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An analysis of coastal sand dune management in Oregon (United States) from the 19th to the 21st century

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ABSTRACT

The Drivers-Pressures-State-Impact-Response (DPSIR) framework was employed to understand the land use policies developed to manage coastal sand dunes and their consequences in Oregon, United States of America, during two contrasting periods: from the 19th to the late 20th century and from there to the early 21st century. A combination of historical data and scientific literature was used for this study. Dune destabilization became a socio-economic issue as Euro-Americans settled in Oregon in the 19th century. *Ammophila arenaria* and *Ammophila breviligulata* were widely used for stabilization. This led to a paradigm shift regarding dunes, at a time when their management was becoming more complex due to socio-natural factors. As non-native beachgrasses turned invasive causing the loss of biodiversity and habitats, their removal became the focus to restore the active dunes to support the natural processes of the ecosystem. However, the removal of these beachgrasses, particularly, *Ammophila arenaria,* results in low dune heights, increasing the risk of coastal flooding by reducing their effectiveness as a natural defense against sea-level rise and extreme storm surges. The reason for the contrasting dune management policies in Oregon since the 1930 s is that the management response to environmental impacts due to human drivers creates new drivers, pressures, and corresponding impacts, as shown in the DPSIR analysis. Thus, land use policies for managing coastal dunes in Oregon and other places must balance efforts to restore the native biodiversity while minimizing coastal flooding in a context of accelerating and continuous sea-level rise in the 21st century.

1. Introduction

Coastal sand dunes form naturally above the tidal limits of a beach as a result of sediment transport processes controlled by tides, waves, wind, and vegetation (Sloss et al., 2012a). Such landforms represent a complex and dynamic ecosystem resulting from hydrodynamic and sedimentary processes, as well as feedback and interactions with other geomorphic features of the fluvial and marine environment (Hansom, 2001; Sloss et al., 2012b). Dunes play a dual role as sediment sinks or sources to maintain the long-term resilience of a coastal system as long as natural environmental functioning is not restricted by human activities (Sabatier et al., 2009). For example, dunes can adapt to sea-level rise if there is sufficient sediment supply to the system and no human or natural barriers to their landward migration (Davidson-Arnott and Bauer, 2021). Dunes provide valuable goods and services such as nutrient cycling, habitat for fauna and flora, coastal defense, employment, and leisure and recreation opportunities (Marshall et al., 2014; Lozoya et al., 2011). Managing the natural processes that occur in coastal areas and the human uses of these territories is a complex issue nowadays (Freitas, 2021). A holistic approach is needed to scientifically explore the links between socio-economic drivers; the observed impacts of human uses; and the long-term environmental consequences of the land use policies and management responses to such impacts.

In this study, the Drivers-Pressures-State-Impact-Response (DPSIR) framework was used to examine the relationship between dune responses to human activities and management based on land use policies over a period of time. The objective is to understand the impacts of sand dune management policies on the Oregon coast in the United States during two different periods: from the 19th to the late 20th century and from there to the early 21st century. As an indicator-based environmental reporting approach for sustainable development (Borja et al., 2006), the DPSIR framework aims to describe environmental problems by identifying cause-and-effect relationships between the environment and various anthropogenic activities within a broader socio-economic

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context (Song and Frostell, 2012).

2. The study area

2.1. Geomorphological and hydrological characteristics

The length of the coastline of the State of Oregon is 580 km (Fig. 1), which includes sandy beaches with dune fields (OPDR, 2010; Itzkin et al., 2020). Dunes are extensive in the northern part of the coast, especially north of Coos Bay, while they are small and scattered in the south, limited by the presence of sea cliffs and headlands. The most extensive dune fields extend from Heceta Head south to Coos Bay and from the Clatsop Plains near the Columbia River south to Tillamook Head (McLaughlin and Brown, 1942). In the 1950s, the Clatsop Plains consisted of developed foredunes just above the high tide line of a prograding beach; shore-parallel ridge dunes with deflation plains created by wind scouring sand down to the summer water table that supported streams, lakes, and marshes; and older stable dunes far from the beach (Crook, 1979). In Lincoln, Tillamook, and Curry counties on the north-central Oregon coast, vegetated hummock dunes occurred immediately after the deflation plain (Crook, 1979). Transverse ridge dunes as high as 60 m (200 ft) occurred on large open sand plains in Lane, Douglas, and Coos counties in south-central Oregon, while further inland they were usually on the flanks of massive oblique dunes (Crook, 1979). Dunes on the southern Oregon coast were limited by the presence of sea cliffs and headlands (Dicken et al., 1961). However, the human activities associated with the dune fields in Oregon resulted in significant changes in the morphology of the dunes while creating new

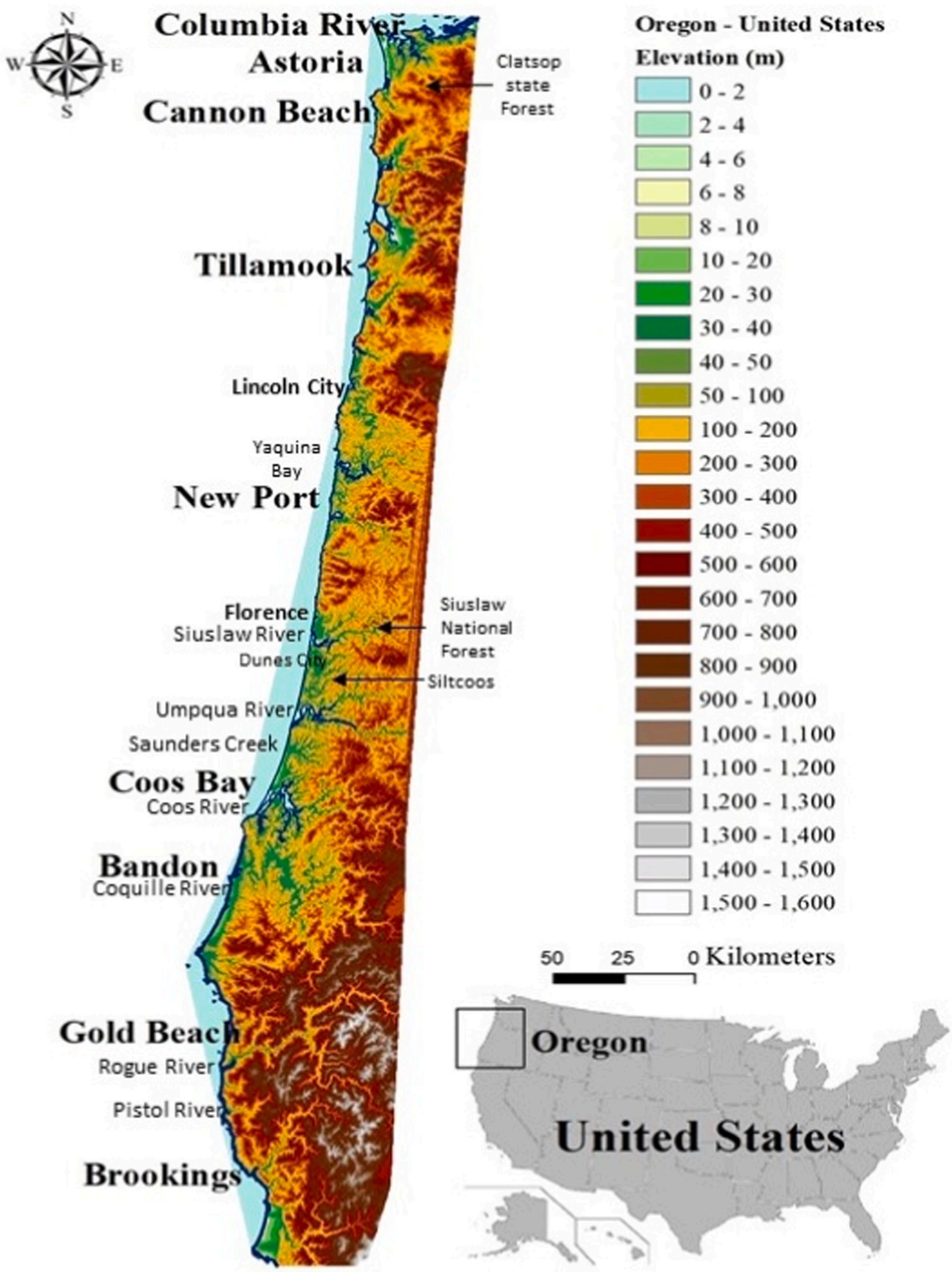

Fig. 1. Study Area: A Digital Elevation Model of the Oregon Coastline.

environments and socio-economic concerns (Freitas, 2021).

The major natural drivers of morphological change along the Oregon coast are waves, currents, tides, storms, wind, and surface runoff, including floods and mass movements such as landslides (Ruggiero et al., 2005). Dunes are formed from sand carried by rivers or material derived from coastal erosion (Ruggiero et al., 2018). According to Dicken et al. (1961), this coastline is humid with moderate temperatures (Fig. 2). Historical climate data from the Astoria weather station from 1953 to 1995 show that the mean annual temperature is 10.5 °C (Mcinerney, 1996). A 40-year weather record shows that the length of the frost-free season for vegetation growth is approximately 273 days (Schwendiman, 1977). Temperature conditions are conducive to the maintenance of complete vegetation cover where other ecological factors, such as soil moisture, are also favorable. (Dicken et al., 1961). The annual rainfall is 1967 mm (Schwendiman, 1977).

The average wind speed during the winter season is 23 km/h. Occasionally, the wind speed exceeds 88 km/h (Schwendiman, 1977). The prevailing direction is from the southwest (Mcinerney, 1996). Wind speeds during storms can exceed 90 mph (136 km/h) to 145 km/h (90 mph) and move enormous amounts of sand, causing blowouts and covering vegetation (Schwendiman, 1977). The dominant direction of summer winds is north to northwest with an average speed of 20 km/h. On rare occasions it can exceed 64 km/h (Schwendiman, 1977).

The Oregon coast is a meso-tidal system, and tides play an important role in changing the coastline. High tides are particularly important during storm surges, when the most severe erosion occurs on the backshore. The wave climate of the Pacific Northwest is known for its severity, with winter storms typically generating significant wave heights (SWHs) of more than 10 m (about one event of this magnitude per year) (Ruggiero et al., 2018). The largest storms in the region have generated SWHs in the range of 14–15 m (Allan and Komar, 2002). High and long-period waves (mean height 3 m; period 12–13 s; direction west-southwest) characterize the winter months (November to February), while small waves (significant wave height - 1 m; period - 8 s; direction - west-northwest) are typical during the summer (May to August) (Ruggiero et al., 2018, 2005). Currents along the coast are weak and generally southward. There is a strong northward drift in the shallow water during severe storms in winter (Dicken et al., 1961).

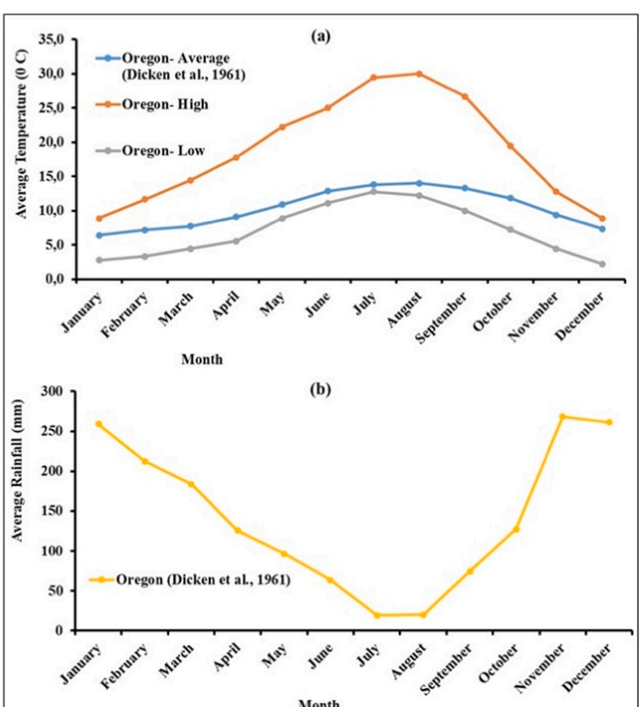

Fig. 2. Distribution of the historical climate data (a) Temperature and (b) Rainfall on the Oregon Coast (Data: Dicken et al., 1961, US Weather Bureau).

2.2. *Natural evolution of coastal dune fields in Oregon*

The modern coastal geomorphology of the Pacific Northwest is the result of erosion that has occurred over the past 5 million years (Ruggiero, 2013). According to Cooper (1958) and Reckendorf (1998), the largest dune fields in Oregon are associated with pre-Holocene dune deposits on uplifted coastal terraces. When the first dunes formed along the Oregon coast from Heceta Head north of Florence to Cape Arago south of Coos Bay, they were the result of wind-driven landward movement of sand (Fig. 3a, Stage 1). The Oregon coastline was generally prograding, as there was an abundant supply of sediment from major rivers into the ocean. This allowed for the creation of new foredunes. As sand was moved landward from active foredunes, new dunes were formed where eolian sand was deposited due to the loss of momentum (Fig. 3b, Stage 2). Some native vegetation would cover them (Fig. 3c, Stage 3). As described by Crook (1979), wind scouring created deflation plains ideal for lake and salt marsh development. Inland stable dunes were covered by forests (Fig. 3d, Stage 4).

3. Methodology

3.1. *Definition of the DPSIR components*

Elliott et al. (2017) extended the DPSIR framework to DAPSI(W)R(M), where Drivers of basic human needs require Activities that lead to Pressures; these are the mechanisms of State change on a natural system that then lead to impacts (on human Welfare) that require Responses (as Measures). However, as the present study covers a time frame from the 19th century onwards, with a limited number of accurate data and impact assessments, the classical DPSIR analysis (Fig. 4) was preferred. Thus, the components of this DPSIR approach reflect only simple cyclical cause-effect relationships (Smeets and Weterings, 1999). The following definitions from Gari et al. (2015) and Semeoshenkova et al. (2017) were used as references.

Drivers are functions of social, demographic and economic developments in societies and related human activities that may intentionally or unintentionally exert **Pressure** on the environment. Pressures result in changes in the **State** of the environment and reflect the level and trends of its degradation. The current state of the environment determines its capacity to support demands and provide sustainable ecosystem services for human benefit. For the study, the state was defined in terms of 1) Physical variables 2) Chemical variables, and 3) Biological variables. Changes in the quality and functioning of the ecosystem have an **Impact** on human welfare or well-being through the provision of ecosystem services (e.g. human life and safety, public health; economy and employment). The **Response** is the management actions and societal attempts to prevent, compensate for, or adapt to changes in the state of the environment by seeking to 1) control drivers or pressures through regulation, prevention, or mitigation; 2) maintain or restore the state of the environment; or 3) "do nothing".

3.2. *Data for establishing the DPSIR framework*

This analysis focused on the land use policies or practices that resulted in negative impacts on dunes, and then on the policies adopted to manage such dunes and the associated environmental and social impacts. The study considered only socioeconomic drivers for the 19th and 20th centuries, while socioeconomic and climate drivers were included for the 21st century. Elements of each component of the DPSIR framework were evaluated and categorized through a comprehensive literature review of Oregon's social-ecological system. Data came from peer-reviewed scientific articles, science and history books, newspapers, Oregon state and U.S. federal legislation, impact assessments, and

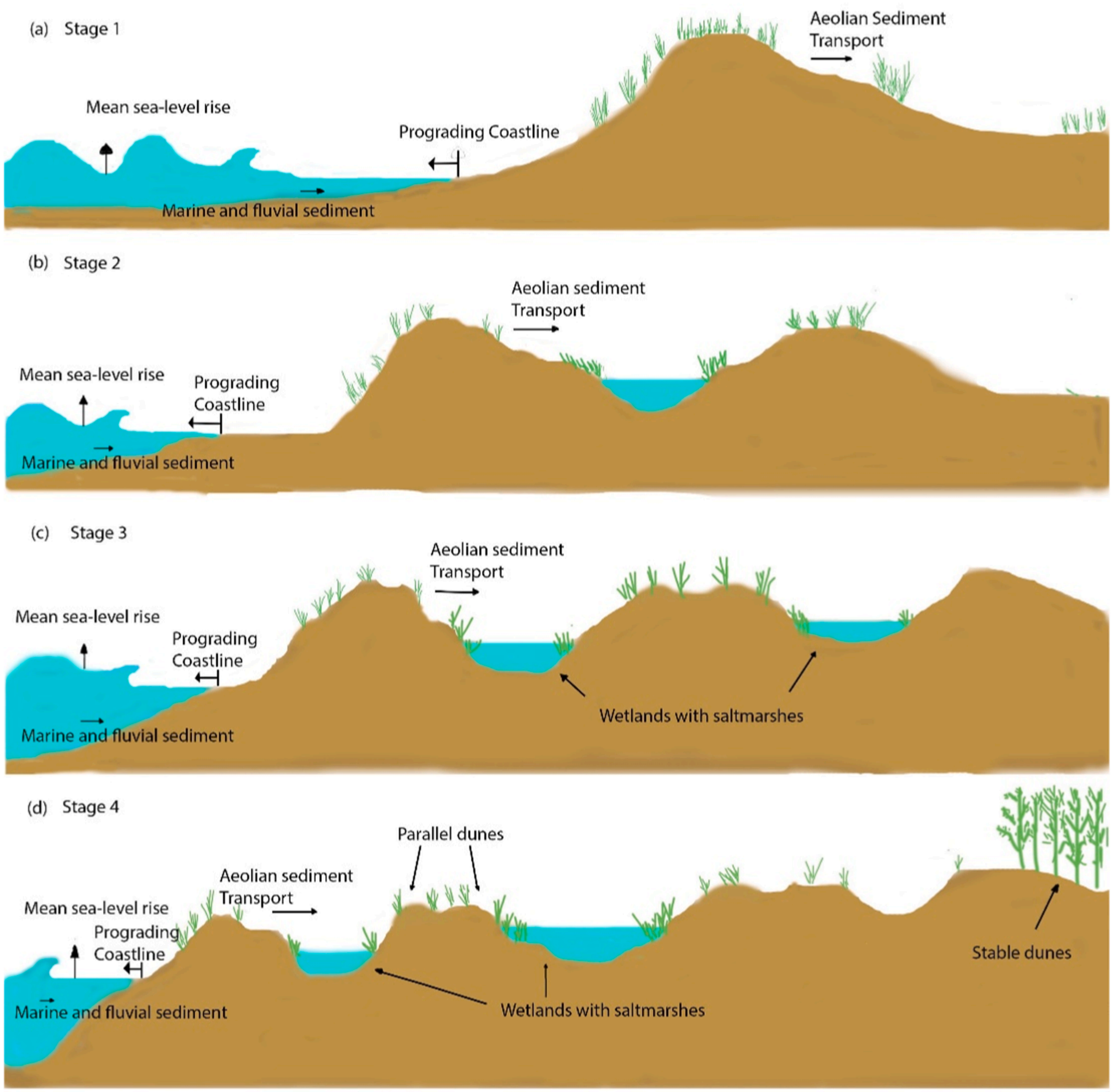

Fig. 3. Simplified stages of conceptual dune evolution in Oregon.

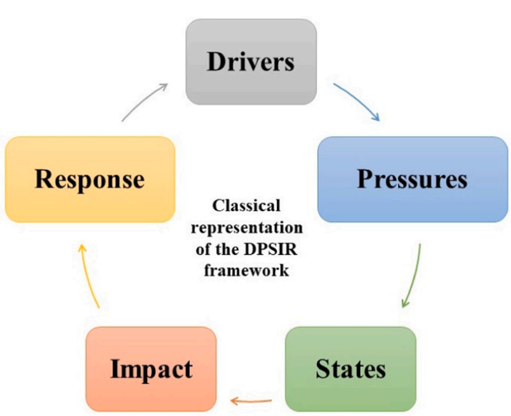

Fig. 4. Classical representation of DPSIR framework (Smeets and Weterings, 1999).

planning and policy reports from coastal management agencies and local councils. Some unpublished data, including dissertations, were used when other information was lacking. In addition, some drivers, such as demographic dynamics, were established using census data from the Census Bureau of the United States. The data source for the livestock and agriculture time series was the Oregon Field Office of the National Agricultural Statistics Service of the United States Department of Agriculture. The contribution of livestock and agriculture to gross domestic product and per capita income was obtained from the Regional Economic Accounts of the Bureau of Economic Analysis of the Department of Commerce of the United States. The paper focuses primarily on the coastal counties of Clatsop, Coos, Curry, Douglas, Lane, Lincoln and Tillamook. For Lane and Douglas counties, data from the cities of Florence and Reedsport were used in some analyses, as the counties extend significantly away from the coast. Table 1 shows the typology of the materials used for this study and their percentage.

3.3. Change in land use and land cover

A series of land use maps of coastal counties in the state of Oregon were developed for the years 1879, 1937/1938, and 2021/2022 to show the changes in land use from the late 19th century to the present. Map features were digitized using ArcGIS tools. There is a lack of data to develop a complete set of land use maps from the 19th to the late 20th century. Therefore, two land use maps for 1879 and 1937/1938 were

Table 1
Classification of literature based on its source.

Type	Typology	Number
1	National and International articles in journals, proceedings and books	46
2	Laws, regulations and policies of the United States Federal Government and the State of Oregon	5
3	Scientific reports published by the United States Federal Government and the State of Oregon and other scientific reports	27
4	Databases	2
5	Doctoral and other dissertations	1
6	Websites	2
7	Newspapers (All five referred to one reference)	8
8	Maps	3
Total		94

created using historical general maps. The first was based on a map of the State of Oregon published by the US General Land Office in 1879 (Williamson, 1879). The scale is 1: 950,400. In addition to features such as rivers, dunes, and mountain formations, the map shows the administrative boundaries of the counties and the names of their county seats. It also includes major townships, cities, and villages. Fig. 12b was created by combining the features of two maps from 1937 and 1938. The 1937 map (Gousha Company, 1937) is a road map produced for the Standard Oil Company of California. It provides information on roads, highways, cities, towns, national forests, rivers, and drainages. The 1938 map (Petrucelli and Appleton, 1938) is a pictorial map that uses artwork to depict major land uses in Oregon and Washington. Although the exact extent of land use activity is not available in the 1938 pictorial map, information on land use activity was extracted and overlapped with the digital map created for 1937.

The source of the 2021/2022 (Oregon GEOHub Repository, 2022) land use and land cover map is the National Land Cover Database (NLCD) of the Multi-Resolution Land Characteristic Consortium (https://www.mrlc.gov/data). It provides nationwide data on land cover and land cover change at a resolution of 30 m. The land use map for Oregon's coastal counties was derived by clipping the nationwide raster dataset. The land cover categories were then reclassified for simplification and better visualization within the coastal counties. The land cover map includes developed areas and various grades of roads. A digital layer of the 2022 road network from the Oregon GEOHub repository (https://geohub.oregon.gov/) was overlapped with the 2021 land cover raster dataset for clarity.

4. Results and discussion

4.1. Dune stabilization from the 19th to late-20th century

4.1.1. Drivers

The DPSIR cycle for the period from the 19th to late-20th century is shown in Fig. 5. The Oregon coast was under the influence of human activities long before Euro-Americans settled in the area (Douglas, 1914; Dicken et al., 1961), as Native Americans manipulated and shaped their environment, using fire for gathering and hunting to improve their subsistence (Deur, 2016). The significant changes, however, began in the 1840s with the large-scale immigration of Euro-American settlers (Fig. 6).

The newcomers introduced a new set of land use practices: the establishment of farmsteads, villages and towns, plowing the land, stock farming, cutting timber and mining the soil. According to Robbins (1997), initial subsistence land use practices were gradually turned into a commercial scale. The construction of railroads for stimulating commercial agriculture in the 1870s-80s accelerated the pace of ecological change. In the early 20th century, coastal areas were subjected to intensive modifications to support commercial activities, for instance, channels and jetties were built at the mouth of the Columbia, Yaquina Bay, Coos Bay, Coquille, and Umpqua rivers. Industrial activities such as

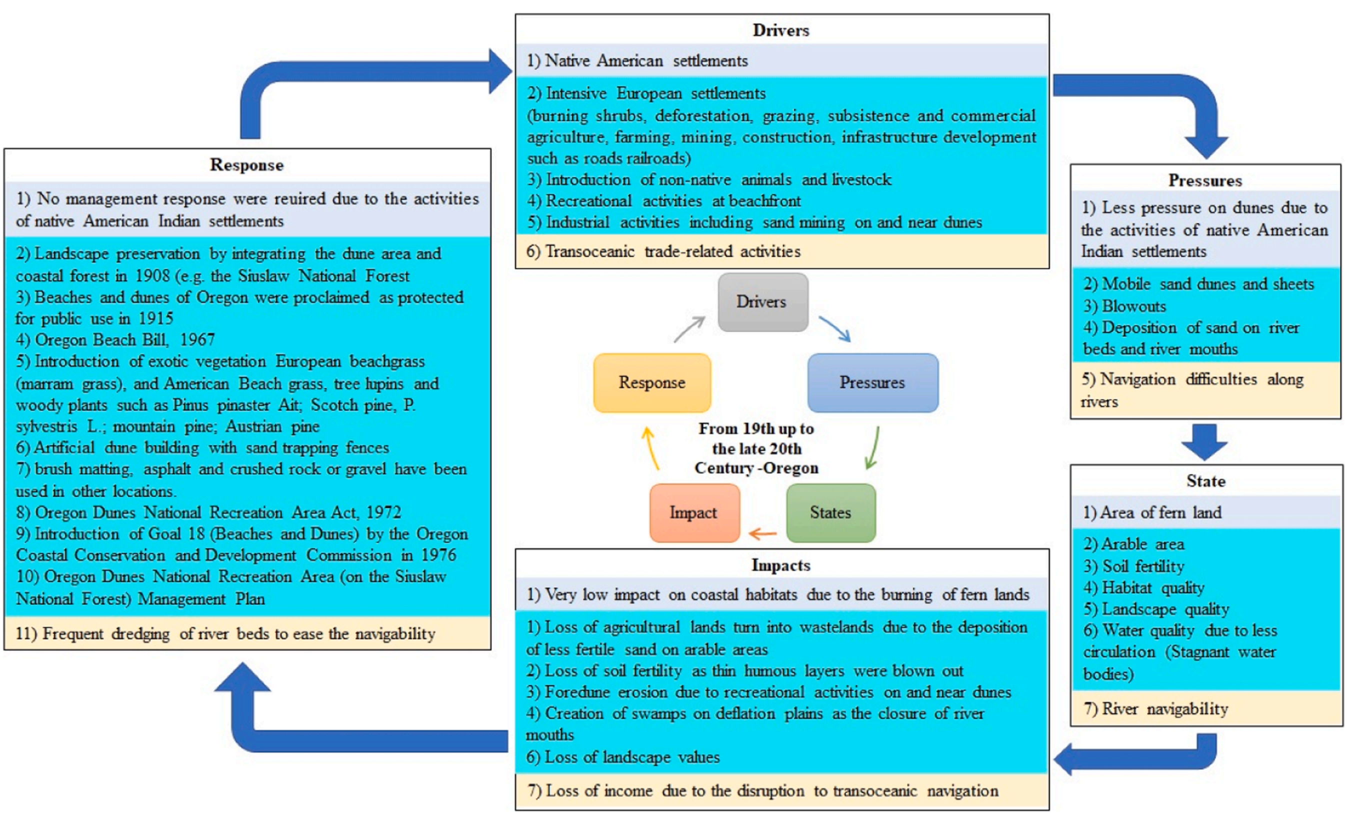

Fig. 5. DPSIR analysis of sand drifting in the 19th and up to the late 20th centuries. Different colors indicate the Pressures, States, Impacts and Responses corresponding to a particular set of Drivers.

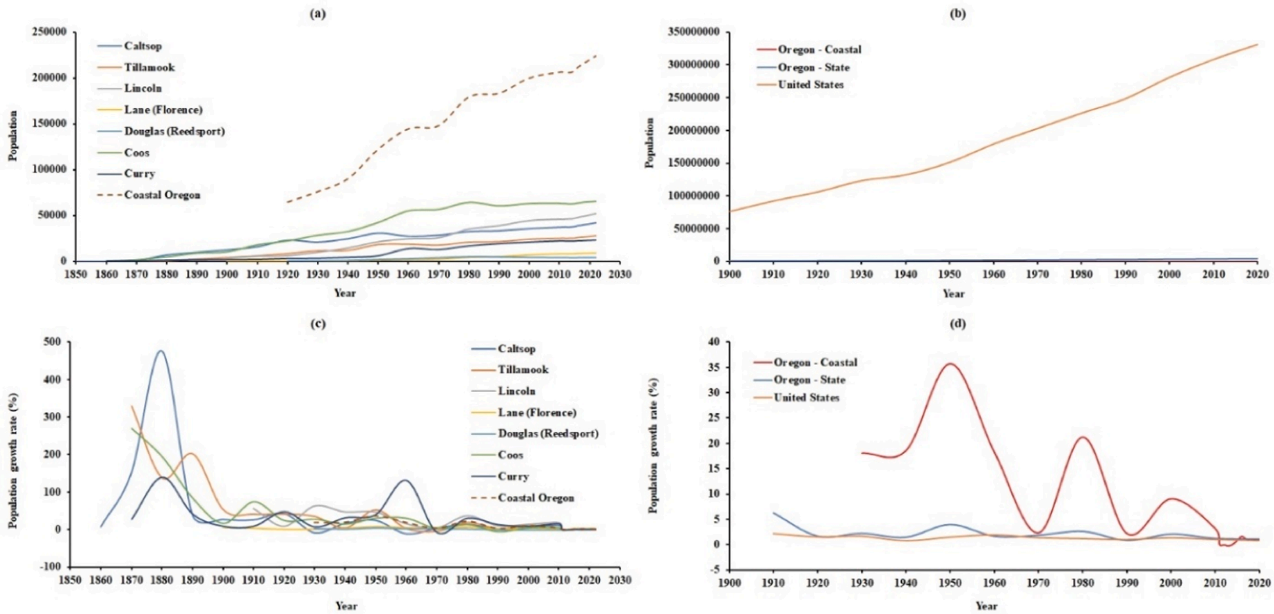

Fig. 6. Population dynamics in Oregon State, Coastal counties of Oregon and the United States.

fish canneries and sawmills developed along the coast (Robbins, 1997). At the same time, beachfront property was sold for the construction of the first seaside resorts (Oregon Sunday Journal, 1909). All these activities had impacts on the dunes, but stock farming was one of the main causes of dune destabilization. Sheep were the most important livestock, but after the 1930s they declined rapidly. Cattle, on the other hand, increased steadily until the 1980s and then showed a slow decline (Fig. 7a). Agricultural land was 20,000,000 acres in 1950 and has slowly decreased over time (Fig. 7c). However, the average value of farmland and buildings per acre increased in all coastal counties, especially after 1970. Compared to the average value of farmland at the state and national levels, farmland values in coastal counties were high. This indicates a comparatively high demand for agricultural lands and livestock production in the coastal counties (Fig. 7d).

The contributions of agriculture, livestock, and forestry services to Oregon's gross domestic product (GDP) have not been significant since the 1970s (Fig. 8a). Although the per capita income of coastal counties has increased since then (Fig. 8c), the contributions of agriculture, livestock, and forestry services to GDP as a percentage of total GDP for the state of Oregon have decreased (Fig. 8d).

4.1.2. Pressures

Native American burning practices influenced the extent and composition of forests and grasslands and probably the amount of sediment reaching the coast. Beginning in the 1850s, however, soil erosion and stream siltation increased as Euro-Americans cleared riparian areas and hillsides for land improvement, ditched and drained prairie grasslands, disturbed native plants, and created ideal conditions for the spread of readily adaptable exotic species (Robbins, 1997). Hydraulic mining in mountainous areas and increased water infiltration on slopes due to human activities led to more landslides (Dicken et al., 1961). Excessive livestock grazing destroyed the wild vegetation that covered the sea ridges (Tri-Weekly Astoria, 1874). Sand mining for ceramics, glass, and foundry molds occurred on dune areas in Coos and Curry counties (Sterrett, 1958). Sand for construction purposes was mined primarily in Lincoln County (Rea, 1974). As beach use increased, real estate speculation and resort development put more pressure on the dunes. Breakwaters disrupted sediment transport by altering depositional and erosional areas (Dicken et al., 1961). All of these activities expanded and intensified during the 20th century (Fig. 5).

4.1.3. State

During the period studied, the characteristics of the Oregon coast changed (Cooper, 1958). Inland human activities affected the natural functioning of ecosystems. Soil erosion contributed to the filling of rivers and estuaries, the suspended sediment changed water quality (e.g., high turbidity), and more sediment reached the coast (Dicken et al., 1961). Roads, railroads, jetties, breakwaters, houses, and practices have altered the hydrodynamic and sedimentary processes along the coast (Ruggiero et al., 2012, 2013). Excess sand deposition near jetties contributed to the increase in mobile dunes (Komar et al., 1976). However, other areas suffering from sand deficit due to construction and dredging were affected by erosion, causing the destabilization of the stable frontal dunes (Ruggiero et al., 2012, 2013). Land use changes in the coastal environment affected the quality of the landscape and habitats. Blowouts caused fine sand particles to be suspended in the air with the wind (Deur, 2016), resulting in poor air quality. Deposition of mobile sand in agricultural areas and removal of humus layers reduced soil fertility and increased leaching (McLaughlin and Brown, 1942), affecting soil quality.

4.1.4. Impacts

Where dune vegetation was destroyed, windblown sand encroached on forests, farmland, homes, roads, and railroads. On the Clatsop Plains, landward dune migration affected valuable public and private property (McLaughlin and Brown, 1942). By 1935, "an estimated 40 million cubic yards of sand had blown inland from the old foredune that extended from the Columbia River to Tillamook Head" (Deur, 2016). Lakes and marshes developed as the rivers were partially trapped by the sand (Dicken et al., 1961). On the Siltcoos, Tahkenitch, and Nestucca Rivers, shoaling threatened fish migration (McLaughlin and Brown, 1942). Decreased soil fertility and increased soil acidity resulted in loss of arable land (McLaughlin and Brown, 1942).

4.1.5. Responses

Until the late 20th century, the prevalent dune management policy on Oregon's coastal counties was to stabilize the sand and protect economic activities. The dune stabilization methods used in Oregon and other parts of the world evolved from European techniques developed by the French engineer Nicolas Brémontier in the late 18th century and implemented on a larger scale by the French Forestry Service in Gascony

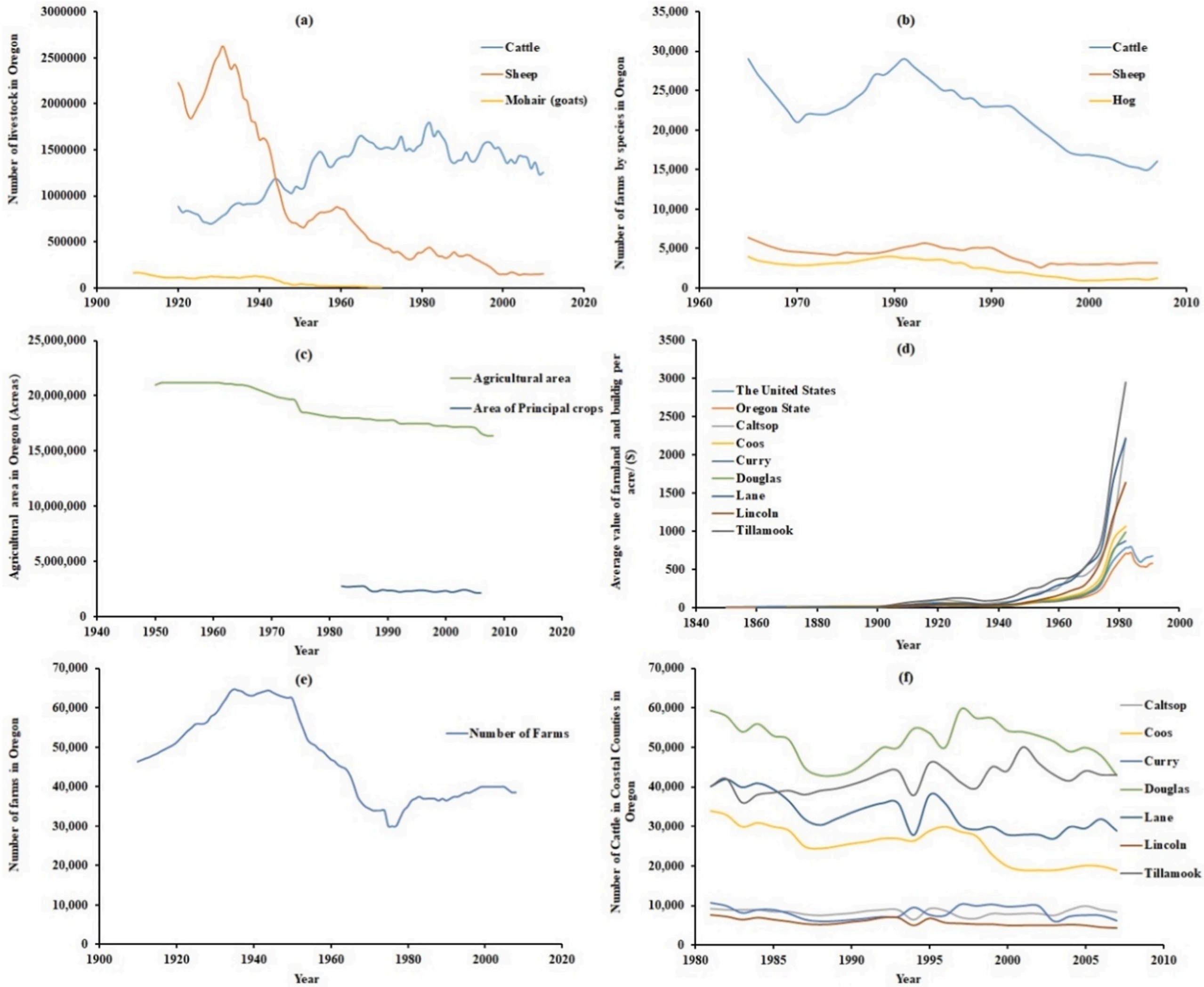

Fig. 7. Time series of livestock and agricultural data for Oregon State, in the United States.
Source: United States Department of Agriculture – National Agricultural Statistics Service Oregon Field Office.

in the 19th century. These techniques were later adopted by other European nations facing similar problems with drifting sands, such as Denmark, Portugal and Spain. A good example of how such practices span the globe is the case of sand dune stabilization in South Africa, Australia and New Zealand, where the British empire's network of experts, European migrants, and scientific societies contributed to the spread and adoption of European sand dune control methods (Sampath et al., 2021, 2022). Following the established methods, *Ammophila arenaria* (European beachgrass) was introduced and planted in the U.S. Pacific Coast around 1869, in the Golden Gate Park, San Francisco. The seeds appear to have come from Australia. (Lamson-Scribner, 1895; Lamb, 1898). *Ammophila arenaria* was expected to prove as valuable in the Pacific as it had been on the European Atlantic coast (Lamson--Scribner, 1895; Morning Oregonian, 1900b). In the late 19th century, the U.S. Department of Agriculture (USDA) and the Oregon Railroad Navigation Company worked together to test the adaptability of various grasses in the region (Heppner Gazette, 1899). A state experiment station for sand-binding plants (i.e., plants that effectively trap the sand and reduce wind erosion) was established at Gearhart Park, Clatsop (Morning Oregonian, 1900a). In the early 20th century, a few attempts were made to fix the dunes along the coast, such as experiments with willows near Florence by the forester in charge of the Siuslaw Forest (Coos Bay Times, 1913); or the planting of sand-binding grasses on the north side of Coos Bay to prevent drifting sand from encroaching on the railroad (Morning Oregonian, 1916).

In the 1930s, the threat posed by dunes prompted Clatsop County residents and officials to request assistance from the USDA Soil Conservation Service (SCS) (Deur, 2016). An extensive dune control effort - the Warrenton Dune Demonstration Project - was implemented by the SCS with support from the Civilian Conservation Corps and the Oregon Coastal Conservation and Development Commission between 1935 and 1941 (Schwendiman, 1977; Reckendorf et al., 1985; Deur, 2016). On the Clatsop Plains, many acres of shifting sands were gradually stabilized through the creation of a foredune and plantings. Three main species - *Ammophila arenaria*, *Ammophila breviligulata* (American beachgrass), and *Elymus mollis* (American dunegrass) – were used (Schwendiman, 1977; Crook, 1979; Wiedmann, 1998). Ammophila arenaria, Ammophila breviligulata are congeneric species and non-native to the State of Oregon. The success of this initiative subsequently provided the technical information for a standardized approach and the incentive to use human-driven dune stabilization as a management tool on the West Coast (Reckendorf et al., 1985) (Table 2).

In the 20th century, in accordance with a new perception about the coastline, resource exploitation, as well as recreation and conservation concerns, set the tone for the relationship between people and the dunes in Oregon. In an early development of landscape conservation policy, a portion of the dune area and coastal forest was incorporated into the Siuslaw National Forest by President Theodore Roosevelt in 1908

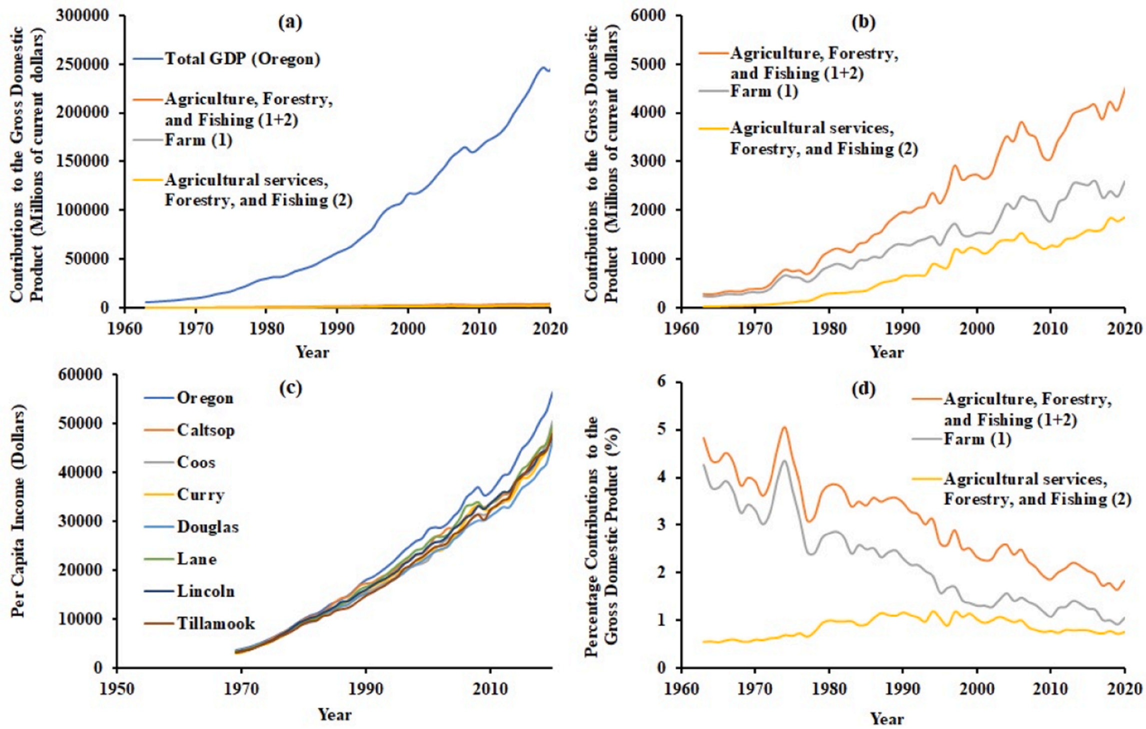

Fig. 8. Contribution from livestock management and agriculture to the Gross Domestic Product and per capita income in the Oregon State and its coastal counties. *Source: U.S. Department of Commerce / Bureau of Economic Analysis / Regional Economic Accounts.*

Table 2
The sequence of the dune stabilization approach (based on Schwendiman, 1977).

Step	Activity
Primary stabilizer	Built catching fences Foredune formation Plantings: mainly European beachgrass, *Ammophila arenaria* (L.) Link, American beachgrass, A. *breviligulata* Fern., or American dunegrass, *Elymus mollis* Trin. Use Nitrogen fertilizer during the dormant season.
Secondary stabilizer	Permanent grasses and legumes are seeded 2 years later Plantings: seaside lupine, *Lupinus littoralis* Dougl., purple beachpea, *Lathyrus japonicus* Willd., seashore bluegrass, *Poa macrantha* Vasey., and native red fescue, *Festuca rubra* L.
Tertiary Stabilizer	The final control was with woody plants that are well adapted to rough areas. Plantings: Scotch broom, *Cytisus scoparius* (L.) Link. Hooker willow, *Salix hookeriana* Barratt, Nootka rose, *Rosa nutkana* Prese., and shore pine Pinus contorta Dougl.

(ODRC, 2018). Such early efforts with foresight were taken to establish landscape conservation policies in several states including the Oregon State. In 1913, the state government passed legislation to ensure public access to Oregon's beaches (Deur, 2016). In 1967, the Oregon Beach Bill established public ownership of land from the waterline to sixteen vertical feet (4.88 m) above mean low tide (OSG, 1967). The Oregon Dunes National Recreation Area Act of 1972 guaranteed the recreational use and enjoyment of a stretch of coastline, dunes, forests, freshwater lakes, and facilities for present and future generations (OSG, 1972). In 1973, the Oregon Coastal Conservation and Development Commission (OCCDC) recognized beaches and dunes as one of the resource categories of the Oregon Coastal Planning Program. The OCCDC developed an inventory and drafted the preliminary policy statements and recommended actions that became the basis for Goal 18 - Beaches and Dunes (Fig. 9), adopted in 1976, based on the Coastal Zone Management Act of 1972 (Lindberg, 1979). In general, since then, coastal zone land use policies should be consistent with coastal goals 16 to 18.

Goal 18 requires that all uses be based on the capabilities and limitations of beaches and dunes and the adverse impacts they may have on the sites and adjacent areas. It regulates any development, including residential, commercial, or industrial buildings, on beaches, foredunes subject to ocean undercutting or wave overtopping, and interdune areas subject to ocean inundation. All actions on beaches and dunes should be regulated to minimize the resulting erosion, including the destruction of vegetation and the construction of shoreline structures. Based on Goal 18, cities and counties adopted local coastal comprehensive plans in the 1980s, establishing special zoning or overlay zones that required any proposed development or dune disturbance to be approved by local officials. They also imposed minimum setbacks from the shoreline. Nevertheless, many foredune areas were zoned for residential use prior to the plans and were still able to be developed (ODLCD, 1989).

4.2. Dune issues from the late-20th to early 21st century

4.2.1. Drivers

Demographic changes and socioeconomic reasons led to further concentration of population (Fig. 6) and activities (Figs. 7 and 8) along the Oregon coast during the last decades of the 20th century (Ruggiero et al., 1997). Urbanization, coastal and river engineering, dredging, and resource extraction have continued. Persistent use of European and American beach grasses during the 1900s, with improvements in planting techniques and use of fertilizers (Schwendiman, 1977), resulted in the dominance of these non-native grasses. In some places, tall vegetated dunes were perceived as a nuisance, blocking views of oceanfront homes (ODLCD, 1989). At the same time, the perception about dunes changed, their dynamic characteristics were accepted as being part of the system function, and having stable vegetated dunes is no longer the main purpose of dune intervention. The idea that "bare sand is good" (Delgado-Fernandez et al., 2019) is a significant shift from the 19th and early 20th century view of unvegetated, barren dunes as wastelands.

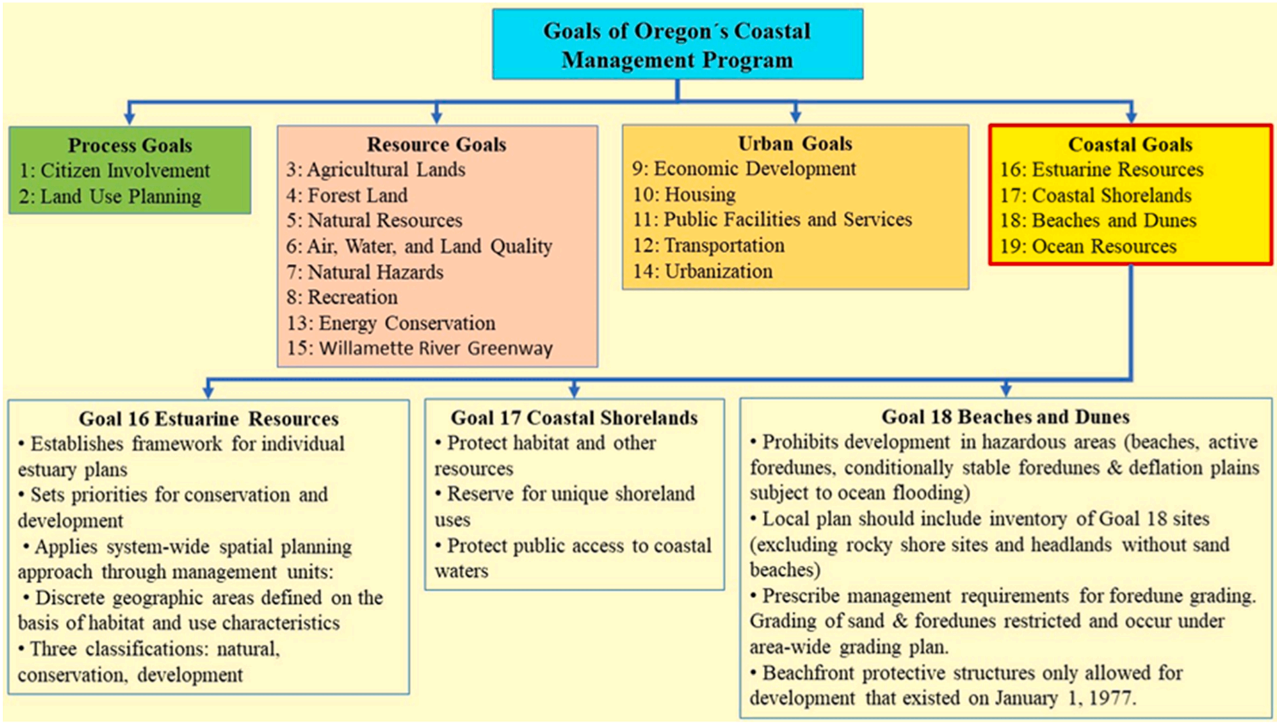

Fig. 9. Policy framework: State goals of the Oregon Coastal Management Program (Based on Snow, 2019; Spangler, 2019a; b; Reed et al., 2019).

Recreational and esthetic fulfillment, conservation concerns, and risk awareness became important aspects of land use policy. As a result, dunes came to be valued for the ecological services they provide and are considered critical for protecting developed beaches from flooding and erosion. Grading dunes, maintaining vegetation, or removing invasive grasses are now important management issues. Drivers related to climate change (e.g. sea level rise) are also relevant. The setbacks of old responses combined with new factors are driving a new cycle of pressures and impacts on the environment and society (Fig. 10).

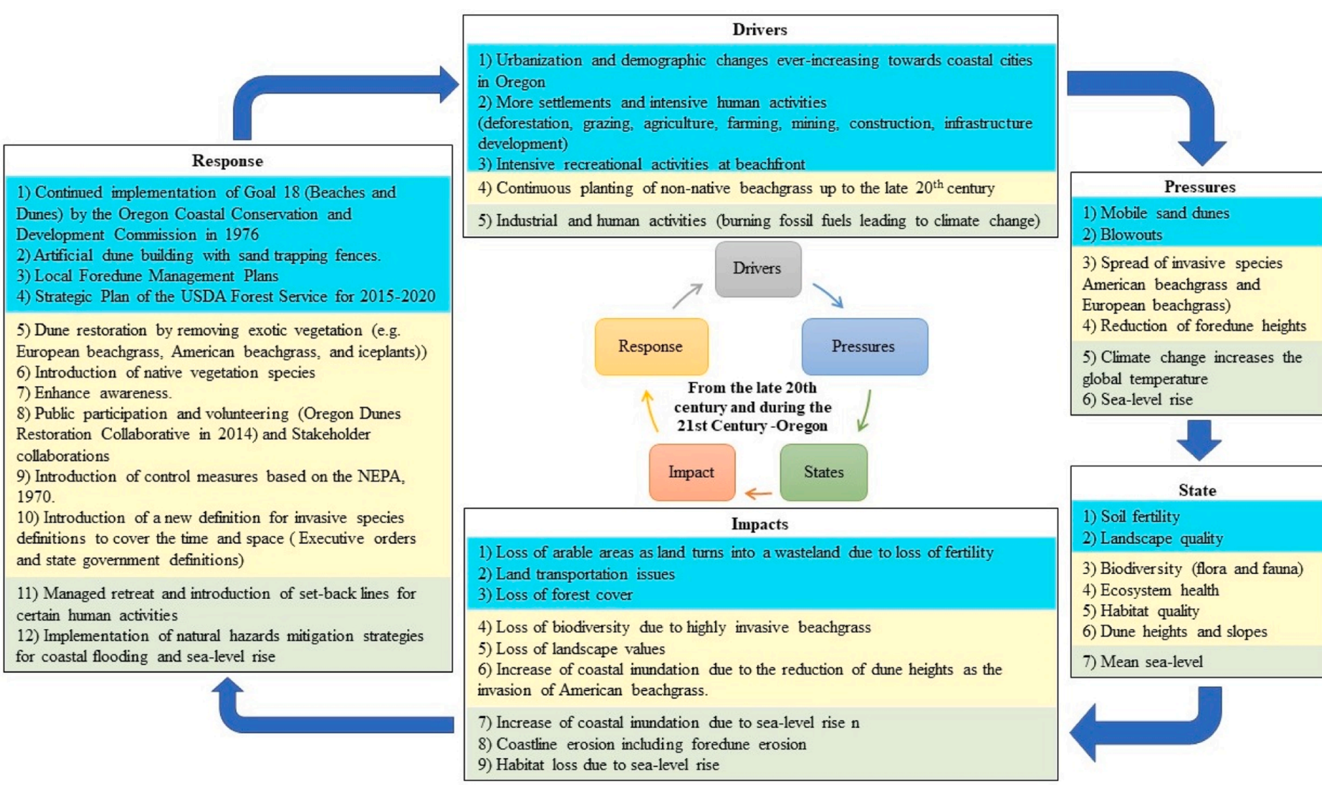

Fig. 10. DPSIR analysis of sand drifting from late-20th to early-21st century. Different colors indicate the Pressures, States, Impacts and Responses corresponding to a particular set of Drivers.

4.2.2. Pressures

The planting of non-native beachgrasses for dune stabilization has resulted in the spread of some species, that became invasive and contributed to the reduction of the native flora and fauna of these areas (Stein, 2015). Large vegetated foredunes were a consequence of the introduction of European beachgrass. In recent years, however, American beachgrass has become the dominant species, overtaking European beachgrass. Surveys along the Oregon coast have shown that its current range extends from Long Beach in Washington State to Pacific City in Oregon. Meanwhile, human infrastructure and activities are disrupting the functioning of natural systems, affecting the amount and distribution of sand to the beaches and the natural evolution of dunes. Sea level rise and more extreme storm surges due to global climate change added to human and other natural factors are putting more pressure on coastal areas.

4.2.3. State

The state of the dune landscape changed as the non-native vegetation species became dominant. They contributed to the stability of the sand and led to the emergence of foredunes and deflation plains, new wetlands and valleys (Hacker et al., 2012; Ruggiero et al., 2018). On the other hand, the invasion of American beachgrass reduced the height of dunes previously colonized by the European beachgrass, because the American species originates the creation of lower dunes. The lack of sediment supply also reduces the size of the beaches and the volume of the dunes in some places. But in others, such as Seaside, the beaches are accreting, resulting in further dune growth due to an abundant sediment supply.

4.2.4. Impacts

Non-native grasses have altered the ecological conditions of the mobile dune environment. European beach grass with its deep-rooted rhizomes, stout culms and tall leaf blades effectively traps the sand and reduces wind erosion, causing less fresh wind-blown sand from reaching the area behind the foredune. In the leeward areas, the wind blows the sand to the water table, creating a deflation plain where, over time, permanent wetlands and woodlands replace open shifting sands (ODRC, 2018; Bowker, 2015). Changes to the habitat of native species affect biodiversity (dunes and associated environments are home to more than 400 species of wildlife), putting plants and animals, such as the pink sand verbena and the western snowy plover at risk (ODRC, 2018). In some places, the vegetated dunes have grown so much that coastal residents complain of being landlocked (Cannon Beach Gazette, 2015). In recent years, however, the proliferation of American beachgrass has resulted in low dune heights, which some fear may compromise the natural function of dunes as coastal defenses against flooding during extreme events (Ruggiero et al., 2018). In addition, recent developments bring another factor of uncertainty: a case study of 12 coastal sites in Washington and Oregon showed that the two non-native, congeneric, dune-forming beach grasses (*Ammophila arenaria* and *A. breviligulata*) have hybridized in the sand dunes of the US Pacific Northwest coast (Mostow et al., 2021). Although the shoot height exceeds that of either parental species, the hybrid plant exhibits many morphological traits common to both parental grasses (Mostow et al., 2021 (Fig. 11).

Oregon has one of the highest wave climates in the world. On this coastline, the erosive effects of increasing wave heights are greater than the effects of sea level rise due to climate change (Ruggiero, 2013).

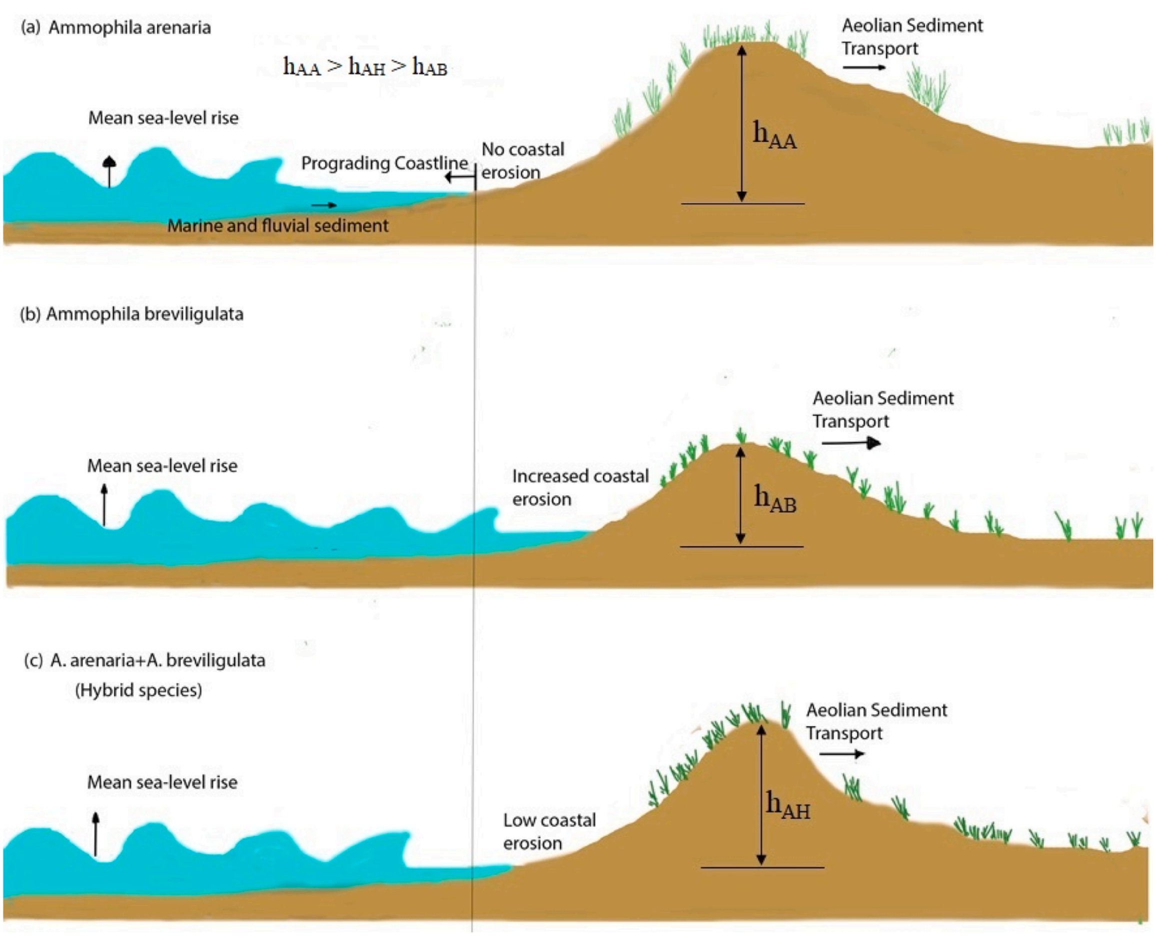

Fig. 11. Response of dunes to different species of beachgrass in Oregon in the United States.

Nevertheless, the cumulative effects of both forms of erosion will be severe in Oregon during this century. The degradation of natural defenses will also contribute to increased impacts on human settlements and economic activities on developed coasts during extreme sea-level rise events (Allan et al., 2017).

4.2.5. Responses

Statewide Planning Goal 18 remains the guiding principle for beach and dune management in Oregon. Its application is administered by local governments through comprehensive plans that have been updated since the 1980s. In 1984, an amendment was made to allow for foredune grading, which requires the preparation of local Foredune Management Plans (ODLCD, 1989; Shoreland Solutions, 1996; CCB, 2020). Remedial dune grading was the solution found for sand inundation of developed beaches with large accumulations of sediment. The removed sand was not taken out of the system but placed on the foreshore slope of the foredunes. The dunes were then stabilized with non-native beachgrasses such as *Ammophila arenaria* (TFGS&LCPD, 2012; Shoreland Solutions, 1996; ODLCD, 1989). State regulations on foredune alterations have attempted to balance the enjoyment of ocean views, sand inundation reduction, and the protection of ecosystem values and functions (ODLCD, 1989). The comprehensive plans of the 1980s already aimed to maintain the sea erosion/flood protection function of the foredune (Shoreland Solutions, 1996). In recent decades, natural hazard mitigation strategies have become more prominent in local plans (ONHMP, 2015) and regulations due to regional sea level rise projections and improved understanding of the vulnerability of sandy beaches and dunes to coastal erosion and ocean flooding (Weber, 2015). For example, the updated version of the Cannon Beach Foredune Management Plan adds an additional elevation requirement to the minimum FEMA BFE+4 feet for foredunes lowered by grading to protect the community from the impacts of climate change. In this plan, grading is prohibited for ocean views, and the overall goals are to achieve a balance in dune maintenance to withstand the erosive effects of extreme weather by maintaining adequate sand volume and reinforcing weak points, to protect valuable plant and animal habitats, the integrity and beauty of dunes, and assuring public access, facilities and utilities (CCB, 2020).

In the early 21st century, another approach is influencing land use policy for coastal dune restoration projects in the US that benefits native ecosystems, natural processes, and the listed species that inhabit or use these environments. As described in the coastal dune restoration environmental assessment by the National Park Service (NPS, 2015) dune habitat restoration is guided by the National Environmental Policy Act of 1970. NPS (2015) recommendations indicate the removal of highly invasive non-native plant species that have severely altered dune structure, natural processes, vegetation communities, and habitat function for native plants and animals. At the federal level, invasive species management was based on the 1999 Executive Order (EO) 13112 (EO, 1999), which reiterated the 1977 EO 11987 (EO, 1977) on exotic organisms. EO 13112 was the first to coordinate federal action on the complex impacts of invasive species on the economy and human health (Meyerson et al., 2019). In 2016, EO 13751 (EO, 2016) expanded EO 13112 by explicitly linking invasive species to national security, human health, and military readiness, recognizing the impacts of climate change, and highlighting the need for interagency cooperation, public education, and technology to prevent and manage bio-invasions (Meyerson et al., 2019).

At the local level, public participation is encouraged through hearings and community engagement programs (ODLCD, 2014). Non-profit organizations and volunteer initiatives are at the forefront of promoting dune restoration and public awareness of invasive species encroachment. In 2014, the Oregon Dunes Restoration Collaborative was created to formulate an action strategy, prioritize restoration projects, pursue funding opportunities and build public support to stop the spread of invasive beachgrasses. The ODRC is committed to slowing landscape change and restoring wind-blown sand dunes by removing invasive species using fire, herbicides, hand pulling and bulldozing (ODRC, 2018).

4.3. Change in land use and land cover from the late 19th to the early 21st century

The 1879 map shows the degree of urbanization and settlement in the coastal counties at that time (Fig. 12a). There was already a railroad network and probably some roads connecting the major towns and villages, but they were not depicted. Rivers were the better way to travel inland at that early period. By 1937, roads were classified as paved (asphalt), improved (gravel, stone, and shell), graded (drained and maintained), dirt (sand and mud), and under construction (Fig. 12b). By this time, the number of coastal cities had increased significantly. Interstate Highway 101 was built from 1920 to 1936, cutting through the dunes in many places. State highways and other types of roads were also built near the coast. Information from 1938 indicates the approximate area of timber production, livestock production, farms, fish and dairy processing industries, and mining sites. Timber and livestock production were especially popular in Clatsop, Tillamook, and Coos counties.

The 2021/2022 land use and land cover maps show the current high to medium-intensity development in the coastal areas (Fig. 12c and d). Agricultural activities occur in Coos and Curry counties but are primarily concentrated in counties such as Washington, Yamhill, Polk, Benton, and Lane. These, along with the coast, are highly urbanized areas. Evergreen forest, mixed forest, and shrub and brush are the predominant vegetation types near the Oregon coast. Emergent herbaceous wetlands are found near bays and estuaries.

4.4. Aspects for long-term sustainable coastal sand dune management

A long-term analysis of land use policies (Table 3) and the socio-environmental conditions of the region was undertaken using a DPSIR framework to understand the main issues of dune management on the Oregon coast. This study shows that the problems with the dunes are related to the introduction of new socio-economic practices by European-American settlers in the 19th century. These resulted in a series of environmental changes that caused several setbacks, including increased dune drift problems. Dune mobility was seen as a nuisance as sand encroached on agricultural land, settlements and other infrastructure (Sherman and Nordstrom, 1994). Dune stabilization was the solution adopted, following what had been done in other countries. The main strategy was the planting of European beachgrass, based on the European experience and the San Francisco experiments. By the 1970s, stabilization techniques had been standardized and widely implemented (Schwendiman, 1977). The work was supported by the US federal and state government through local agencies.

During the 20th century, the socio-environmental context of Oregon's coastal region changed dramatically. As the demographic, economic and social core of the region moved to the coast, more pressure was placed on the area (Deur, 2016). Urbanization, coastal and river engineering, dredging and resource development altered the balanced functioning of coastal ecosystems by reducing their resilience (Hansom, 2001). The last decades of the century were marked by a new understanding of beaches and dunes throughout the world, as the development of scientific knowledge on coastal systems clarified their role and importance in the natural dynamic processes. Resource exploitation and the commodification of nature began to run parallel to concerns about the esthetic significance of landscapes and ecosystem conservation (Geelen et al., 2015; Houston, 2016). This it can also be seen in the passage and final adoption of the Coastal Management Act of 1972, when the Congress for the first time declared a national interest in land use decisions that had previously been considered local (Malone, 1991). Awareness of the vulnerability of beach-dune systems and the inherent risk of allowing development in such a geologically active environment

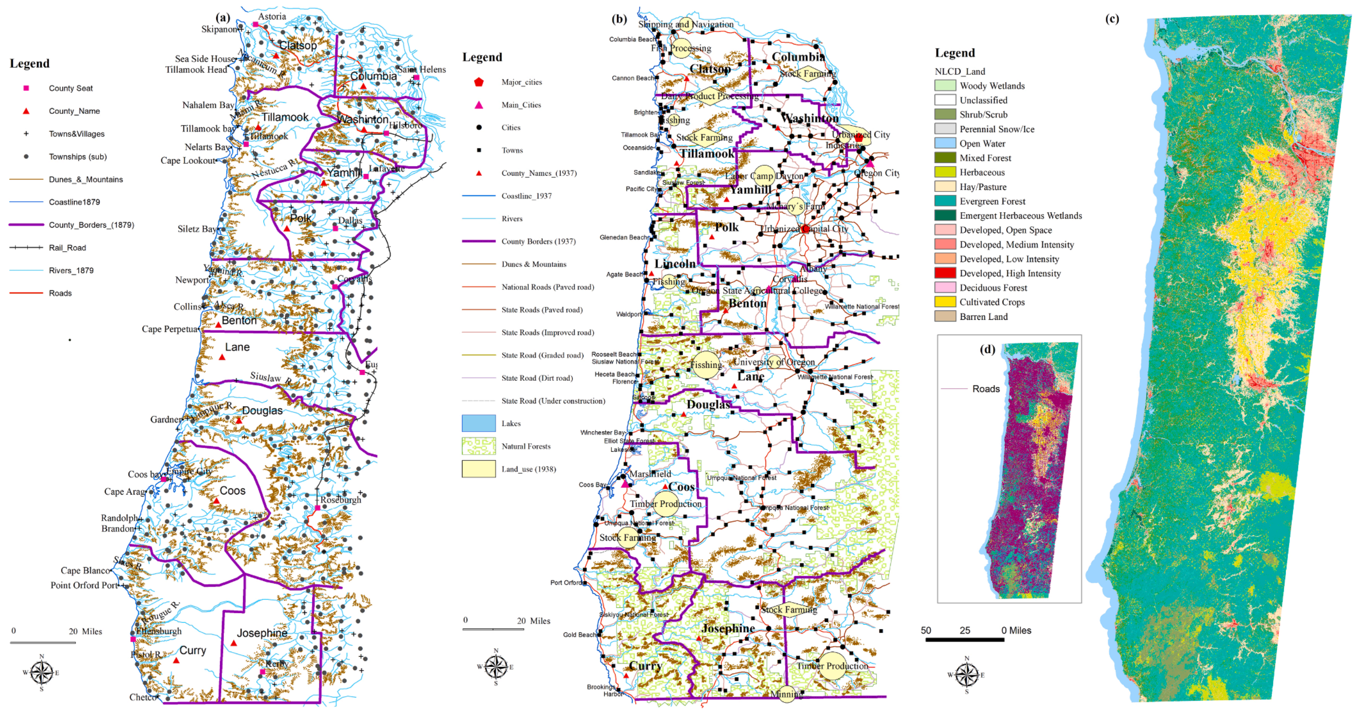

Fig. 12. Land use in the coastal counties of the Oregon State in the US from a) 1879, b) 1937/1938 and c) 2021/2022. (Sources: for maps 13a and 13b, David Rumssy map collection and for maps 12c) and 12d) National Land Cover Database (NLCD, 2021) of the Multi-Resolution Land Characteristic Consortium and Oregon GEOHub Repository, respectively).

Table 3
Important policy and legal tools related to the management of coastal sand dunes in the State of Oregon, United States.

Year	Important policy and legal tools related to the management of dunes in Oregon
1908	Integration of dune and forest areas by President Theodore Roosevelt
1913	Oswald West Act, declares all "wet" sand beaches to be public highways and assure public access to Oregon beaches
1919	Oregon legislature permits cities to zone private land
1947	Oregon legislature permits counties to zone private land
1967	Oregon Beach Bill: Provides for public use, recreation and enjoyment of the ocean shore in perpetuity, dry sands well as "wet". established the Ocean Shore Recreation Area, public access policy, and shore protection permits; Administered by Oregon Parks and Recreation Department
1967-2003	Submerged/Submersible Lands - managed in the public trust by the Dept. of State Lands (DSL) and State Land Board [amendments from 1967 to 200]
1969-1970	National Environmental Policy Act (NEPA)
1971	Oregon Coastal Conservation and Development Commission (OCC&DC)
1973	Oregon Land Use Planning Act (SB 100 – Senate Bill 100 (ORS 197): Creates the Land Conservation and Development Commission (LCDC) and charges it with adopting statewide planning goals
1975	OCC&DC Final Report to Legislature
1975	Legislature makes the Department of Land Conservation and Development (DLCD) Oregon's CZM agency. LCDC adopts State-wide Planning Goals 1-14.
1976-1977	LCDC adopts Coastal Goals: 16) Estuarine Resources, 17) Coastal Shorelands, 18) Beaches and Dunes, 19) Ocean Resources.
1977	Oregon Coastal Management Program receives federal approval from NOAA
1977	Executive Order 11987 (Exotic Organisms)
1976-1986	LCDC acknowledges all city and county comprehensive plans
1994	Oregon Dunes National Recreation Area Management Plan ~ 1994
1999	Executive Order 13112 (Invasive species)
2014	Oregon Dunes Restoration Collaborative creation
2015	Oregon natural hazards mitigation plan (DLCD)
2016	Executive Order 13751 (Invasive species)

has led to changes in their management. At the same time, it became clear that the planting of beachgrasses had unexpected consequences, as they became invasive and out of control, changing the environmental conditions of the dunes at a rapid pace (Meyerson et al., 2019). The formation of tall vegetated foredunes led to the creation of extensive deflation plains and wetlands and the stabilization of the sand. The invasion of non-native species threatened the survival of native flora and fauna and contributed to the development of a new dune environment, where open bare sand was replaced by vegetated dunes, changing the landscape that people were used to seeing (Hacker et al., 2012).

Such phenomena have been experienced in various regions of the world (Hilton, 2006), and many dune restoration projects have been implemented since the early 21st century (Hoffmann et al., 2001; Rhind and Jones, 2009; Arens et al., 2013; Jenks, 2018; Ruessink et al., 2018). Twenty-first century dune management in Oregon - and globally - is a rather complex and paradoxical task due to the interplay of multiple natural and human factors: sea level rise, higher wave heights, increasing coastal flood risks, sand scarcity, invasive species, biodiversity loss, and human values. Groups such as the Oregon Dunes Restoring Collaborative are working to restore open sand dunes by removing non-native vegetation. The recreational opportunities offered by open sand and ocean views are particularly important to coastal cities with a tourist-based economy (Shoreland Solutions, 1996).

However, restoring active dune processes to establish some specific habitats may compromise the ecosystem services of the dunes as a natural coastal defense against storm surges (Ruggiero et al., 2018). The removal of the *Ammophila sp.* may increase the risk of frequent coastal flooding and the threat to areas of high socio-economic value. The efficiency of sand capture by vegetation is an important issue, especially where sand supply rates are low (Zarnetske et al., 2015), and many beaches in Oregon have serious coastal erosion problems (Allan et al., 2015). In the context of climate change, the cumulative impact of coastal flooding due to sea level rise and storm surge cannot be underestimated. Using nearly three decades of wave buoy observations along the Pacific Northwest coast, Ruggiero (2013) found that the increase in wave height of storm surges has played a more significant role in the increased frequency of dune overtopping and erosion than sea-level rise over the same period. However, the cumulative effect of storm surges with increased wave heights and long-term sea level rise would cause significant damage to dunes.

Attempting to define two distinct chronological/paradigmatic phases in dune management is problematic, as old drivers, pressures, impacts and responses continue and interact with new drivers, pressures and impacts determining present responses. There has clearly been a paradigm shift in the way dunes have been viewed in recent decades, as they have become valuable resources. However, current expectations about these ecosystems are in some cases contradictory, leading to different positions on their management and future. In the 21st century, as global environmental changes threaten human materialities and practices on coasts worldwide, communities are trying to protect the uniqueness of their local environment and safeguard their properties and assets. Dunes are one of the tools to do this. The responses adopted are mainly aimed at controlling the driving forces or pressures (prevention, mitigation), maintaining or restoring the state of the environment or helping to absorb the impacts (adaptation). Doing nothing seems to be less of an option (Gabrielsen and Bosch, 2003; Perrings, 2005).

Whatever land use policy is adopted, allowing natural dune building processes to occur is essential to the balanced functioning of the whole ecosystem. If sand is available and there is space to move away from the rising sea, dunes will migrate further inland as a dynamic geomorphological feature. Therefore, the best approach to dune management would be to avoid disturbing natural processes and to establish setback lines for human activities. This must be coordinated with solutions that meet the expectations of local communities.

5. Conclusion

The present study is an attempt to establish the relationships between human activities, dunes responses and, management solutions. The Drivers-Pressures-State-Impact-Response (DPSIR) framework was employed to understand the land use policies and other strategies developed to manage coastal sand dunes and their consequences in Oregon, United States of America, during two contrasting periods: from the 19th to the late 20th century and from there to the early 21st century. A combination of historical data and scientific literature was used to identify and analyse drivers, pressures, states, impacts and responses related to dunes during these two periods. As Euro-Americans settled in Oregon in the 19th century, they destroyed the dunes or removed dune vegetation for agricultural and stock farming activities and infrastructure construction. Consequently, coastal sand dunes were destabilized and wind-blown sand invaded human settlements, damaging agricultural fields and infrastructures. Thus, dunes were perceived as a threat and dune destabilization became a socio-economic issue. Non-native *Ammophila arenaria* and *Ammophila breviligulata* were then widely used for stabilization. Meanwhile, scientific development on coastal areas and new ideas about the recreational use of the beaches led to a paradigm shift regarding the dunes. This occurred at time when their management was becoming more complex due to socio-natural factors. As non-native beachgrasses turned invasive causing the loss of habitats and native biodiversity, their removal became the focus to restore the active dunes and support the natural processes of the ecosystem. However, the removal of these beachgrasses, particularly, *Ammophila arenaria,* results in low dune heights, increasing the risk of coastal flooding by reducing their effectiveness as a natural defense against sea-level rise and extreme storm surges. It's clear that the reason for the contrasting dune management policies in Oregon, as shown in the DPSIR analysis, is primarily due to human drivers, as their perceptions and activities have created new drivers, pressures, and corresponding impacts that required new measures and actions in response. Thus, land use policies for managing coastal dunes in Oregon and other places must balance efforts to restore the native biodiversity while avoiding new drivers with pressures and negative impacts on the ecosystem, such as coastal flooding in the context of accelerating and continuous sea-level rise in the 21st century.

CRediT authorship contribution statement

D.M.R. Sampath: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **J.G. Freitas:** Writing – review & editing, Supervision, Software, Project administration, Funding acquisition. **J.A. Dias:** Writing – review & editing.

Declaration of Competing Interest

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However, all authors declare that the study is not influenced by any institution that supported financial grants and there is no personal influence by any person whatsoever.

Data availability

Data will be made available on request.

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