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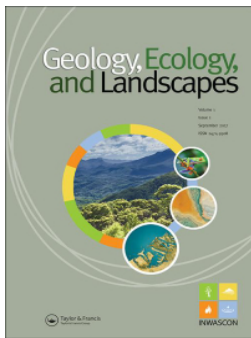
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An evaluation of coastal sand dune flora of Cuddalore District, Tamil Nadu, India: perspectives for conservation and management

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ABSTRACT

Most of the sand dunes close to the Cuddalore coast of India have been destroyed due to human pressure. The remaining coastal sand dune (CSD) is under extreme threat due to unplanned development. The purpose of this study is to investigate the species diversity, plant communities in different morphological types, spatial-temporal changes in the distribution of sand dunes, and the state of their conservation. In the coastal dunes of Cuddalore, 25 perpendicular transects parallel to the coast were sampled. Following analysis, 105 vascular plants from 39 plant families and 85 genera were identified as part of the CSD flora. The least disturbed sites harbored more species than the heavily disturbed sites. Members of the Poaceae and Fabaceae families dominated the flora, and 68% of the species in the dunes were herbaceous. The sand dune cover is significantly reduced and fragmented in various parts of the study area, and negative changes have been observed at a rate of more than 100 ha per year between 2003 and 2020. A CSD conservation policy that ensures species succession in the form of a three-layered zone is proposed as a long-term sustainable option for preserving Cuddalore coastal flora biodiversity.

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Conservation; coastal sand dunes; plant diversity; Spatial-temporal changes; zonal distribution

Introduction

Coastal ecosystems are made up of a mosaic of highly diverse plant communities that play an important role in ecological and economic balance (Sutton-Grier & Sandifer, 2019). Coastal sand dunes (CSD) are complex and dynamic ecosystems. They are zones of transition between terrestrial and marine biomes. The size, range, and sand stabilization vary depending on the distance from the sea, topography, and disturbance, and it supports a variety of habitats (Van der Maarel & van der Meulen, 2004). Worldwide zonation is very stable, with a consistent sequence of biotic gradients (Attorre et al., 2013; Doing, 1985). Flora and fauna communities in sand dunes have very specific ecological requirements, which determine their position along the environmental gradient from the seashore region (Carboni et al., 2010). Beaches and mobile dunes are considered azonal vegetation (Doing, 1985), whereas stable dunes inland are occupied by plant communities that are adapted to their local conditions (Buffa et al., 2012; Šilc et al., 2017).

CSD are formed primarily as a result of the interaction of tides, waves, and sand particle size, and they serve as a natural barrier against waves and windy storms (McLachlan & Defeo, 2001; Šilc et al., 2017). This region's biota is subjected to a number of limiting

factors such as soil fertility, marine aerosol, sandblasting, and sand burial (Oosting & Billings, 1942). Sand, wind biocrust, rainfall, flora dune covers and human activities will lead to formation of mobile (active), semi-active, or fixed (stable) dunes (Kinast et al., 2013). Biocrust and native vegetation play a significant role in mobility and dune stability (Yizhaq & Ashkenazy, 2022). Hanoch et al., 2018, further classified coastal dune based upon their rate of wind regime, sand deposition, and vegetation as, transverse dunes, barchans, linear dunes, parabolic dunes, and star dunes. These coastal ecosystems are considered extremely threatened on a global scale (Kutieli et al., 2000), and they suffer from heavy biodiversity loss and habitat simplification (Dolan & Walker, 2006), owing primarily to a steady increase in anthropogenic pressures such as urbanization, tourism, shoreline erosion, climate change, and biological invasion over the last decades (Acosta et al., 2009; Anderson et al., 2015; Brown & Zinnert, 2018; Carboni et al., 2010; Curr et al., 2000; Feagin et al., 2005; O'shea & Kirkpatrick, 2000; Prisco et al., 2020; Reidsma et al., 2006). Aside from acting as natural barriers against various coastal calamities such as tsunamis and cyclones, coastal sand dunes play an important role in preventing saltwater intrusion into fresh aquifers by preserving the aquifer in coastal areas and

coastal agriculture by preventing salt-laden winds gusting from the sea (Namboothri et al., 2008). Highly adapted flora and fauna groups, such as *Spinifex littoreus*, withstand harsh conditions and aid in the formation, stabilization, and post-storm recovery process. Climate change, sea-level rise, natural erosion, grazing, fire, and land transformation all have an impact on CSD (Aucelli et al., 2018; Davenport & Davenport, 2006; Feagin et al., 2005; Hernández-Cordero et al., 2017; Malavasi et al., 2016; Prisco et al., 2021).

Coastal sand dunes are a fragile unique ecosystem that was constantly under pressure caused due to both natural and man-made calamities. Especially population growth, urbanization and sea-and-sand tourism leads to increased alteration in the coastal areas, nearly 11% of global urbanization occurs in low elevation at 10 m above sea level and at present it supports about 400 million occupants worldwide (IPBES, 2019; Salgado et al., 2022). Average rate of urban expansion is comparatively higher in coastal regions than in islands, making coastal areas to be densely populated (Barragán & De Andrés, 2015; Seto et al., 2011). Coastal dunes are further destroyed due to extreme trampling, intrusion of off-road vehicles, restructuration of dune, flora elimination, and sand extraction (Hesp et al., 2010). All these factors lead to loss of native dune flora, while leads to the instruction and expansion of invasive species, which affects dune structure and alters its flora and fauna composition (Tordoni et al., 2019). Over a period of time coastline, urbanization and land changes increased as a result species richness decreased along with the alternation of functional traits in plants. The native psammophytes and halophytes dune species were found to be decreased with increased urbanization rate, whereas alien and non-dune species increased in their abundance (Salgado et al., 2022).

The Government of India designated coastal stretches influenced by tidal action as Coastal Regulation Zones in 1991 (CRZ). Among the four categories, CRZ I includes ecologically sensitive areas such as sand dunes, mangroves, and genetically diverse areas. India has a coastline of approximately 7516.6 km, which is shared by nine states and two union territories. The coastal line of Tamil Nadu is approximately 1076 kilometers long, accounting for approximately 15% of India's total coastal length (Arulmoorthy & Srinivasan, 2013). Indian CSDs have been extensively researched and documented in terms of their geological, physical, biological, and restoration characteristics. Despite the fact that coastal sand dune ecosystems are ecologically sensitive, their biotic composition is unknown. Local coastal human communities are heavily reliant on sand dune vegetation for a variety of reasons, including food, health, fodder, manure, and recreation. We assumed that increased

human activity is changing the original species composition, diversity, and distribution. As a result, in order to provide useful insights for the management of the fragile coastal ecosystem, we conducted an analysis with the goals of (1) quantifying the species richness, abundance, and diversity of the plant community in relation to disturbance, (2) assessing the conservation status of the different morphological dune types based on diversity, and (3) understanding the spatial-temporal change in sand dune distribution between 2003 and 2022.

Study area

Cuddalore is one of the fastest-growing industrial belts in Tamil Nadu's southern state. This area is specifically located on the Coromandel coast between 11°44'39" N and 79°47'00" E, south of the Puducherry Union Territory (Figure 1). Cuddalore is bounded on the east by the Bay of Bengal and on the south by Chidambaram. Cuddalore is a coastal town 10 m above sea level (Singh et al., 2021). The annual mean temperature is 27.8°C. The average annual rainfall in the district is 1206.7 mm, with summers (81.7 mm) receiving more rain than winters (44.1 mm). The region receives 697.8 mm of rainfall from the North-East monsoon and 383.1 mm of rainfall from the South-West monsoon. The average wind speed over the last year was 4 km/h.

Cuddalore, with a coastline of 57.5 km, has been designated as a multi-hazard prone district due to the effects of cyclonic depressions, heavy rains resulting in floods, and the severe damage caused by the 2004 Tsunami (Muthusankar et al., 2018). The coastal villages such as Pudukuppam (11°31'11.8" N and 79°45'50.7" E), TS Pettai (11°24'35.0" N and 79°48'04.8" E), Samiyaarpettai (11°32'37.1" N and 79°45,31.0" E), Kayalpattu (11°34'51.2" N and 79°45'25.2" E) and Rasapettai (11°39'27.7" N and 79°45'58.0" E) were among the study sites chosen for the dune diversity assessment and disturbance impacts on vegetation. Parangipettai, also known as Porto Novo, is a coastal town in the district's south that is densely populated and serves as a major industrial hub. The establishment of the IL&FS Thermal Power Plant in Pudukuppam, as well as the upcoming chain of large- and small-scale industries, has encouraged unsustainable coastal development projects, which pose a significant threat to the coastal ecosystem in a variety of areas.

Materials and methods

Floristic sampling

A comprehensive survey of plant species was initially conducted along India's Cuddalore coastline in order

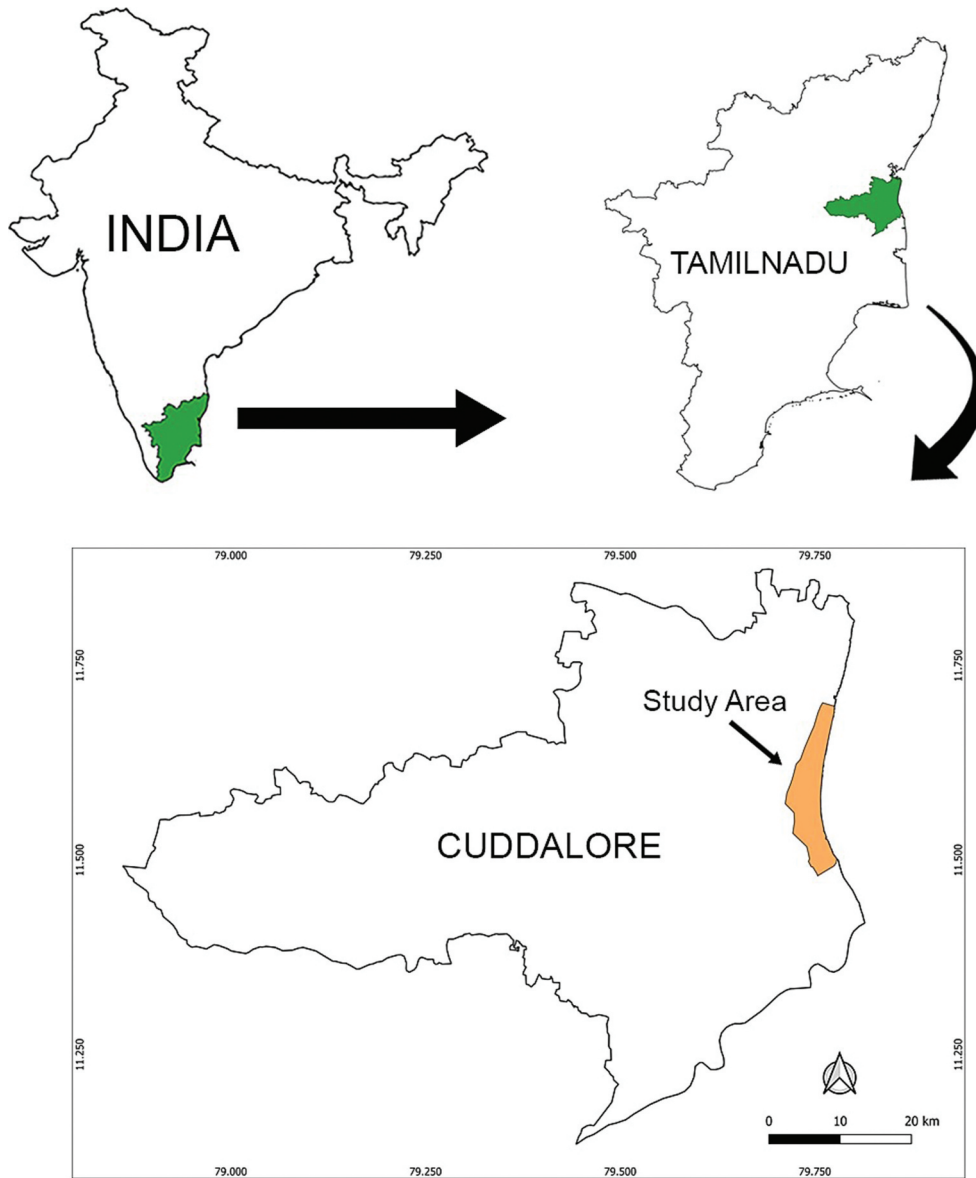


Figure 1. The geographical location of the study area.

to perform a representative sampling of different morphological dune habitats with varying levels of human disturbance. As a result, 25 perpendicular transects to the seashore were established in the study area (5 in each site) to investigate dune zonation, beginning with the annual vegetation of incipient dunes and progressing to the mixed vegetation of hind dunes. The length of each transect varied according to the morphology and width of the dunes. The percent cover of each vascular plant present was visually estimated, and frequency was calculated by counting the number of each species that occurred in the studied plots within different morphological dune types in contiguous 1 m × 1 m plots. This size was deemed adequate for the herbaceous vegetation studied in this study, primarily to avoid overlapping samples from different plant communities.

The following five disturbance factors affecting the conservation status of plant communities were

recorded for each transect: overgrazing, industrial scrap dumping, urbanization (settlements, road construction, and industries), recreation, and the presence of invasive species. Based on field observations, the degree of such human-induced disturbances was graded for each transect on an ordinal scale ranging from absent (0) to low (1), moderate (2), high (3), and severe (4). Furthermore, the distance from the sea and the total length of each transect (in metres) were examined as natural features.

Analysis of sand dune distribution changes

We used the spatial-temporal analysis of moving polygons (STAMP) framework to understand the spatial-temporal change in sand dune distribution between 2003 and 2020 (Robertson et al., 2007). At four levels of increasing complexity, this framework reports

spatial-temporal change events among polygons. The second level of this framework was used, which categorizes changes in sand dune distribution between 2003 and 2020 as disappearance, contraction, stable, expansion, and dunes generation. Stable areas are those that did not change, while lost areas are classified as contraction or disappearance based on their connectivity or lack thereof with stable areas.

Data analysis

Following Magurran, the diversity indices Shannon (H), Simpson (D), and Evenness were calculated (Magurran, 2004). Using Microsoft Excel 2019, the data were also analyzed using One-way ANOVA and the t-test to see if the population in each site was significantly different. Biodiversity Pro, version 2, was used for the Bray-Curtis analysis.

Results

Floristic composition in the study area

In the current study area, 105 vascular plant species from 85 genera and 39 plant families were identified (Table 1). The most common families were Poaceae, Fabaceae, Cyperaceae, and Rubiaceae (14, 13, 10, and 6 taxa, respectively; Figure 2). Only one species represented each of the 15 families. Herbaceous species made up the majority of the vegetation (68%) followed by climbers and creepers (14%), and trees and shrubs (18%) (Figure 3). Five invasive alien species (*Anacardium occidentale*, *Cocos nucifera*, *Croton bonplandianus*, *Dactyloctenium aegypticum*, and *Prosopis juliflora*) were found in the studied CSD, while only two endemic species (*Blumea eriantha* and *Cleome felina*) were found. In terms of life duration, 61 species (52%) were annuals, while 44 species (42% were perennials). The number of species in terms of diversity and abundance increased with increasing distance from the shoreline.

Diversity analysis

The species diversity was highest in the moderately disturbed site, which had the most species (21), followed by the less disturbed sites. Shannon's index for the primary dunes is higher in the highly disturbed site than in the slightly disturbed site, which was already higher than in the moderately disturbed site (Table 2). Even Simpson's index exhibits a similar pattern. Evenness (J) is equal to 0.89 in moderately disturbed and highly disturbed sites, and 0.87 in slightly disturbed sites. Among the primary dune sites, it is clear from the results that they are significantly different since the P values obtained for all the t-test and the ANOVA were less than 0.5.

Vegetation classification

Based on the coverage of 105 plant species recorded in the current study sites, it was possible to identify three vegetation groups associated with the different morphological dune types: beach berm/Incipient dune, Fore dune, and Hind dune, each with a specific plant cluster (Figure 4).

Incipient Dune

This group was characterised by *Canavalia cathartica*, *Cyperus arenarius*, *C. pygmaeus*, *Ipomoea pes-capre*, *Dactyloctenium aegypticum*, *Fimbristylis cymosa*, *Murdannia spirata*, *Spinifex littoralis* which are herbaceous perennial plant and *Casuarina equisetifolia*, *Cocos nucifera* are found on the Beach berm/Incipient dune. Species such as *Ipomoea pes-capre*, *Cyperus arenarius* and *Spinifex littoralis* occurred on seaward slope of Incipient dune.

Fore Dune

This group was characterised by *Borassus flabellifer*, *Casuarina equisetifolia*, *Cocos nucifera*, *Brachiaria distachya*, *Euphorbia rosea*, *Cyperus arenarius*, *Ipomoea pes-capre*, *Petalium murex*, *Spinifex littoralis* and *Spermacoce articularis* found in semi-stable dune which was located 60 m inland from the shoreline and the further landward zone. These species were the indicator species that separate incipient dune from foredune.

Hind Dune

Indicator species of this group were *Calophyllum inophyllum*, *Garcinia spicata*, *Fluggea leucopyrus*, *Phoenix pusilla*, *Gmelina asiatica*, *Gloriosa superba* and *Petalium murex*. More protected areas behind dense *Syzygium cumini* and *Calophyllum inophyllum* are characterized by various species such as *Asparagus racemosus* and *Azadirachta indica* with the admixture of the inland plants including *Capparis zeylanica*, *Coccinea grandis*, *Rivea hypocrateriformis* etc. The spaces between hind dune were covered with grasses and herbaceous plants. Notably, species such as *Spinifex littoralis*, *Cyperus arenarius*, *Euphorbia rosea*, *Desmodium triflorum*, *Oldenlandia corymbosa*, and *Ipomoea pes-capre* are very well presented on three dune types.

Spatial-temporal changes in sand dune distribution (2003-2020)

Within the nearshore area, the dune land cover consists of sandy beaches, incipient dunes, fore dunes, hind dunes, and associated landforms. The characteristics of this class have changed rapidly over time as a result of marine and coastal processes, as well as other anthropogenic activities such as plantations. This class's total area

Table 1. The list of sand dune flora under different zones from Cuddalore coast.

Species	Family	Habit	Native/Exotic	Annuals/Perennials	Beach berm/Incipient Dune	Fore Dune	Hind Dune
					0–20 m	21–60 m	61–120 m
<i>Abrus precatorius</i> L.	Fabaceae	Climber	N	P			*
<i>Achyranthes aspera</i> L.	Amaranthaceae	Herb	N	A		*	
<i>Aeschynomene aspera</i> L.	Fabaceae	Herb	N	A			*
<i>Almania nodiflora</i> (L.) R. Br. ex Wight.	Amaranthaceae	Herb	N	A		*	*
<i>Alysicarpus monilifer</i> (L.) DC.	Fabaceae	Herb	N	A	*	*	*
<i>Anacardium occidentale</i> L.	Anacardiaceae	Tree	E	P			*
<i>Asparagus racemosus</i> Willd.	Asparagaceae	Climber	N	P			*
<i>Axonocarpus compressus</i> (Sw.) P.Beauv.	Poaceae	Herb	N	A			*
<i>Azadirachta indica</i> A. Juss.	Meliaceae	Tree	N	P		*	*
<i>Blumea eriantha</i> DC.	Asteraceae	Herb	N	A			*
<i>Boerhavia diffusa</i> L.	Nyctaginaceae	Herb	N	P		*	*
<i>Borassus flabellifer</i> L.	Arecaceae	Tree	N	P		*	*
<i>Brachiaria distachya</i> (L.) Stapf	Poaceae	Herb	N	A		*	*
<i>Brachiaria reptans</i> (L.) C. A.Gardner & C.E. Hubb.	Poaceae	Herb	N	A			*
<i>Bulbostylis barbata</i> (Rottb.) C.B.Clarke	Cyperaceae	Herb	N	A		*	*
<i>Caesalpinia bonduc</i> (L.) Roxb.	Fabaceae	Climber	N	P		*	
<i>Calophyllum inophyllum</i> L.	Calophyllaceae	Tree	N	P			*
<i>Calotropes gigantea</i> (L.) R.Br.	Apocynaceae	Shrub	N	P			*
<i>Canavalia rosea</i> (Sw.) DC.	Fabaceae	Climber	N	P	*	*	
<i>Capparis zeylanica</i> L.	Capparaceae	Climber	N	P			*
<i>Casuarina equisetifolia</i> L.	Casuarinaceae	Tree	N	P		*	*
<i>Citrullus colocynthis</i> (L.) Schrud.	Cucurbitaceae	Climber	N	A			*
<i>Cleome felina</i> L.f.	Cleomaceae	Herb	N	A			*
<i>Cleome viscosa</i> L.	Cleomaceae	Herb	N	A		*	
<i>Coccinea grandis</i> (L.) Voigt	Cucurbitaceae	Climber	N	P			*
<i>Cocos nucifera</i> L.	Arecaceae	Tree	E	P			*
<i>Crotalaria pallida pallida</i>	Fabaceae	Herb	N	A			*
<i>Croton bonplandianus</i> Baill.	Euphorbiaceae	Herb	E	A			*
<i>Cynodon dactylon</i> (L.) pers.	Poaceae	Herb	N	P			*
<i>Cyanotis axillaris</i> (L.) D. Don ex Sweet	Commelinaceae	Herb	N	A			*
<i>Cyperus arenarius</i> Retz.	Cyperaceae	Herb	N	A	*	*	*
<i>Cyperus castaneus</i> Willd.	Cyperaceae	Herb	N	A			*
<i>Cyperus compressus</i> L.	Cyperaceae	Herb	N	A			*
<i>Cyperus pygmaeus</i> Rottb.	Cyperaceae	Herb	N	A	*		
<i>Cyperus rotundus</i> L.	Cyperaceae	Herb	N	A			*
<i>Cyperus stoloniferus</i> Retz.	Cyperaceae	Herb	N	A	*		
<i>Dactyloctenium aegyptium</i> (L.) Willd.	Poaceae	Herb	E	A	*	*	*
<i>Desmodium biarticulatum</i> (L.)F. Muell.	Fabaceae	Herb	N	P			*
<i>Desmodium triflorum</i> (L.) DC.	Fabaceae	Herb	N	P	*	*	*
<i>Dolichos trilobus</i> L.	Fabaceae	Climber	N	P			*
<i>Eleocharis atropurpurea</i> (Retz.) J.Presl & C. Presl	Cyperaceae	Herb	N	A			*
<i>Eragrostis plumosa</i> (Retz.) Link.	Poaceae	Herb	N	A			*
<i>Eragrostis tenella</i> (Linn.) P Beauv.	Poaceae	Herb	N	A			*
<i>Eragrostis viscosa</i> (Retz.) Trin.	Poaceae	Herb	N	A	*	*	*
<i>Euphorbia rosea</i> Retz.	Euphorbiaceae	Herb	N	A	*	*	*
<i>Ficus amplissima</i> Sm.	Moraceae	Tree	N	P			*

(Continued)

Table 1. (Continued).

Species	Family	Habit	Native/Exotic	Annuals/Perennials	Beach berm/Incipient Dune	Fore Dune	Hind Dune
					0–20 m	21–60 m	61–120 m
<i>Fimbristylis cymosa</i> R.Br.	Cyperaceae	Herb	N	A	*		*
<i>Fimbristylis falcata</i> (Vahl) Kunth	Cyperaceae	Herb	N	P			*
<i>Fluggea leucopyrus</i> Willd.	Phyllanthaceae	Shrub	N	P			*
<i>Garcinia spicata</i> (Wight & Arn.) Hook.f.	Clusiaceae	Tree	N	P			*
<i>Ocimum tenuiflorum</i> L.	Lamiaceae	Herb	N	P			*
<i>Gisekia pharnaceoides</i> L.	Molluginaceae	Herb	N	A		*	*
<i>Glinus oppositifolius</i> (L.) Aug. DC.	Molluginaceae	Herb	N	A			*
<i>Gloriosa superba</i> L.	Colchicaceae	Climber	N	A			*
<i>Gmelina asiatica</i> L.	Lamiaceae	Shrub	N	P			*
<i>Gomphrena celosioides</i> Mart.	Amaranthaceae	Herb	N	A			*
<i>Hedyotis graminifolia</i> L.f.	Rubiaceae	Herb	N	P		*	*
<i>Hedyotis herbacea</i> L.	Rubiaceae	Herb	N	A			*
<i>Hibiscus ovalifolius</i> (Forssk.) Vahl.	Malvaceae	Shrub	N	A			*
<i>Ipomoea pes-caprae</i> (L.) R.Br.	Convolvulaceae	Herb	N	P	*	*	*
<i>Ipomoea pes-trigridis</i> L.	Convolvulaceae	Herb	N	A			*
<i>Lannea coromandelica</i> (Houtt.) Merr.	Anacardiaceae	Tree	N	P			*
<i>Launaea sarmentosa</i> (Willd.)	Asteraceae	Herb	N	A	*	*	*
<i>Limnophila indica</i> (L.) Druce	Scrophulariaceae	Herb	N	A			*
<i>Lindernia crustacea</i> (L.) F.Muell	Linderniaceae	Herb	N	A			*
<i>Ludwigia perennis</i> L.	Onagraceae	Herb	N	A			*
<i>Mollugo disticha</i> (L.) Ser.	Molluginaceae	Herb	N	A		*	*
<i>Mollugo nudicaulis</i> Lam.	Molluginaceae	Herb	N	A			*
<i>Mollugo oppositifolia</i> L.	Molluginaceae	Herb	N	A			*
<i>Murdannia spirata</i> (L.) G. Brückn	Commelinaceae	Herb	N	A	*		*
<i>Oldenlandia corymbosa</i> L.	Rubiaceae	Herb	N	A	*	*	*
<i>Oldenlandia umbellata</i> L.	Rubiaceae	Herb	N	A	*	*	*
<i>Panicum repens</i> L.	Poaceae	Herb	N	A			*
<i>Panicum</i> sp.	Poaceae	Herb	N	A			*
<i>Paspalidium scrobiculatum</i> L.	Poaceae	Herb	N	P			*
<i>Pedaliium murex</i> Linn.	Pedaliaceae	Herb	N	A		*	*
<i>Perotis indica</i> (L.) Kuntze	Poaceae	Herb	N	A		*	*
<i>Phoenix pusilla</i> Gaertn.	Arecaceae	Shrub	N	P			*
<i>Phyla nodiflora</i> (L.) Greene.	Verbenaceae	Herb	N	A			*
<i>Phyllanthus amarus</i> Schum. & Thonn.	Phyllanthaceae	Herb	N	A		*	*
<i>Phyllanthus virgatus</i> G. Forst.	Phyllanthaceae	Herb	N	A			*
<i>Phyllanthus reticulatus</i> Poir.	Phyllanthaceae	Shrub	N	P			*
<i>Polycarpaea corymbosa</i> (L.) Lam.	Caryophyllaceae	Herb	N	A			*
<i>Polygala arvensis</i> Willd.	Polygalaceae	Herb	N	A			*
<i>Portulaca tuberosa</i> Roxb.	Portulacaceae	Herb	N	A			*
<i>Prosopis juliflora</i> (Sw.) DC.	Fabaceae	Tree	E	P		*	*
<i>Rivea hypocrateriformis</i> (Desr.) Choisy	Convolvulaceae	Climber	N	P			*
<i>Scoparia dulcis</i> L.	Plantaginaceae	Herb	N	P		*	*
<i>Senna occidentalis</i> (L.) Link.	Fabaceae	Tree	N	A			*
<i>Sida cordifolia</i> L.	Malvaceae	Herb	N	A		*	*
<i>Spermacoce articularis</i> L. f.	Rubiaceae	Herb	N	P	*	*	*
<i>Spermacoce hispida</i> L.	Rubiaceae	Herb	N	P	*	*	*
<i>Spinifex littoralis</i> (Burm. f.) Merr.	Poaceae	Herb	N	P	*	*	*
<i>Syzygium cumini</i> (L.) Skeels	Myrtaceae	Tree	N	P			*
<i>Tephrosia villosa</i> (L.) Pers.	Fabaceae	Herb	N	A			*

(Continued)

Table 1. (Continued).

Species	Family	Habit	Native/Exotic	Annuals/Perennials	Beach berm/Incipient Dune	Fore Dune	Hind Dune
					0–20 m	21–60 m	61–120 m
<i>Thespesia populnea</i> (L.) Sol. Ex Correa.	Malvaceae	Tree	N	P			*
<i>Tiliacora acuminata</i> (Lam.) Hook. f. & Thoms.	Menispermaceae	Climber	N	P			*
<i>Tinospora cordifolia</i> (Willd.) Hook. f.	Menispermaceae	Climber	N	P			*
<i>Trachys muricata</i> (L.) Pers. ex Trin.	Poaceae	Herb	N	A		*	*
<i>Tylophora indica</i> (Burm. f.) merr.	Apocynaceae	Climber	N	P			*
<i>Vernonia cinerea</i> (L.) Less.	Asteraceae	Herb	N	A		*	*
<i>Waltheria indica</i> L.	Malvaceae	Herb	N	P			*
<i>Wattakaka volubilis</i> (Lf) Stapf.	Apocynaceae	Climber	N	P			*
<i>Ziziphus oenoplia</i> (L.) Miller	Rhamnaceae	Climber	N	P			*
<i>Zornia diphylla</i> (L.) Pers.	Fabaceae	Herb	N	A			*

N-native; E-Exotic; A-Annual; P-Perennial; *-Presence.

is estimated to be 210 ha in 2003 and 92 ha in 2020. The sand dune cover is significantly reduced and fragmented in various parts of the study area, and negative changes at a rate of more than 100 ha have been observed between 2003 and 2020 (Figure 5). The sand dune formed a single large patch in 2003, but by 2020, it had fragmented into 21 small patches. The majority of the berm/incipient dune and foredune was converted to plantations, including Casuarina and the aromatic grass Vettiver.

Discussion

Species diversity and disturbance

During the survey, 105 species from 85 genera and 39 plant families were recorded in the study area. Nearly 70% of the Indian Coromandel coastal sand dune plants recorded so far (154) were found in the study area. The Coromandel coastal sand dunes are made up of 154 species from 108 genera and 41 families (Arun et al., 1999; Muthukumar & Samuel, 2011; Rao & Sherieff, 2002). The Poaceae family was found to be the dominant flora in our study. Several studies have found that temperate coastal sand dunes are dominated by Poaceae members, whereas the dominant plant families in the Indian and other tropics are Asteraceae, Cyperaceae, Fabaceae, and Poaceae (Arun et al., 1999; Rao & Sherieff, 2002; Sridhar & Bhagya, 2007; Arun & Sridhar, 2004; Rodrigues et al., 2011). Though the current findings are significant, they do not match those of a similar study conducted by Poyyamoli et al. (2011). The species diversity was highest in the moderately disturbed site, according to these authors, whereas our study found higher diversity and density in the highly disturbed sites of all dune types.

Disturbed dunes exhibit greater diversity as anthropogenic activities such as cultivation, industrial establishment, and recreational pressure increase, which may aid in the direct or indirect introduction of new species and associated species, as well as non-native or exotic species. Similarly, extensive grazing observed in the Pudukuppam site may be a cause of non-native species propagation via seed dispersal by cattle. Plants such as *Ipomea pes-caprae* and *Spinifex littoreus* were found on the primary dunes, and most importantly, clear zones of these two species were found in the moderately disturbed Kayalpattu site. *Ipomea pes-caprae* also allowed other species to grow in the site. This suggests that these species occur on dunes that are stabilized or moderately disturbed. In the same Kayalpattu region, the *Ipomea pes-caprae* zone was followed by the continuous growth of *Canavalia rosea*. The typical psammophytes are gradually being replaced by invasive plants such as *Prosopis juliflora*, which are also a result of increased human activity and conservation strategies that have failed. *P. juliflora* is a fast-growing invasive species that can withstand harsh conditions and produces roots faster than shoots (Gupta & Balara, 1972). They are also known for producing a large number of pods that are consumed and dispersed by cattle, assisting in the species' rapid propagation (Muthana & Arora, 1983). Furthermore, Arulmoorthy and Srinivasan (2013) reported that the Pudupettai dunes in Cuddalore are harmed by the construction of a thermal power plant, and the vegetation of the Annankoil dunes is also harmed by the harbor construction.

The presence of specialized plants such as *Ipomea pes-caprae* and *Spinifex littoreus*, which are capable of maintaining dune stability but can also colonize patches of sandy bare area and grow quickly down an eroded

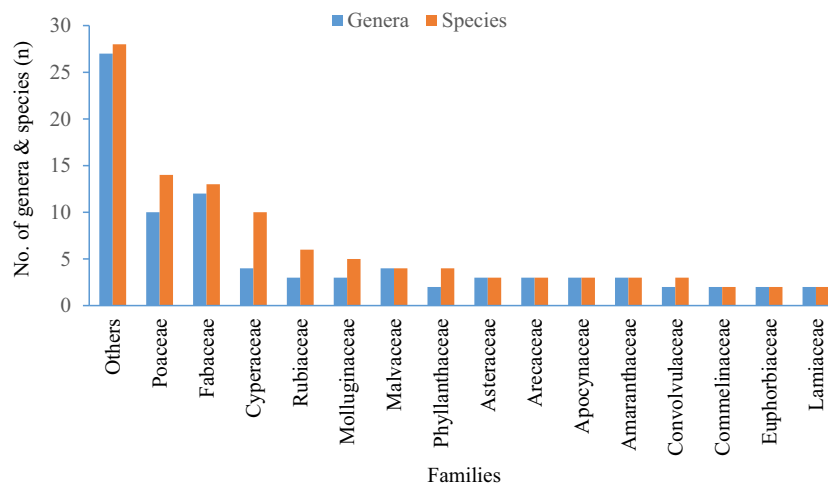


Figure 2. Contribution of plant species from families of the coastal sand dune.

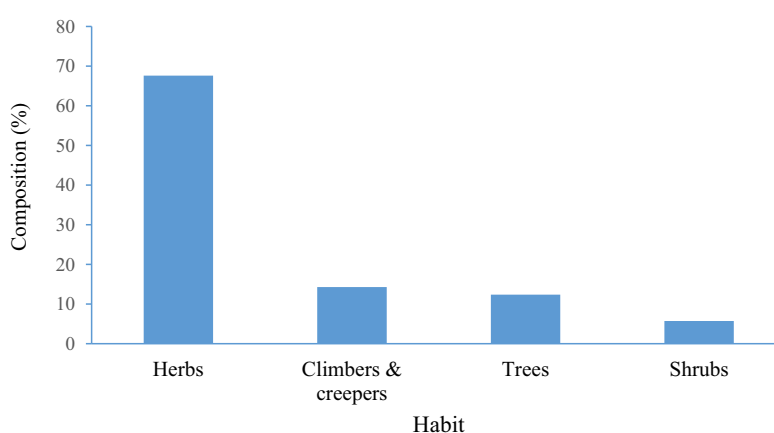


Figure 3. Percentage of coastal sand dune species representing different habit types.

Table 2. Diversity indices values of the study sites.

Sl. No.	SITE	SHANON'S INDEX (H)	SIMPSON'S INDEX (D)	Hmax	Evenness J = H/Hmax
1	IL&FS*	2.52	0.89	3.05	0.82
2	Samiyar pettai**	2.37	0.88	2.77	0.85
3	TS Pettai***	2.14	0.85	2.56	0.83
4	Ashley's Broken Bridge*	2.28	0.88	2.56	0.89
5	Kayalpattu**	1.96	0.84	2.19	0.89
6	Rasapettai***	2.17	0.87	2.48	0.87

*Highly disturbed **Moderately disturbed ***Slightly disturbed

face to help build and restore the dune profile, is critical to the formation, stabilization, and post-storm recovery process (Muthukumar & Samuel, 2011). Plantations of species such as *Casuarina equisetifolia* are well adapted to the coastal region and protect dune sites from erosion and natural disasters along the shoreline; however, it is important to note that the growing need for cultivation has negative effects on native populations and suppresses local species by lowering the water table (Anbarashan et al., 2017, 2020; Namboothri et al., 2008). Coastal communities most often encourage the presence of commercially important non-native species, resulting in the extinction of native species.

Unsustainable activities and their adverse effects

Based on field observations and interactions with locals and experts, it is clear that the currently operational IL&FS thermal power plant and the remnants of NOCL (Nagarjuna Oil Corporation Limited) projects have harmed the locals and the environment, as well as impacted the study area's land use pattern. Due to opposition from the local population, IL&FS, a coal-based power plant, had previously caused respiratory, visibility, and other issues due to the dispersion of fly ash, which was later reduced by installing fly ash capture screens within the industrial premises. Similarly, the NOCL project, which is currently on hold, has had a significant impact on the landscape due to the dumping of construction debris on the coastal dunes near the industrial site. The industrial projects also include the construction of a port and the construction of bridges and structures near the sea in order to transport raw materials to the industries via conveyer belts. With the exception of these, the development of industries prior to IL&FS, such as SIPCOT in Cuddalore, has been a major reason for road construction, resulting in increased access to coastal dune

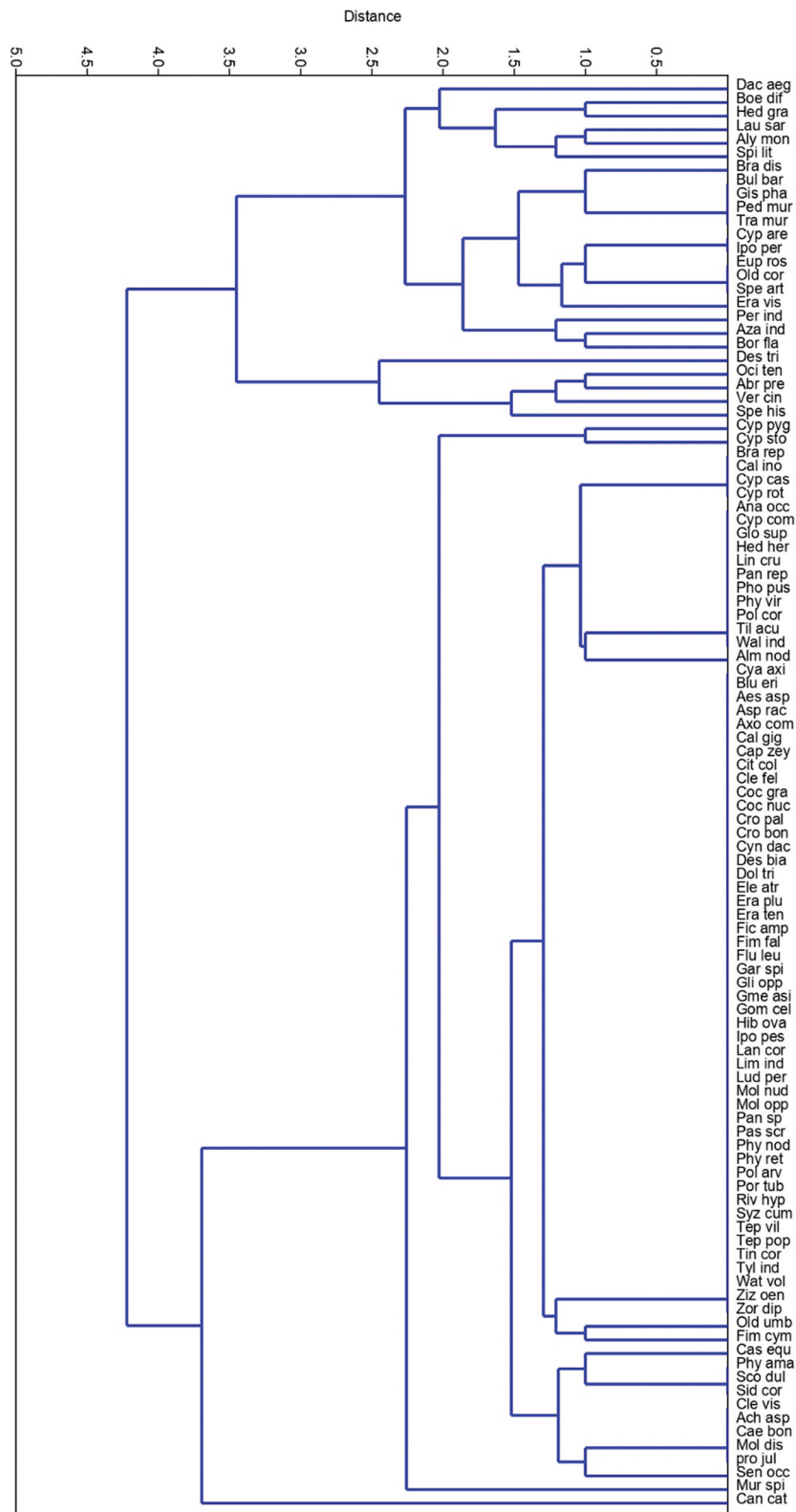


Figure 4. Plant species contributing to the similarity in Bray-Curtis clusters.

systems and encouraging additional farming practices, commercial cultivation of *Casuarina*, recreational, and tourist spots that are not environmentally friendly. It is frequently observed that increased grazing and practices to obtain food, timber, and fuel are occurring as a result of the access provided by coastal roads. In the region, intensive plantation activities such as

Casuarina equisetifolia, *Anacardium occidentale*, *Azadirachta indica*, and *Vetiver* monoculture have been carried out extensively (Pers. Obs. And Singh et al., 2021). *Casuarina* plantations are said to be one of the factors affecting dune diversity and negatively impacting native dune species, as well as lowering the water table.

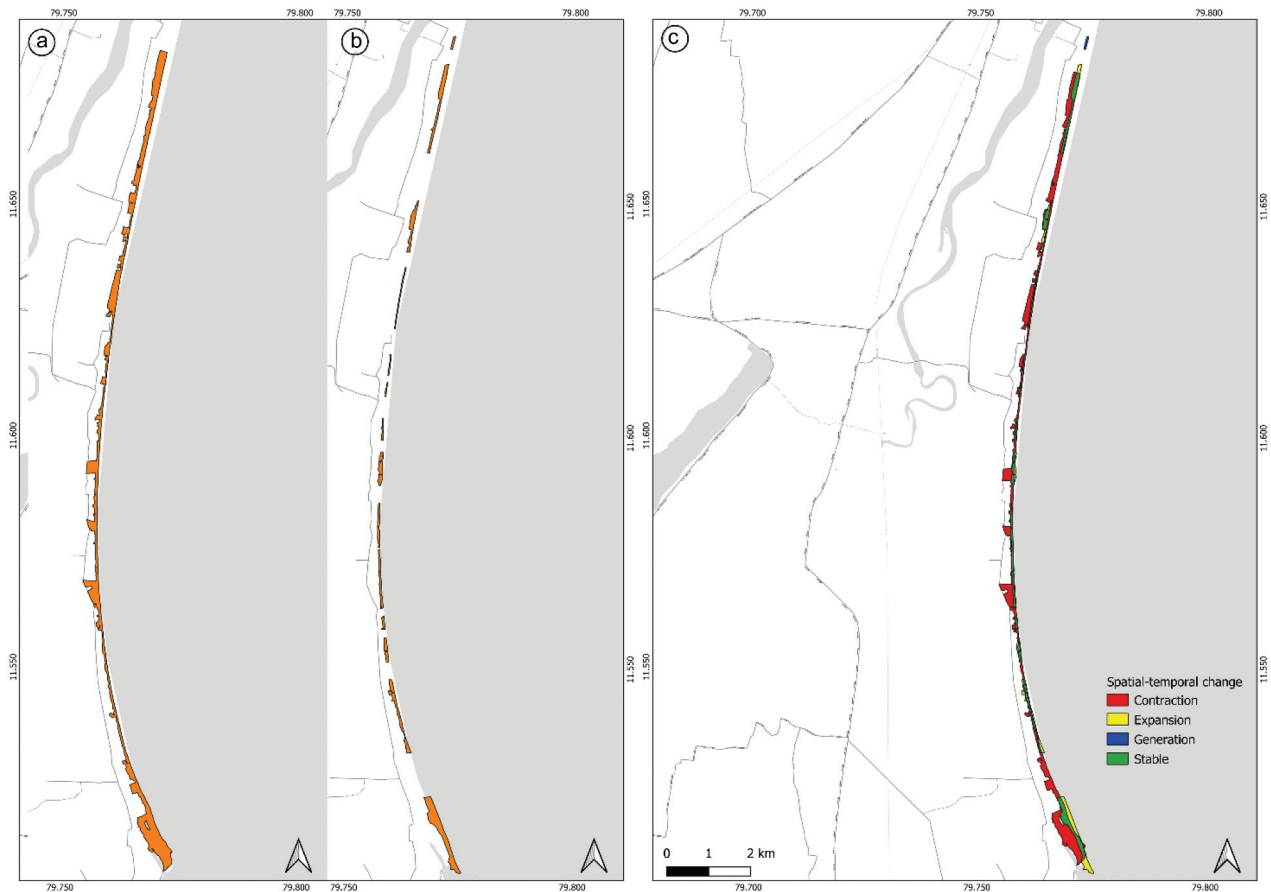


Figure 5. Changes of sand dune distribution between 2003 to 2020: (a) sand dune distribution in 2003 (b) in 2020 and (c) changes between 2003–2020.

Conservation and management perspectives

In the current situation, transects across the dune coast of Cuddalore, Tamil Nadu, show a mixed disposition of floral species. Although herbs cover most of the dunes, tall hinterland trees such as *C. nucifera*, *Casuarina equisetifolia*, *Anacardium occidentale*, and the aromatic herb Vetiver can be found along the frontal dune. The primary cause could be attributed to a lack of planning and management initiatives, but it could also be attributed to haphazard plantation programmes. Inappropriate plant species selection in different zones of the beach/dune, combined with poor planning, results in potentially high environmental stress on the fragile coastal ecosystem (Martinez et al., 2006; Rodrigues et al., 2011). Such unscientific plantation methods cannot ensure the health of coastal dune vegetation.

Following that, a succession of sand dune species landward from the dune is proposed, which could be expected to form a functional buffer zone: incipient dune (zone 1: Figure 6) would consist of pioneer shallow-rooted herbs such as *Bulbostylis barbata*, *Cyperus arenarius*, and *Spinifex littoreus* on the frontal zones. *Ipomoea pes-caprae* and *I. Pes-trigris* would also be ideal in the zone and species because they can withstand burial by sand and salt stress, as the

incipient dune receives the most salt spray due to its proximity to the sea. Zone 2 (Foredune) would be a mid-coast zone of herbs and medium-rooted shrubs. *Fimbristylis cymosa*, *F. falcata*, *Launnaea sarmentosa*, *Ludwigia perennis*, *Perotis indica*, and *Tephrosia villosa* are some of the species that could be used. Species from zone 1 could also be used in conjunction with zone 2 to achieve natural succession of vegetation. The use of *C. equisetifolia* and vetiver would not be recommended in the foredune and mid-shore areas as they are known to pose a threat to marine fauna such as marine turtles and may hinder the natural succession pattern of CSD vegetation. Deep-rooted dune species of taller shrubs, climbers, and trees such as *Calotropis gigantea*, *Coccinea grandis*, *Anacardium occidentale*, *Ziziphus oenoplia*, *Casuarina equisetifolia*, and *Cocos nucifera* could represent Zone 3 (Hind dune). Some of the plants, such as *A. occidentale* and *Cocos nucifera* species proposed in the hind dune are not native to India and were introduced and naturalized in the area centuries ago. While these tree species provide socio-economic benefits to local communities, their impact on native flora is minimal. For this purpose, several kilometers of coastal sand dunes in India were flattened to make way for these plantations, which ultimately destroyed sea turtle nesting habitat and

reduced the natural effectiveness of coastal dune topography, which provides protection from storms.

Conclusion

Given the current findings, there are several important considerations for managing fragile coastal dune systems in the areas studied. First, coastal plantations such as *Casuarina* and *Vetiver* in the foredune are the most significant source of disturbance, altering the typical spatial pattern of dune plant communities. Because erosion processes shifted the down drift of harbours and other engineering structures in recent years, the construction of protective structures (such as groyens, seawalls, and jetties) along the coastal traits affected by erosion has been a solution only for urgent local problems. These phenomena have resulted in the degradation of several coastal stretches, necessitating ongoing management actions. It is possible to conclude that, as a result of economic

growth and infrastructure expansion, local development and conservation policies have failed to address the well-being of our coastal ecosystems. We rely heavily on the services provided by sand dunes, and we are constantly exploiting the resources without regard for conservation or their own dynamics. The CSD and beaches are under increasing strain, and unsustainable coastal development projects are destroying these ecosystems. Coastal dune vegetation, on the other hand, plays an important role in encouraging floral and faunal diversity in the areas. Native dune species aid in dune formation and erosion prevention. The assessment of vegetation in disturbed areas revealed that disturbed sites are more vulnerable to activities such as trampling, grazing, cultivation, and invasion. The evaluation of coastal dune sites along the Cuddalore stretch aids us in understanding the alteration of shorelines caused by increased human activity, which increases the likelihood of coastal hazards. The anthropogenic

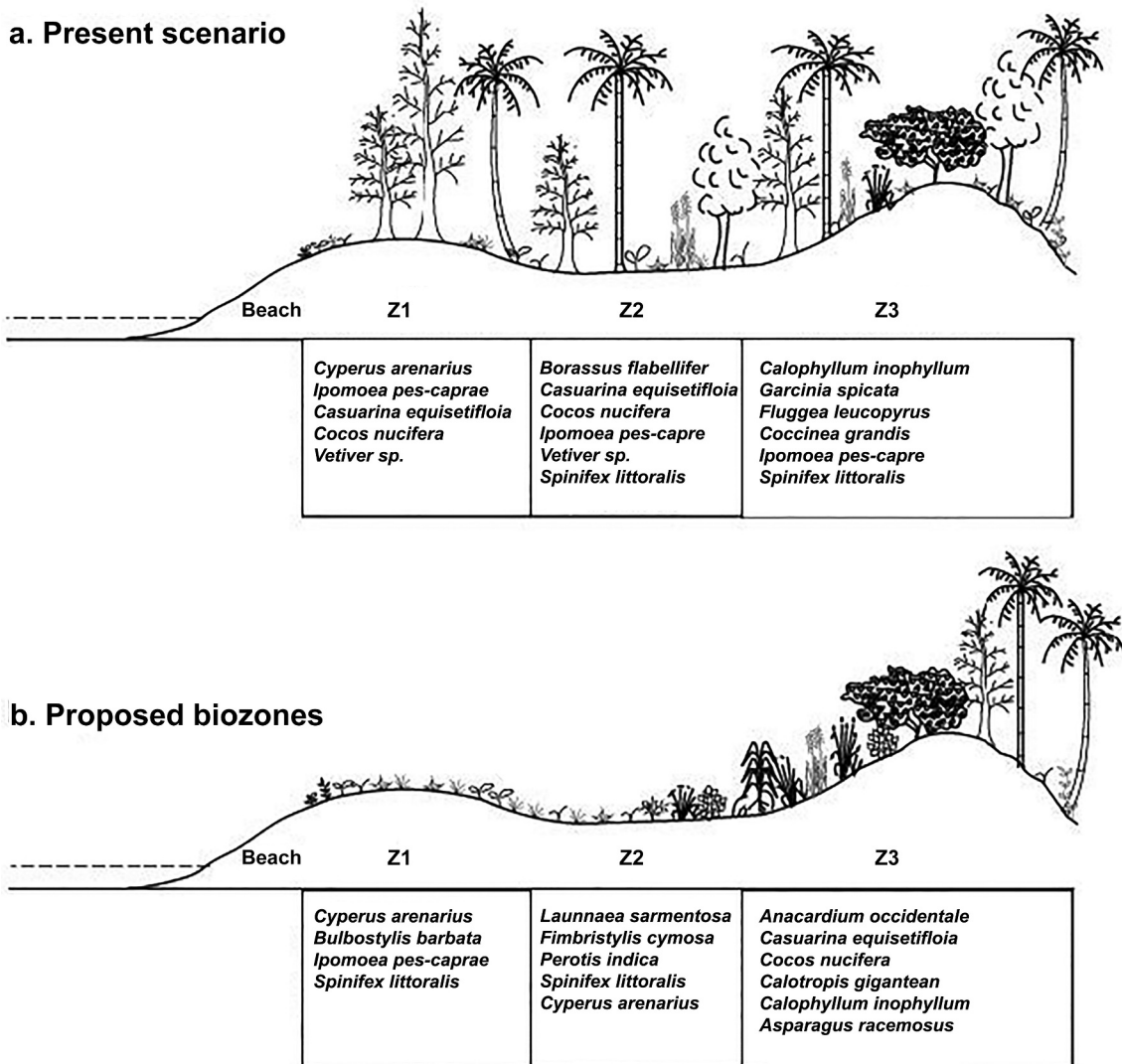


Figure 6. A schematic diagram representing coastal sand dune flora: (a) Present scenario depicting a mixed species disposition of vegetation (b) Species proposed as structured biozone so as to enhance conservation efforts.

disturbances investigated in this paper contribute to the loss of uniqueness of these sites. To summarise, the response to effective management of ecologically sensitive coastal ecosystems should be the development of a new coastal vegetation conservation policy, the implementation of existing ones, continuous monitoring, and the creation of awareness among local peoples with the goal of promoting CSD social-ecological stewardship (Mathevet et al., 2018). Encouragement of appropriate plantation programmes appears to be the most long-term management option for ensuring the conservation of the vulnerable coastal sand dune habitats of the study area.

Disclosure statement

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