. Sand dunes act as a natural defence against extreme events of sea-level rise protecting areas with high socioeconomic values from coastal inundation. The elimination of European beachgrass to regain active dunes may compromise the ecosystem services of dunes as a natural coastal defence against storm surges. These complex issues may force the coastal managers to find an optimized solution between dune restoration and stabilization.

The analysis using the spiral DPSIR framework proved that any management initiatives to control the environmental impacts due to drivers have to be addressed with caution as the present-day response can create new drivers, pressure and negative environmental and socio-economic impacts in the future. If there is a comprehensive understanding of a particular management response to mitigate or adapt to environmental impacts, socioeconomic and environmental damages may be minimized using optimum alternatives.

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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