

Dynamics of Coastal Vegetation in Martinique: Methodological Contributions to a Spatio-Temporal Analysis Framework

Séverine Ely-Marius^{1,2}, Stéphane Sophie^{1,2}, Philippe Joseph^{1,2}, Yelji Abati^{1,2}

¹Institut de la Biodiversité et de l'Écologie, Université des Antilles-Pôle Martinique, Fort-de-France, France

²UMR Espace-Dev-Pôle Antilles-BIORECA, Université des Antilles-Pôle Martinique, Fort-de-France, France

Email: elymariuss@gmail.com, Severine.Ely-marius@univ-antilles.fr

How to cite this paper: Ely-Marius, S., Sophie, S., Joseph, P. and Abati, Y. (2025) Dynamics of Coastal Vegetation in Martinique: Methodological Contributions to a Spatio-Temporal Analysis Framework. *Natural Resources*, 16, 429-453.

<https://doi.org/10.4236/nr.2025.1613021>

Received: March 11, 2025

Accepted: December 26, 2025

Published: December 29, 2025

Copyright © 2025 by author(s) and Scientific Research Publishing Inc.

This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).

<http://creativecommons.org/licenses/by/4.0/>



Open Access

Abstract

Plant communities on the sandy beaches of Martinique are subject to anthropogenic and abiotic disturbance. This study assesses disturbance regimes and the resulting diversity of ecotones by analysing floristic assemblages, historical orthophotography and field observations. The concepts of dynamic state mosaics and tipping points are used to interpret the evolutionary trajectories of these formations. The results reveal the coexistence of plant communities at different successional stages, influenced by past and present pressures. Interactions with adjacent agrosystems, informal uses, developed infrastructure and coastal erosion modulate the resilience of these communities, favouring the emergence of steep, progressive, mosaic ecotones. Underscoring the importance of integrated, adaptive management of coastal zones, the accumulation of disturbances beyond critical thresholds can lead to irreversible ecological change.

Keywords

Coastal Vegetation Dynamics, Sandy Beach Ecosystems, Spatio-Temporal Analysis, Ecological Succession, Dynamic State Mosaics, Tipping Points, Ecological Resilience, Disturbance Regime, Diachronic Analysis, Integrated Coastal Management, Anthropogenic Pressures, Regime Shifts, Ecotone Structure, Caribbean Coastal Ecosystems, Vegetation Monitoring, Adaptive Management, Ecological Restoration

1. Introduction

Coastal zones, complex interfaces between marine and terrestrial environments, are dynamic and fragile environments, characterized by a wide variety of forms

and functions [1]-[3]. Our study focuses on plant communities on the sandy beaches of Martinique in particular embayed beaches (also named “pocket beaches”), which represent around 75% of the island’s beaches [4]. A number of theoretical models can be applied to analyse these specific coastal zones. The dynamic gradient model proposed by Professor Joseph [3]-[6] will serve as the main theoretical framework for studying ecological successions and characterizing the evolutionary stages of these formations. Complementary bio-geomorphological approaches enrich the understanding of beaches as dynamic systems, where interactions between sedimentary landforms and plant communities shape ecological structures [7] [8].

The concepts of dynamic state mosaics and tipping points enable the analysis of critical transitions and multiscale interactions in a context of increasing disturbance.

In ecology, a disturbance is generally defined as a one-off event in time and space that modifies the structure of an ecosystem, a community or a population, and alters the availability of resources or local abiotic conditions [9]. This classic definition emphasises the disruptive effect of disturbances on the biotic and abiotic components of the system. However, more recent research in ecosystem ecology broadens this perspective by integrating the notion of ecosystem functioning: a disturbance can simultaneously stimulate certain functions, reduce others, or generate new ones [10]. The multifunctional nature and variability of responses to a disturbance require an integrative approach that takes into account temporality, intensity, frequency, spatial distribution, and the nature of the affected components [11].

Dynamic state mosaics delineate the coexistence of ecological communities at different successional stages, thereby connecting community dynamics to key disturbance attributes—such as frequency, intensity, and biotic legacies—arising from local influences and biotic-abiotic interactions [12] [13]. Furthermore, tipping points represent critical thresholds where ecosystems rapidly—and often irreversibly—transition to a new stable state due to complex disturbances or feedback mechanisms. A thorough understanding of these thresholds is crucial for sustainable management, as it allows for the timely identification of corrective measures to maintain coastal ecosystem resilience [14] [15].

In the context of long-term strategic planning for the coastline of Martinique, a fundamental challenge lies in achieving a discerning approach between the imperative of ecological preservation and of socio-economic development. As Huang observes [16], integrated coastal planning must take into account the mounting pressures resulting from human activity, including urbanisation and tourism, while relying on participatory and adaptive frameworks. Resilience refers to the capacity of an ecosystem to absorb disturbances, reorganise itself and maintain its essential functions, structure and identity. This fundamental property stems from complex interactions between processes operating at different spatial and temporal scales. Dynamics at higher levels (e.g. climate, land use) and lower levels (e.g. functional diversity, ecological microprocesses) modulate the stability of the

system and determine its ability to persist or transform in the face of pressures [17]. The preservation of the ecological resilience of Martinique's coastal plant communities relies on balanced governance mechanisms, as illustrated by the management strategy for the maritime public domain in Martinique [16] [18].

Maintaining this resilience requires stabilising desirable ecosystem states via positive feedback loops and mitigating anthropogenic pressures [19]. An integrated management approach that accounts for ecological and socio-economic dynamics, while addressing power asymmetries among stakeholders, is crucial for optimising ecosystem service utilisation. Finally, anticipating critical transitions (tipping points), often irreversible and caused by complex interactions between environmental and socio-economic pressures, requires adaptive, multi-scale approaches [19] [20].

Despite the high prevalence of bay beaches in the Caribbean islands [21] [22], the functional dynamics of coastal forest formations and their relationship with these geomorphological characteristics have only been the subject of a limited number of studies [3] [23] [24]. This research gap is particularly worrying given that these ecosystems play a key role in the resilience of coastal areas to natural and anthropogenic disturbances.

In this context, sustainable management of embayed beaches in Martinique necessitates an integrated scientific approach that considers both ecological dynamics and site-specific anthropogenic pressures. Based on ecological models and spatio-temporal analyses, the work presented here aims to enhance our understanding of the dynamics of plant formations on embayed beaches in Martinique, thereby providing valuable insights for preserving their ecological resilience.

The eight sites selected for this study represent an exploratory and foundational step toward a broader-scale investigation (**Figure 1**). This initial research phase is designed to test the relevance and robustness of the theoretical framework applied to these coastal ecosystems, while developing a replicable methodology that facilitates future comparative studies. The selected protocol integrates floristic inventories, geomatic analyses, and ecological indicators, offering a coherent model to characterise successional stages and assess disturbances and their regimes.

This study should thus be understood as a methodological reference point: it establishes a reproducible analytical structure that can be extended to other sites in Martinique and adapted to comparable coastal environments across the Caribbean. Despite its limited sample size, the approach enables the identification of significant local patterns and general ecological mechanisms, thereby contributing to the development of informed and context-sensitive management strategies.

2. Materials and Methods

2.1. Geological and Climatic Context of Martinique's Sandy Coastal Formations

Martinique is part of the Lesser Antilles volcanic arc. This island has a complex geology resulting from several eruptive phases and major tectonic movements.

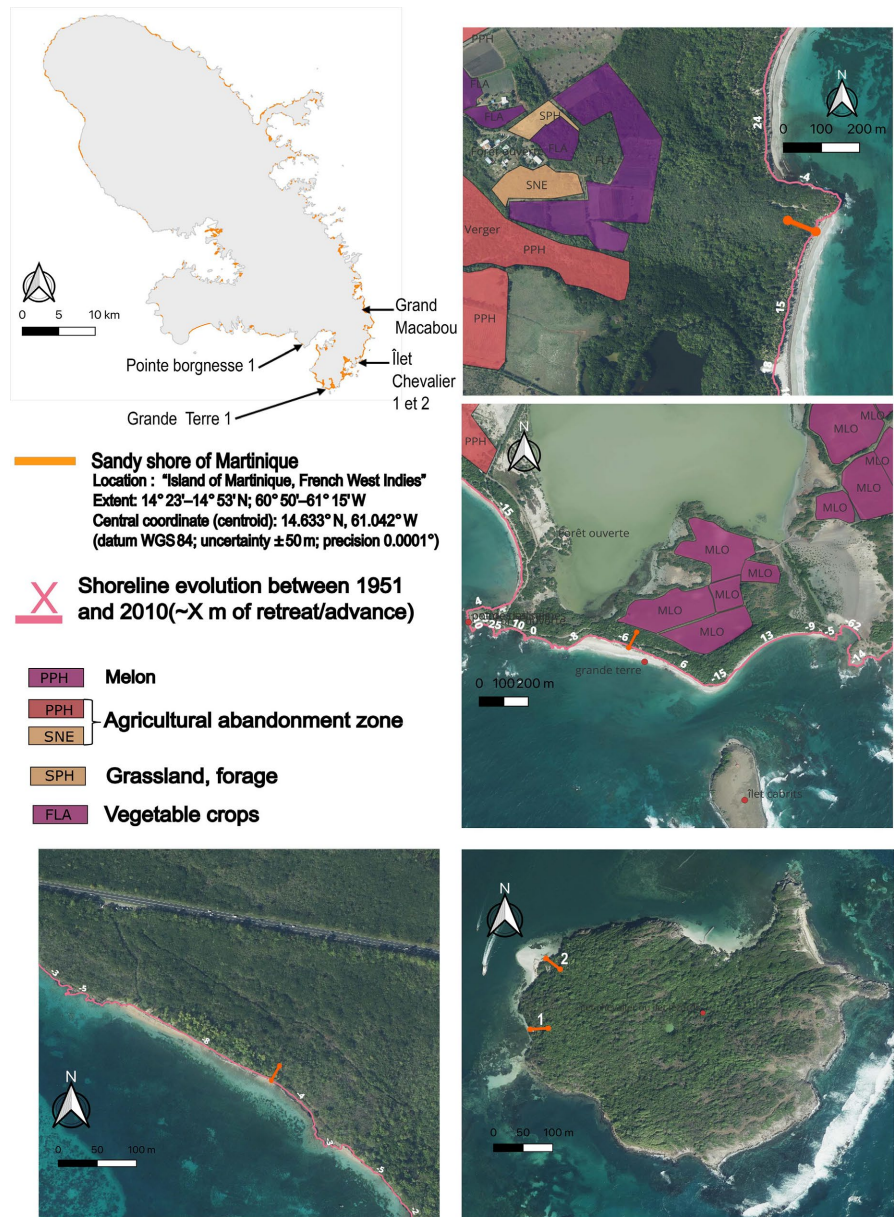


Figure 1. Location of study sites Sources des données cartographiques utilisées: [25]–[27]. The white number along the pink line indicate shoreline change, expressed in millimetres, between 2004 and 2010.

These processes have shaped a diversity of landforms and soils, significantly influencing current coastal dynamics [28] [29]. The island's tropical climate, moderated by the trade winds, is characterized by an average annual temperature of 26.5°C and abundant rainfall, averages 1950 mm per year. This rainfall, concentrated between June and November, coincides with the cyclone season, during which cyclones, storms and flooding episodes are major disturbances for sandy coastlines [30].

A sandy beach is defined as an area dominated by accumulations of clastic sediments, forming a sedimentary cell. These geomorphological units are delimited

by natural (rocky headlands, river mouths) or anthropogenic (dykes, groins) obstacles and are characterized by a relative autonomy of longitudinal and transverse sediment transfers [31]. In this study, we focus on areas dominated by sediments with grain sizes ranging from 0.0625 mm to 10.24 cm, according to Wentworth's (1922) classification [32]. In Martinique, sandy coastlines account for around 12% of the 450 km coastline (including islets), with a wide variety of morphologies influenced by natural factors such as tides, hydrodynamics and local geological features [4] [31]. However, these beaches are also subject to increasing anthropogenic pressures, including urbanization and tourism [33] [34], which alter their sediment dynamics and ecological resilience [1] [3] [23]. Two key morphodynamic processes determine the evolution of these beaches: tilting and oscillation of the coastline. Tilting, induced by swell variations, generates lateral displacements of sediment within the bays, while oscillation, linked to storms and seasonal shoreline oscillation, causes the coastline to alternate between advancing and retreating. These processes directly influence the stability of beaches and their ability to absorb energy disturbances, potentially leading to a net loss of sand [4].

In Martinique, 117 sediment cells have been identified, including open beaches and embayed beaches [4]. Open beaches, with few indentations, extend over long sandy stretches and present relatively simple dynamics. On the other hand, embayed beaches, occupying the bottoms of convex bays and often fed by adjacent rivers, make up nearly 75% of the island's sandy beaches. Although small in size, these beaches have complex sediment transport dynamics due to the structures that delimit them and the sedimentary flows that feed them [4]. Their high sensitivity to climatic variations and anthropogenic pressures makes them particularly vulnerable ecosystems [3] [4] [7].

2.2. The Ecosystem Potential of Sandy Coastal Zones of Martinique as a Plant Community

The ecosystem potential of the high islands of the Lesser Antilles, including Martinique, is mainly forested. However, topographical diversity, combined with local variations in bioclimate and recurrent disturbances (landslides, windthrow, Inversion of relief, cyclones), results in a complex mosaic of biotopes. These are home to diverse assemblages of phytocenoses, or plant communities, which contribute to the ecological heterogeneity of the territory [6].

Figure 2 illustrates the correspondence between bioclimates and sylvatic potential on the high islands of the Lesser Antilles. Four main bioclimates, defined by a rainfall gradient influenced by the organization of the relief, are associated with specific forest types. These bioclimates structure distinct plant stages, characterized by particular associations of phytocenoses and unique biocenotic organizations [3] [5] [6].

The recent history of Martinique's ecosystems has been profoundly marked by anthropogenic transformation, which has transformed primitive pre-Columbian forests into a mosaic of diversified formations. This dynamic has resulted in a juxtaposition of herbaceous, shrubby and pre-forest formations, as well as young

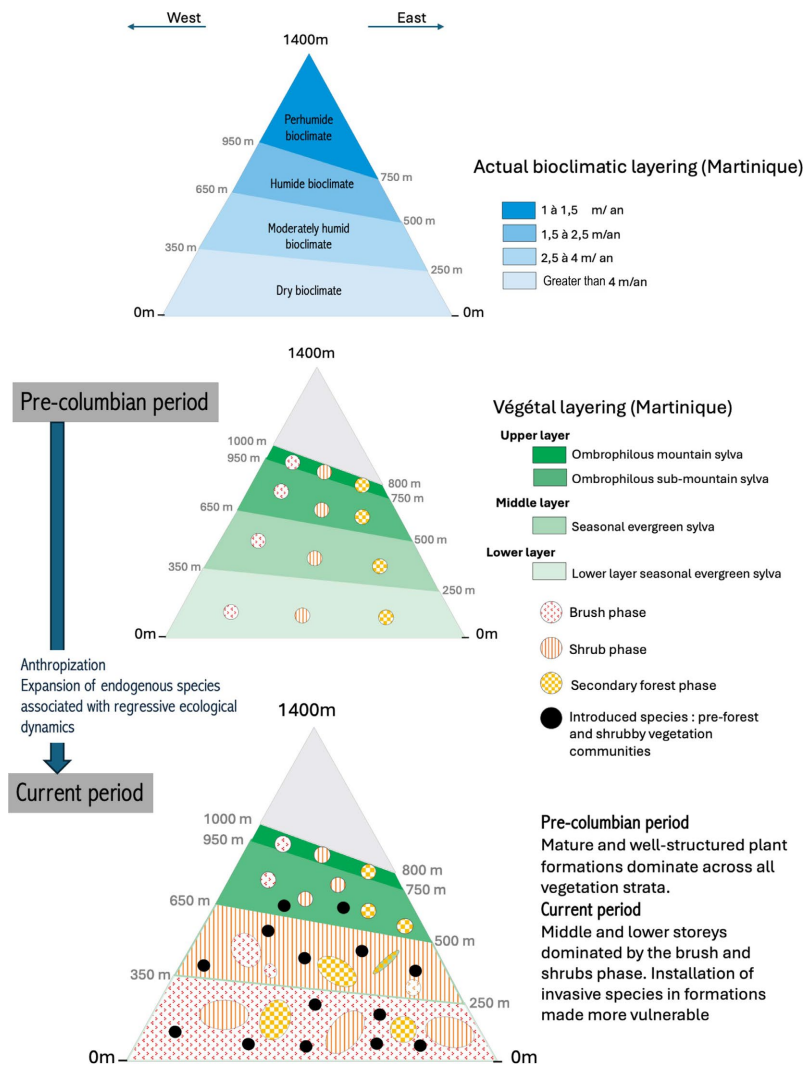


Figure 2. Bioclimates, ecosystem potential and vegetation evolution in Martinique—Modified from Joseph, 2015 [5] with additional data from Joseph *et al.*, 2019 [35].

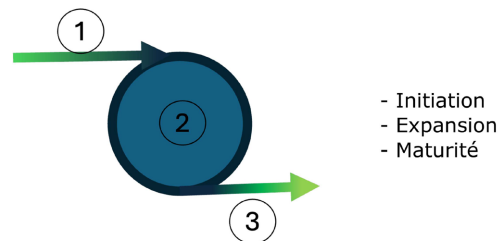
secondary forests and rare relics of climax forests [35]. These vegetation physiognomies reflect different successional stages and highlight the long-term impact of human activities [3] [35] [36]. They also contribute to a high level of structural and biocenotic complexity.

Natural disturbances such as windthrow and cyclones play a key role in maintaining a diverse mosaic of phytocenoses and in the regeneration processes of forest formations [6] [37] [38]. Although destructive, these events promote ecological dynamics by creating openings in the forest canopy, enabling recolonization by pioneer species and the renewal of plant communities.

2.3. Characterising the Organization of Martinique's Forest Ecosystems

The dynamic gradient model of forest ecosystems of lesser Antilla, developed by Professor Joseph [5] [6], is a theoretical framework employed to characterise the

successional stages of the constituent units that comprise the plant mosaic. This model delineates eleven dynamic stages, each structured around distinct phases of installation, expansion and senescence (**Figure 3**).



Stage 1 (F.R.) : Shrubland

Stage 2 (F.R.M.) : Mature shrubland

Stage 3 (F.A.B.) : Bushy formation

Stage 4 (F.A.B.M.) : Mature bushy formation

Stage 5 (F.P.S.) : Pre-sylvatic formation

Stage 6 (F.S.T.S.) : Young structured sylvatic formation

Stage 7 (F.S.S.) : Secondary sylvatic formation

Stage 8 (F.S.S.T.) : Secondary late sylvatic formation

Stage 9 (F.S.P.C.) : Pre-climactic sylvatic formation

Figure 3. The gradient dynamics [6]—Gradient dynamics is a model that characterises the stages of evolution of the units of a plant formation. Modified from Joseph, 2015 [5].

Although sometimes perceived as linear and teleological, this model captures the complexity of the plant formations studied (**Figure 4**). By incorporating the notion of “polyclimax hypothesis”, it offers a flexible representation of the diversity of ecosystem trajectories, particularly in contexts marked by frequent and/or intense disturbance [5] [35].

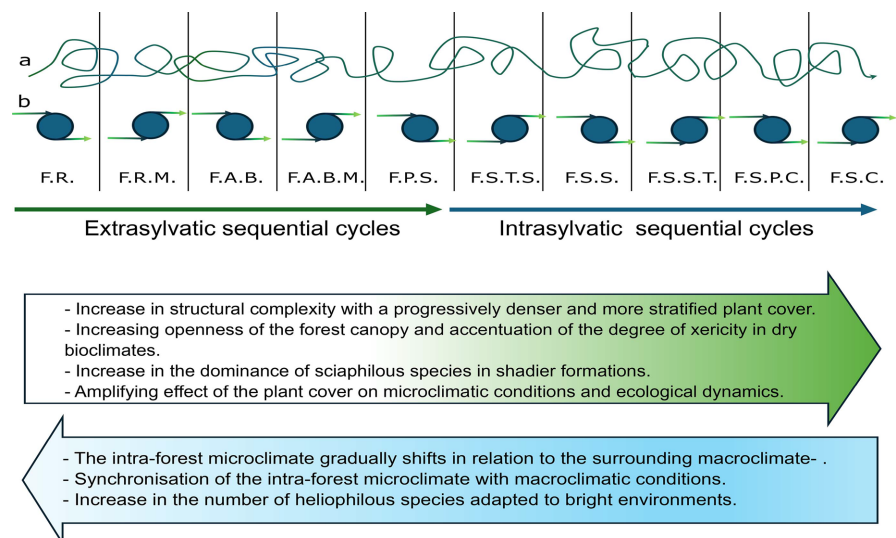


Figure 4. Gradient dynamics: descriptive framework of different stages—a: example of the trajectory of an ecosystem; b: sequence of different stages; c and d: interactions between ecological and microclimatic dynamics within a forest gradient. Modified from Joseph, 2015 [5].

Research on coastal plant formations in the Lesser Antilles remains scarce. Notably, [3] and [5] proposed a reconstruction of their pre-Columbian organisation and documented their transformation under anthropogenic pressure. His work, supported by regional floristic data [39] [40], highlights a spatial gradient from the coastline to inland areas: herbaceous strata dominate nearshore zones, giving way to shrubby and eventually arborescent vegetation inland (**Figure 5**). However, due to the near-absence of climax-stage examples today, this ecological organisation must be interpreted cautiously, as the original structure of littoral phytocenoses remains largely hypothetical.

To understand the non-linear dynamics specific to sandy beaches, this framework is complemented by the dynamic state mosaic model. This concept describes landscapes as assemblages of plant communities in various successional stages, shaped by local disturbances and environmental variations. These transient successional stages play a key role in sediment stabilization and ecological connectivity, contributing to the resilience of littoral systems [9] [40].

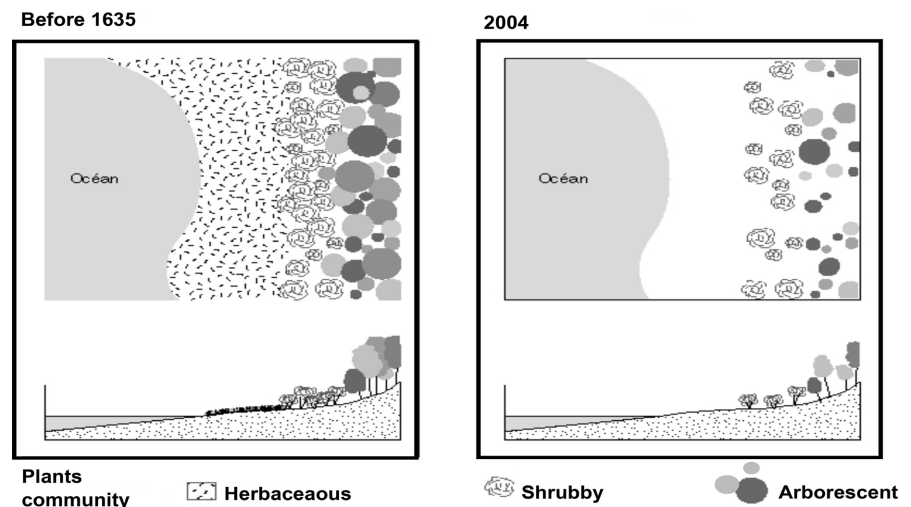


Figure 5. Evolution of coastal vegetation between the pre-Columbian period and 2004. Adapted from Joseph (2006).

In addition, the “tipping points” framework is used to assess the resilience of sandy beaches to diverse disturbance regimes. These critical thresholds, beyond which ecosystems rapidly and irreversibly tip towards a new stable state, enable us to analyse how cumulative events such as coastal erosion or storms modify ecological trajectories [14] [15]. In Martinique, where the diversity of natural and anthropogenic disturbances is marked [5] [6], this framework offers a valuable tool for anticipating potential transformations of sandy beaches.

Articulating these three models within a theoretical framework enables us to examine biotic and abiotic interactions while incorporating spatial, temporal and systemic dimensions. The main objective is to decipher the ecological trajectories of Martinique’s beaches and develop sustainable management strategies adapted to these complex ecosystems.

An ecotone is a transition zone between two distinct ecosystems or ecological communities, characterized by an intermediate species composition and complex interactions. These ecotones can be identified at the interface between the marine environment and the upper-beach vegetation, as well as at the interface with the backshore forest. They form a complex network within the formations, considered as mosaics of dynamic states where different succession strata coexist as a result of interactions between disturbance and plant formation response. These assemblages of plant communities influenced by biotic and abiotic variations can thus be described at different scales. This framework highlights the diversity and connectivity of coastal habitats.

At the same time, tipping points help us to understand how ecotones reach critical thresholds under the effect of cumulative disturbances. These thresholds can lead to rapid, sometimes irreversible transitions, profoundly altering the ecological function of ecotones. These two theoretical frameworks combined enable us to identify the most vulnerable areas and anticipate potential trajectories in the event of increasing pressures, such as climate change or intensive human activities.

2.4. Floristic Surveys and Cartographic Data

Floristic inventories

The work presented here is based on the analysis of data acquired at 8 stations. (see **Figure 1**). In order to characterise the floristic assemblages of these sandy beach plant formations, continuous strip transects were established, covering the plant communities that develop on the sandy substrate (psammophilous vegetation), on dry land (backdune) and in the transition zone. Measurements were taken in 5 m × 10 m quadrats, distributed along the entire transect. In the pioneer fringe dominated by herbaceous species, additional 1 m² quadrats were placed to estimate vegetation cover. has been designed:

- 1) An initial characterization of plant communities specific to Martinique's sandy beaches;
- 2) Identification of local disturbances, with a view to proposing a functional classification and developing tools to assess their impact on ecological resilience.

Quantitative floristic surveys were carried out for each woody species exceeding a height of 1.33 metres. Data collected included:

- Diameter at breast height (DBH, 1.33 m);
- The height of the first branch;
- Species distribution along the transects.

Plant species were identified using Fournet's illustrated flora (2002) [39].

Indicators used to analyse floristic data

Several indicators were used to analyse the data collected:

- 1) **Basal area (BA)**: Total cross-sectional area of all individuals of a species per unit ground area. This indicator provides an estimate of biomass.
- 2) **Distribution index (I.d)**; Developed by Joseph [41], this index is calculated

as I.D: density ($D = Ni/SR$) NI: number of individuals (total number of individuals in the transect considered) fa: absolute frequency (number of quadrats where the species in question is present); fr: relative frequency ($fr = fa/\text{total number of quadrats in the station}$); SR: total survey area.

3) **Dominance index (I.D):** $I.D = I.d \times AB$ [41].

Cartographic data

To complement the floristic inventories, orthophotography from the IGN database [25]-[27] were interpreted to enrich the spatial analysis. An orthophotograph is an aerial photograph that has been geometrically corrected to remove distortion, providing accurate spatial measurements useful for ecological mapping. These high-resolution orthophotography provide an overview of the study areas at different dates. These data allow us to identify and spatialize disturbance zones and extract clues about disturbances and their patterns of occurrence. Interpretation of these images enables us to refine the identification of the spatio-temporal dynamics of plant formations, as a complement to floristic surveys. The organization of plant crowns, identifiable on orthophotography, is interpreted to characterize the vertical structure of forest communities. The combination of cartographic data and floristic inventories provides elements for reconstructing the spatio-temporal analysis.

3. Results and Interpretation

3.1. “Îlet Chevalier 1” and “Îlet Chevalier 2” Stations

L'îlet Chevalier is an islet of around 70,000 m², located on the southeast coast of Martinique, in the commune of Sainte-Anne, 500 m from the coast (Figure 6). A footpath leads around the island. It's a popular site for leisure and tourism activities.

On the Chevalier 1 station transect, quadrat 1 features a herbaceous formation characteristic of forebeach psammophilous formations, dominated by *Ipomea pes-caprae*, *Sporobolus virginicus* and *Canavalia rosea*. Quadrats 2 and 3 are occupied by an undiversified fruiting body dominated by *Clerodendrum aculeatum* (syn. *Volkameria aculeata*). The following quadrats correspond to a pre-shrub formation. The limited presence of large-diameter individuals (*Pisonia fragrans*, *Hippomane mancinella*, *Bursera simarouba*) indicates that a more advanced evolutionary stage probably existed previously, possibly a mature shrub formation. This suggests that the back-beach formation underwent recurrent disturbances that caused local regression.

The trail crosses the transect at the transition zone between the shrub and tree formations. Marked heterogeneity is observed at the transition between the shrub fringe and the backshore forest. This zone includes an ecotone subject to regular disturbance. This zone is thus marked by a strong edge effect, particularly near the path. This favors the appearance of herbaceous species such as *Heliotropium angiospermum*, *Lantana sp.* and *Rivinia humilis*.

On the Chevalier 2 transect, the forebeach zone occupies quadrats 1 to 3, and is

wider than on the Chevalier 1 station, but the herbaceous vegetation has not colonized the entire supra-littoral zone. On this transect, the shrub zone extends from quadrats 4 to 7, with a greater gradient and a protosol on scree (*i.e.*, an early-stage soil developing on unstable rocky debris). On this part of the transect, the fruit-bearing zone is mainly made up of heliophilous shrub species (*Croton bixoides*, *Croton flavens*, *Erytroxylon havanence*) associated with *Pilocereus royeri*. The transect is crossed at quadrat 6 by the path. In this zone, trampling is associated with heavy erosion, exposing outcrops of scree.

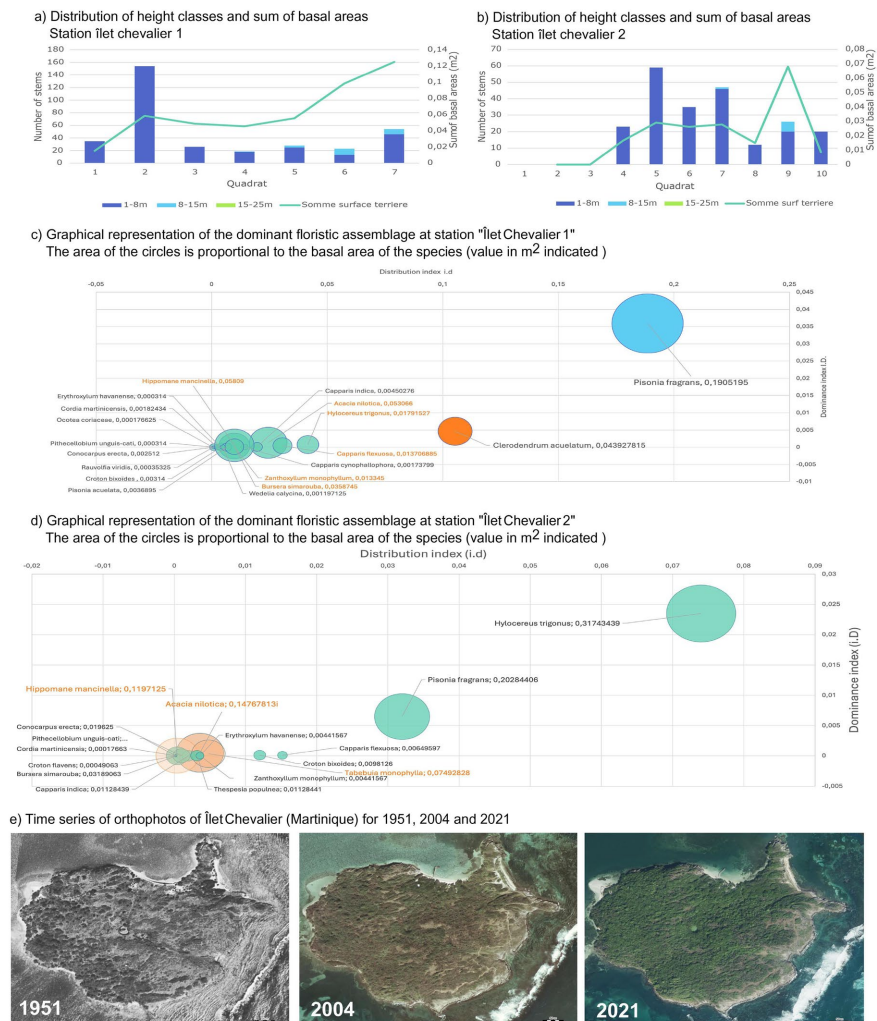


Figure 6. Main descriptive data for stations "îlets chevalier 1" and "îlets chevalier 2".

This zone is home to numerous individuals of *P. royerii*, a highly specialized heliophilous species. These numerous disturbances explain the dominance of *P. royerii* on this transect. The following quadrats belong to the backshore forest. The physiognomy and species distribution in this zone are reminiscent of a shrub formation (*Acacia sp.*, *Croton bixoides*, *Croton flavens*). The following quadrats show a mixture of these indicator species and a few individuals of larger diameter

and height. The latter are probably relicts of young pre-silvicultural formations (*Bursera simarouba*, *Pisonia fragrans*, *Hippomane mancinella*). From a physiognomic point of view, the organization of these two stations conforms to the model sandy beach formations proposed by Joseph, 2006 [3]. However, the organization of the shrub and tree zones shows the presence of a mosaic of different evolutionary stages linked to disturbances of different ages and intensities. Orthophotography of the area shows a tree crown evolution compatible with a strong disturbance regime associated, on the one hand, with leisure activities on the beach and, on the other, with grazing in the back beach zone. The abandonment of grazing activities has allowed these areas to heal more or less completely.

Define abbreviations and acronyms the first time they are used in the text, even after they have been defined in the abstract. Abbreviations such as IEEE, SI, MKS, CGS, sc, dc, and rms do not have to be defined. Do not use abbreviations in the title or heads unless they are unavoidable.

3.2. Grande Terre 1 Station

The station studied is characterized by a highly degraded secondary formation, fragmented into scattered patches of vegetation in the psammophilous zone. This configuration is the result of complex plant dynamics, largely influenced by recurrent anthropogenic disturbances (Figure 7). The herbaceous stratum is totally absent, testifying to significant pressure on the environment. An analysis of the flora reveals three groups:

- The first group is made up of species typical of woodland on sand, such as *Coccoloba uvifera* and *Conocarpus erecta*, which preferentially occupy stabilized areas of sandy substrate.
- A second group, made up of mature individuals (*Bourreria succulenta*, *Tabebuia heterophylla*, *Bursera simarouba*), indicates that the backshore formation corresponds to an advanced shrub stage.
- A third group, marked by the presence of *Sideroxylon obovatum*, suggests the past existence of a more evolved formation, probably a secondary forest. These relict individuals are the remnants of a more complex forest structure and bear witness to a progressive degradation dynamic.

This floristic composition illustrates a process of ecological transition, where the current vegetation structure bears witness to both the persistence of remnants of a more mature sylvatic stage and the persistent influence of environmental and anthropogenic pressures that hinder homogeneous vegetation regeneration.

3.3. Station “Grand Macabou 1”

The area-species curve suggests that this station crosses three distinct floristic complexes (Figure 8). The first group corresponds to the psammophilous procession dominated by *Ipomoea pes-caprae*, *Sporobolus virginicus* and *Canavalia rosea*. This zone is typical of pioneering plant formations on sand, subject to demanding ecological conditions (salinity, insolation, substrate mobility).

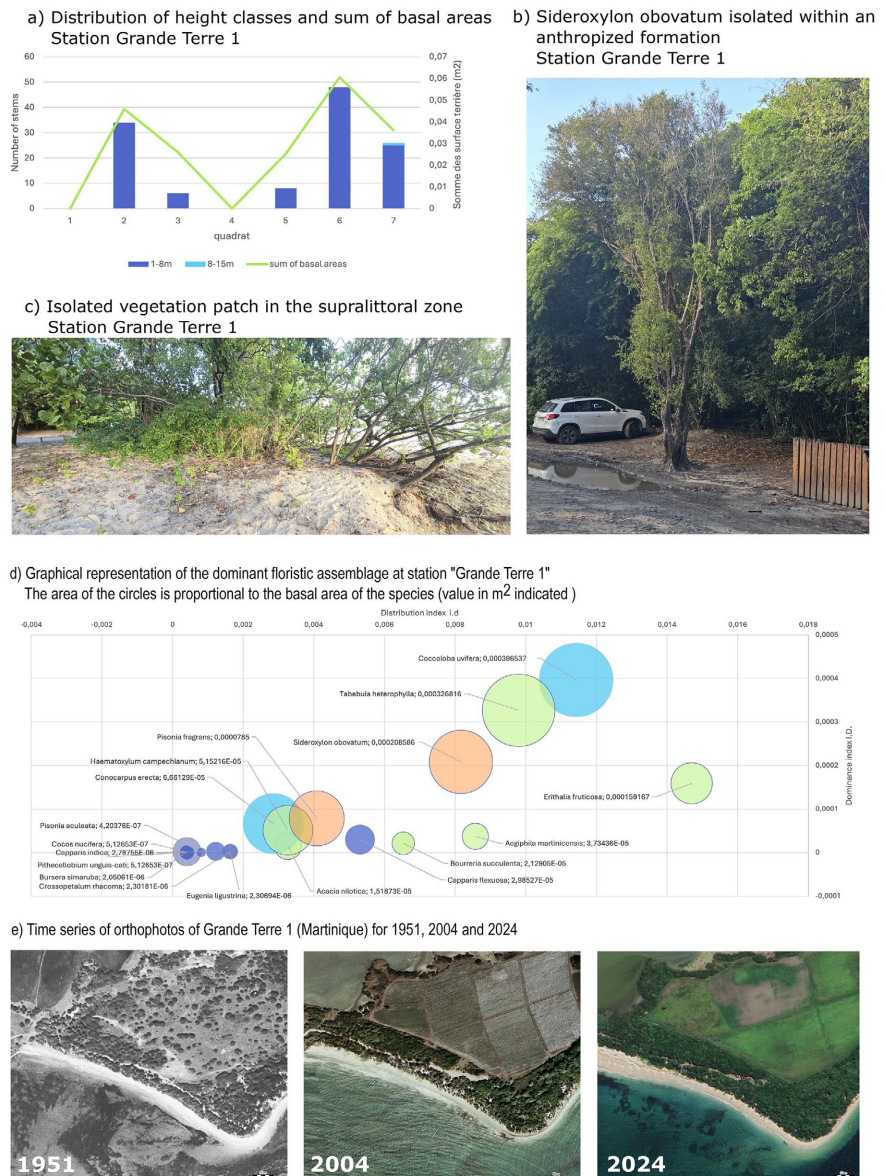


Figure 7. Main descriptive data for stations “Grande Terre 1”.

The second group is characterized by a dense formation dominated by *Coccoloba uvifera*, whose individuals do not exceed 2 m in height, combined with *Cocos nucifera* reaching up to 10 m in height. The woody species in this area have a feathered habit, and environmental conditions seem to limit the growth of potentially arborescent species. This area bears the marks of recent anthropogenic disturbance, notably the removal and on-site consumption of coconuts, as well as the development of trails and bivouac sites. Coconut residues left on the ground are gradually being colonized by lianas of the *Canavalia* genus and by regenerations of *Coccoloba uvifera*.

A plateau of diversification is observed from quadrat 6 onwards on the area-species curve. This indicates a transition to a third floristic group. It is linked to

the presence of the main trail, regularly used by hikers and horse-riding groups. The disturbance creates a gap where a few individuals of *Terminalia cattapa* can settle.

Analysis of the plant stratification reveals a predominance of individuals of low height (1 - 8 m). The plant community in this zone is dominated by shrub species and regenerating tree species.

The intermediate height (8 - 15 m) and tall height (15 - 25 m) classes are under-represented, suggesting a deficit in mature individuals. However, the fluctuating basal area in some quadrats (7, 9 and 11) suggests the persistence of a few older individuals, which could be interpreted as relics of a more developed forest formation, now fragmented. These larger, larger-diameter trees often bear traces of senescence or are lying down.

Dead trees rank third in the floristic assemblage. This may be due to an active disturbance regime (drought stress or salinity variation), natural senescence or the consequences of anthropogenic pressures.

Signs of senescence are mainly observed on *Coccoloba uvifera*, the dominant species in the formation. The most mature individuals show traces of selective cutting associated with the maintenance of the pathway and reception areas by the site managers. At the same time, numerous windthrow and natural treefall debris are visible (volis), particularly on trunks colonized by termites. Here, volis refers to trees that have fallen naturally due to environmental factors (e.g., wind, lightning, or the fall of another tree) or intrinsic causes (such as decay or senescence), without any human intervention. This indicates the gradual weakening of the trees as a result of natural ageing and degradation processes.

A large proportion of mature *Coccoloba uvifera* and *Hippomane mancinella* trees have been windthrown. On these fallen trunks, numerous shoots can be found, helping to regenerate the formation.

The earliest orthophotography (1952) shows that the site was already subject to a variety of anthropogenic disturbance regimes. At that time, the interface between the cultivated fields and the backshore forest was marked by a particularly abrupt transition, probably due to the presence of grazing land. There are also open areas and a network of well-marked paths, reflecting regular human occupation.

The 1972 image reveals an accentuation of these disturbances: the vegetation appears sparse, the coastal fringe is fragmented, and wide paths (4-5 m) are visible. This configuration suggests intensive exploitation of the site, marked by the almost total disappearance of the shrub and herb fringe, probably as a result of the area's development for leisure and beach tourism.

In contrast, recent orthophotography shows a process of vegetation recolonization. A densification and homogenization of vegetation cover is observed, accompanied by a reduction in trail width. This suggests either a reduction in anthropic pressure, or the effect of targeted management measures aimed at limiting the impact of human activities on vegetation dynamics.

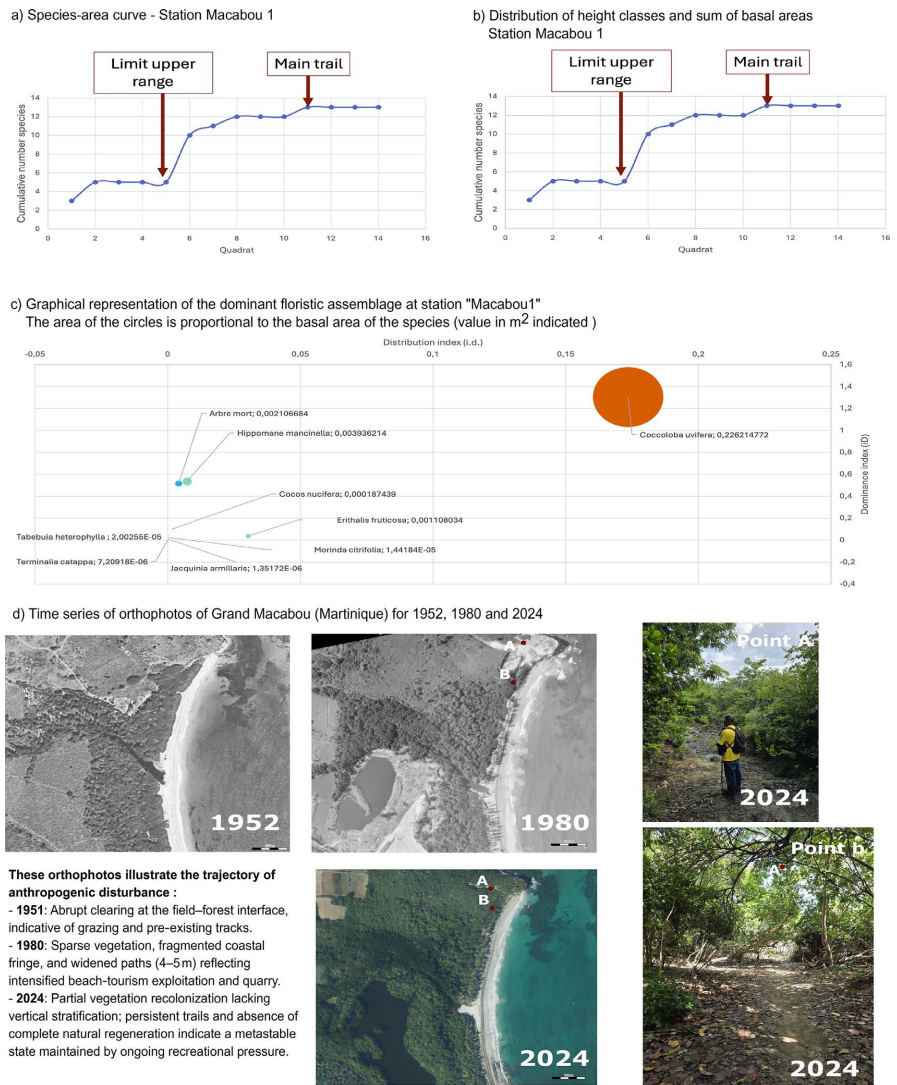


Figure 8. Main descriptive data for GRAND MACABOU 1 station.

However, there are several indications that this recolonization has not been accompanied by a return to a fully functional ecological state. The absence of vegetation stratification and the limited number of regenerations could be explained by the establishment of a metastable state, resulting from the combination of:

- a prolonged disturbance regime that has permanently altered the dynamics of plant succession;
- the maintenance of recurring human activities, less aggressive than in the past, but still present (hiking and horse-riding, regular bivouacs on the beach).

Following a break in the ecological corridors, the station has undergone an intense regime of human disturbance, permanently modifying the vegetation dynamics.

3.4. Pointe Borgnesse 1 Station

Analysis of the plant assemblages shows that the majority of species have low dominance and distribution indices (Figure 9). This indicates intense competi-

tion, without any clear predominance, between the different species that seem to be settling in at. On the other hand, some species, although widely distributed, display moderate dominance.

These are species characteristic of mature shrub formations in dry bioclimates (*Tabebuia heterophylla* and *Erithalis fruticosa*) and an antrophilous species, *Coco nucifera*. *Dichrostachys cinerea* stands out with the highest dominance and distribution indices of the group. This invasive species can aggressively colonize severely degraded areas, particularly abandoned agricultural plots and fallow land in a dry bioclimate [42]. This assemblage therefore suggests that the backshore area has been subjected to a regime of intense disturbance associated mainly with agricultural activities.

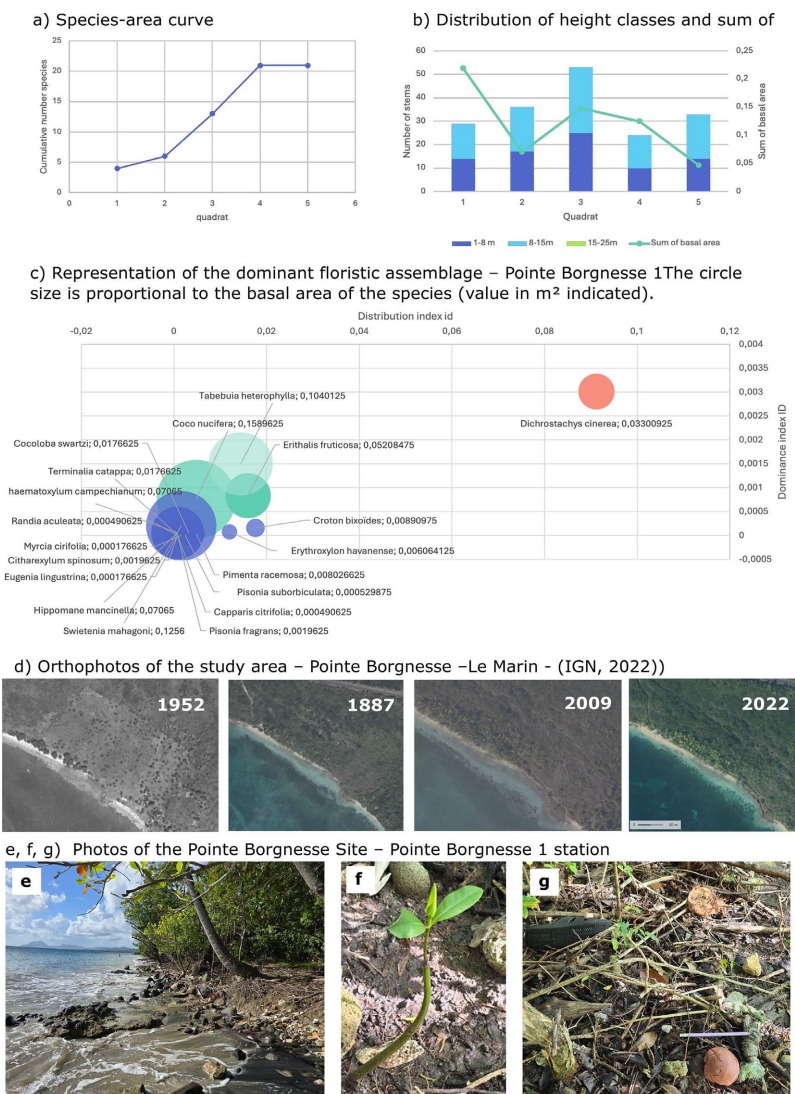


Figure 9. Descriptive data for Pointe Borgnesse 1 station.

This interpretation is supported by the analysis of orthophotography, which reveal four phases:

- 1952: A highly disturbed state with vegetation cover reduced to a herbaceous formation and a few isolated trees. This organization may be associated with agricultural activities, mainly the establishment of pastures, which limit natural regeneration.
- 1987: The images show the beginnings of a recolonization process. The gradual increase in vegetation cover, despite the persistence of open areas, may be due to agricultural abandonment.
- 2009: densification of the forest cover, marked by the appearance of a homogeneous structure thanks to the development of woody species.
- 2022: An almost stable state with almost complete closure of the forest canopy. The reduction in trails and openings reflects either a reduction in human disturbance or the effectiveness of conservation measures implemented.

In addition, the Pointe Borgnesse area is characterized by a retreat of the coastline, associated with significant erosion estimated at around -0.5 mm/year [4].

This coastal dynamic is leading to changes in local morphology (see **Figure 9**, photo e) and influencing vegetation succession, as evidenced by the complete disappearance of herbaceous vegetation in the foreshore zone. The presence of a pathway, combined with beach erosion and episodes of submersion resulting in the addition of waste and an increase in soil salinity, constitutes a major disturbance likely to permanently modify the composition of the vegetation.

A new equilibrium between terrigenous and marine sediment flows is thus likely to be established in this area. A predominance of terrigenous inputs would favour the long-term establishment of species that were previously present on an erratic basis, such as *Rhizophora mangle* (see **Figure 9**, photos f and g).

3.5. Typology of Disturbances and Ecotone in the Five Stations of the Study

The analysis of ecological transitions identifies three types of ecotones, reflecting the variability of disturbance regimes and resilience processes (see **Figure 10**):

- Steep ecotones with sharp transitions between formations, often linked to infrastructure or rapid erosion, marked by an abrupt break in cover (notably a loss of foreshore herbaceous vegetation).
- Progressive ecotones where gradual transitions correspond to natural successions, such as the transition from pioneer to backshore formations, or areas undergoing healing after the abandonment of disruptive activities.
- Mosaic ecotones where fragmented discontinuities due to irregular disturbances or the accumulation of environmental stresses, observable in areas marked by multiple trails, bivouacs or windfalls, fragment the formations.

4. Discussion

4.1. Diversity of Ecological Trajectories and a Mosaic of Dynamic States

A thorough analysis of the plant communities present at these various locations

has been undertaken, thereby confirming the coexistence of communities at different stages of evolution within relatively compact geographical areas. This observed organisation is consistent with the dynamic state mosaic model.

Site	Grazing, Extensive and Semi-Extensive Livestock Farming	Agricultural Practices	Developed Infrastructure (Trails, roads, recreational areas)	Informal Uses (Unregulated recreational and extractive activities)	Abiotic Disturbances	Coastal Dynamics	Ecotone
Grande Terre 1	Continuous grazing, high intensity (1951 – 1992)	Intensive melon cultivation	Presence of a road with a ground impact of 6 m width	Waste accumulation due to beachgoers, including unauthorized camping – high intensity	Submersion episodes leaving waste deposits	Moderate coastal retreat (~ 0.2 m/year)	Abrupt ecotones due to infrastructure (roads, trails) and boundaries with cultivated parcels
Grand Macabou 1	Previous intensive exploitation, high impact at its peak	Not reported (no available data)	Selective branch pruning to maintain trail accessibility – moderate to high intensity	Resource extraction, trail development, and bivouacs – moderate to high intensity , recurrent disturbances	Constraining environmental conditions (salinity, insolation, substrate mobility) and occasional stress episodes	Équilibre	Mosaic ecotone in the foredune zone; fragmentation associated with numerous trails and bivouac sites
Pointe Borgnesse 1	Intense past agricultural exploitation	Not reported (no available data)	Regular trail use by coastal visitors – moderate intensity	Bivouac and occasional beach occupation – picnic waste – moderate to high intensity	Traces of recurrent submersion events with waste deposits and probable salinity increase	Coastal retreat and severe erosion (~ 0.5 mm/year)	Progressive ecotone behind the backshore formation; abrupt ecotone at the foreshore due to erosion and trail impact
Chevalier 1	Initial pastoral activities – moderate to high intensity	Partial progressive regeneration due to agricultural abandonment	Not reported (no available data)	Trampling and selective pruning of woody and herbaceous fringes on the foreshore due to trail presence – moderate intensity	No visible human activity in the backshore formation – low intensity	No observation available	Abrupt ecotone due to a frequently used trail on the upper beach; progressive ecotone with gradual transition between shrub fringe and backshore formation
Chevalier 2	Initial pastoral activities – moderate to high intensity	Partial progressive regeneration due to agricultural abandonment	Not reported (no available data)	Upper beach (herbaceous fringe) – absence of trampling and uprooting traces – low intensity	Evidence of marine resource collection and consumption (sea urchins, queen crabs) in the shrub fringe – moderate to high intensity	No visible human activity in the backshore formation	Mosaic ecotone linked to windthrows and walking paths. Linear ecotone in the front beach area

Figure 10. Typology of disturbances and ecotone in the five stations of the study.

The observed heterogeneity is attributable to anthropogenic disturbances and environmental variations, which modulate the dynamics of the vegetation cover at various scales of time and space.

The evolution of the Grand Macabou landscape is characterised by periods of intense exploitation of the site (agropastoral exploitation, quarrying, construction of paths and roads with significant land take) and periods of recovery of natural vegetation dynamics as human activities decrease. The fragmentation of the vegetation cover, combined with signs of recurrent disturbances (bivouacs, paths, harvesting of plants), suggests an unstable balance between natural regeneration and anthropic pressures. This situation illustrates a mosaic of evolutionary trajectories. Some areas continue to develop into mature formations, while others remain stuck in the early stages.

At Pointe Borgnesse, despite active coastal erosion, the forest cover is gradually recovering. The history of the site shows that after a period of destabilisation linked to agricultural exploitation, a scar-like plant formation has recolonised the area.

The presence of erratic individuals and the establishment of invasive species indicate that, even after disturbance ceased, the future of this formation has been permanently altered. It is conceivable that if the dominance of *Dichrostachys ci-*

nera is maintained, the formation will be permanently blocked in a paraclimax, illustrating a mosaic of dynamic states where certain areas stagnate under the effect of disturbance.

The observed heterogeneity is attributable to anthropogenic disturbances and environmental variations, which modulate the dynamics of the vegetation cover at various scales of time and space.

These observations reveal a mosaic of dynamic states that explain the structural diversity of plant formations as a function of spatio-temporal variations in disturbance and environmental conditions. These results illustrate the need to re-think beach management by integrating the variability of ecological trajectories and resilience processes.

4.2. Tipping Points: Ecological Ruptures and Irreversible Transitions

These observations reveal a mosaic of dynamic states that explain the structural diversity of plant formations as a function of spatio-temporal variations in disturbance and environmental conditions. These results illustrate the need to re-think beach management by integrating the variability of ecological trajectories and resilience processes [13] [43].

Field observations, particularly at the Grande Terre 1, Pointe Borgnesse 1 and Chevalier 1 and 2 sites, reveal contrasting ecological trajectories within the coastal plant formations of Martinique. On these sites, a mosaic of plant units can be observed, resulting from anthropic (urbanisation, agriculture, leisure activities, trampling) and environmental (marine submersion, water stress, retreat of the coastline) pressures. In Grande Terre 1, the formation is characterised by a very high level of insularisation and an almost total disappearance of the herbaceous stratum, as well as seedlings and regeneration.

The rare studies on the regenerative capacity of coastal forests show that the low density of young trees does not always indicate a dysfunction of forest dynamics, but that human activities and the presence of animals can influence forest regeneration. Soil degradation and hydrological changes can reduce the density of young trees [44].

An in-depth analysis is needed to identify the causes and consequences of these low densities. Continued regeneration, even at low density, may be enough to ensure the sustainability of the forest. Long-term monitoring of regeneration indicators and the maintenance of connectivity with areas containing potential seed sources should therefore be considered.

The Pointe Borgnesse 1 station presents several converging signals of an ecological shift that is in progress or has already been completed. The diachronic analysis reveals an apparent trajectory of closure of the forest cover between 1952 and 2022, following the abandonment of agriculture. However, these dynamic masks a functional alteration: the almost total absence of herbaceous stage, a significant retreat of the coastline with a drastic decrease in the size of the supralit-

toral psammophilic domain and, above all, the growing dominance of pioneer and invasive species (notably *Dichrostachys cinerea*), as well as a weak floristic structuring, all of which reflect an unstable state. These elements suggest a metastable regime, potentially indicative of a crossed or imminent tipping point.

The ecological trajectories observed at Grande Terre 1 and Pointe Borgnesse 1 present several characteristic signs of regime shifts as described by [17]: disappearance of functional strata such as herbaceous vegetation, increasing dominance of opportunistic or invasive species, and simplification of plant structure. These alterations reflect a loss of resilience and suggest a shift to an alternative ecological state that is difficult to reverse. This type of transition is reminiscent of other well-documented cases, such as the transition from clear oligotrophic lakes to turbid eutrophic lakes, or the conversion of coral reefs to macroalgae-dominated systems as a result of chronic disturbances.

These findings resonate with the study by Smith *et al.* (2024) [45] on kelp forests in California, which highlights transitions to stable alternative states, induced by multiple stresses, without a collapse of species diversity but accompanied by a major functional reconfiguration. Together, these studies emphasise the importance of integrating systemic indicators – such as fragmentation, disturbance regimes and resilience – to better understand and anticipate the complex ecological trajectories of coastal plant formations.

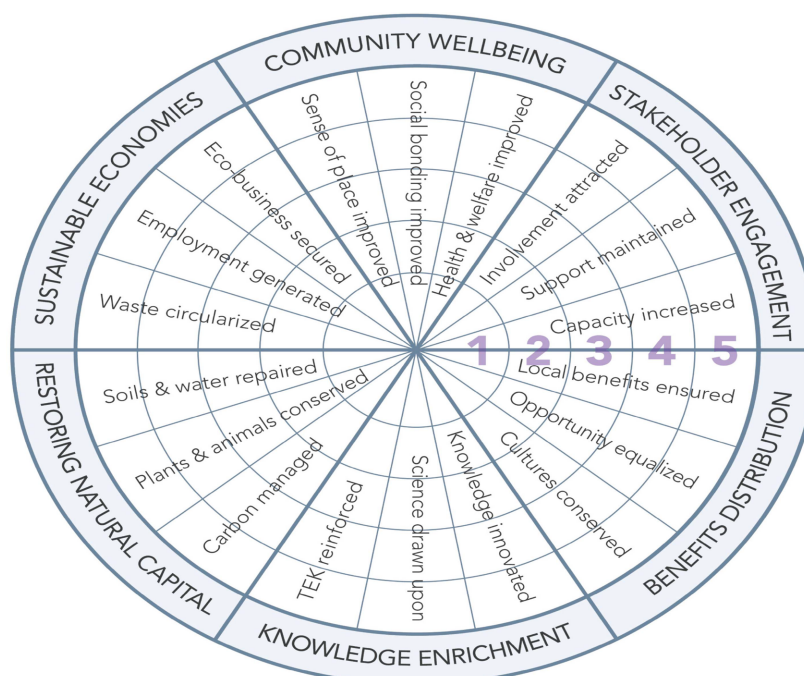
The work of Dai *et al.* (2012) [46] provides a framework that can be used to identify early signs of loss of resilience: increased variance, autocorrelation, time to return to equilibrium or asymmetry of responses [47]. These indicators can be extracted from time series derived from remote sensing, NDVI/EVI indices and georeferenced floristic surveys [47].

A determining factor here is hysteresis, which expresses the asymmetry between the conditions necessary for a shift and those required to return to the initial state. Improving environmental conditions is therefore not always enough to restore a system that has crossed a critical threshold. As shown in [19] and [20] Scheffer *et al.* (2001, 2009), this dynamic makes restoration efforts more uncertain and reinforces the interest of early detection of weak signals of loss of resilience.

In this context, the integration of remote sensing tools, as proposed by McKenna *et al.* (2022) [48], makes it possible to monitor up to 11 of the 18 sub-attributes of the Ecological Recovery Wheel (ERW) [49], including vegetation cover, connectivity and community structure. These methods, combined with field data, form an operational basis for the rigorous monitoring of ecological trajectories and the development of decision-making tools (see **Figure 11**).

5. Conclusions

Understanding the ecological dynamics of coastal plant formations requires an integrated approach capable of grasping the complexity of interactions between abiotic, biotic and anthropic factors. The framework proposed in this study articulates three complementary approaches:



This figure illustrates a visual assessment tool known as the Ecological Recovery Wheel, developed by the Society for Ecological Restoration (Gann *et al.*, 2019).

It is a circular radar diagram designed to provide an integrated evaluation of a restored site's progress toward its reference ecosystem. The model is structured around six key categories of ecological attributes:

- **Physical conditions** (e.g., soil quality, hydrology)
- **Species composition** (e.g., presence of native or exotic species)
- **Community structure** (e.g., stratification, spatial diversity)
- **Ecosystem function** (e.g., productivity, nutrient cycling)
- **External exchanges** (e.g., connectivity, seed dispersal, pollination)
- **Absence of threats** (e.g., anthropogenic disturbance, invasive species)

Each category is broken down into three sub-attributes, scored on a scale from 0 to 5, where 0 indicates no recovery and 5 represents full alignment with the reference ecosystem.

A color coding indicates the level of data collection for each attribute: Dark green: measured with field data, Light green: estimated, Yellow: in process, White: not measured

Figure 11. The ecological Recovery Wheel, a tool for functional and structural assessment of coastal ecosystem.

- diachronic analysis of plant formations;
- geomatic and historical reconstruction;
- and the emic approach mobilising local knowledge.

This triangulation makes it possible to reconstruct past trajectories, anticipate future developments and detect early signals of critical transitions.

The results highlight the existence of mosaics of dynamic states, revealing contrasting trajectories depending on the site. While some (Chevalier 2, Grand Macabou 1) show signs of spontaneous recolonisation, others (Grande Terre 1, Pointe Borgnesse 1) display characteristics of degraded metastable states.

These trajectories suggest that sandy plant communities do not follow a linear succession, but evolve under the effect of complex feedbacks between disturbances and resilience. Observations of the disappearance of functional strata, the dominance of opportunistic species and structural simplification are reminiscent of re-

gime shifts similar to those described in other coastal ecosystems.

The protocol developed here constitutes a reproducible tool for ecological monitoring, by cross-referencing:

- the time series derived from multispectral imaging;
- the georeferenced floristic inventories;
- the resilience indicators (variance, autocorrelation, time to return to equilibrium).

This approach makes it possible to anticipate tipping points and to assess the stability of coastal socio-ecosystems, based on a detailed understanding of their functional and spatial dynamics. The findings support the implementation of adaptive and site-specific management strategies. Key recommendations include:

- Prioritising lightly disturbed areas for minimal intervention;
- Structurally restoring metastable sites to reactivate ecological functions;
- Preserving connectivity with regeneration sources (e.g. seed banks, refuges);
- Incorporating local knowledge and historical land uses;
- Using resilience indicators to guide ecosystem-based restoration.

This approach aligns with the standards of the Society for Ecological Restoration (SER) and recent advances in ecological monitoring via remote sensing. It offers a robust scientific framework for developing predictive decision-making tools, tailored to the specific dynamics of Lesser Antillean sandy beaches under mounting global change pressures.

Acknowledgements

Our sincere thanks go to SOPHIE Théo and BRUSSET Lydie for their invaluable help and patience during the floristic surveys. We would also like to thank the team at “UMR Espace-Dev-BIORECA” and the “Institut de la Biodiversité et de l’Écologie” (Université des Antilles) for their technical support, which was essential for the completion of this study. Finally, we would like to thank Professor Joseph for the opportunity to present this work at the “Îles et Biodiversités” symposium in December 2024, as well as for his advice throughout this research.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

- [1] McLachlan, A. and Defeo, O. (2017) *The Ecology of Sandy Shores*. Academic Press.
- [2] Christian, R.R. and Mazzilli, S. (2007) Defining the Coast and Sentinel Ecosystems for Coastal Observations of Global Change. *Hydrobiologia*, **577**, 55-70.
<https://doi.org/10.1007/s10750-006-0417-4>
- [3] Joseph, P. (2006) Hypothèses sur l'évolution de la végétation littorale des Petites Antilles depuis l'époque précolombienne: Le cas de la Martinique. *Cybergeo*.
<https://doi.org/10.4000/cybergeo.1784>
- [4] Nachbaur, A., Balouin, Y., Nicolae Lerma, A., Douris, L. and Pedreros, R. (2015) Définition des cellules sédimentaires du littoral martiniquais. Rapport final. RP-64499-

- FR. BRGM/RP-64499 (Vol. 95).
- [5] Joseph, P. (2015) The Final Stages of Vegetal Dynamics in the Lesser Antilles (a Few Theories). *International Journal of Science and Research*, **4**, 1151-1164.
- [6] Joseph, P. (2009) La végétation forestière des Petites Antilles: synthèse bi-ogéographique et écologique, bilan et perspectives. KARTHALA Editions.
- [7] Stallins, J.A. (2006) Geomorphology and Ecology: Unifying Themes for Complex Systems in Biogeomorphology. *Geomorphology*, **77**, 207-216. <https://doi.org/10.1016/j.geomorph.2006.01.005>
- [8] Corenblit, D., Baas, A.C.W., Bornette, G., Darrozes, J., Delmotte, S., Francis, R.A., *et al.* (2011) Feedbacks between Geomorphology and Biota Controlling Earth Surface Processes and Landforms: A Review of Foundation Concepts and Current Understandings. *Earth-Science Reviews*, **106**, 307-331. <https://doi.org/10.1016/j.earscirev.2011.03.002>
- [9] Pickett, S.T., Wu, J. and Cadenasso, M.L. (1999) Patch Dynamics and the Ecology of Disturbed Ground: A Framework for Synthesis. In: Walker, L.R., Ed., *Ecosystems of Disturbed Ground*, Elsevier, 707-722.
- [10] Gough, C.M., Buma, B., Jentsch, A., Mathes, K.C. and Fahey, R.T. (2024) Disturbance Theory for Ecosystem Ecologists: A Primer. *Ecology and Evolution*, **14**, e11403. <https://doi.org/10.1002/ece3.11403>
- [11] Pulsford, S.A., Lindenmayer, D.B. and Driscoll, D.A. (2014) A Succession of Theories: Purging Redundancy from Disturbance Theory. *Biological Reviews*, **91**, 148-167. <https://doi.org/10.1111/brv.12163>
- [12] Paine, R.T., Tegner, M.J. and Johnson, E.A. (1998) Compounded Perturbations Yield Ecological Surprises. *Ecosystems*, **1**, 535-545. <https://doi.org/10.1007/s100219900049>
- [13] Turner, M.G. (2010) Disturbance and Landscape Dynamics in a Changing World. *Ecology*, **91**, 2833-2849. <https://doi.org/10.1890/10-0097.1>
- [14] Lenton, T.M. (2013) Environmental Tipping Points. *Annual Review of Environment and Resources*, **38**, 1-29. <https://doi.org/10.1146/annurev-environ-102511-084654>
- [15] Kéfi, S., Saade, C., Berlow, E.L., Cabral, J.S. and Fronhofer, E.A. (2022) Scaling Up Our Understanding of Tipping Points. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **377**, Article ID: 20210386. <https://doi.org/10.1098/rstb.2021.0386>
- [16] Huang, J.C.K. (1997) Climate Change and Integrated Coastal Management: A Challenge for Small Island Nations. *Ocean & Coastal Management*, **37**, 95-107. [https://doi.org/10.1016/s0964-5691\(97\)00042-2](https://doi.org/10.1016/s0964-5691(97)00042-2)
- [17] Folke, C., Carpenter, S., Walker, B., Scheffer, M., Elmqvist, T., Gunderson, L., *et al.* (2004) Regime Shifts, Resilience, and Biodiversity in Ecosystem Management. *Annual Review of Ecology, Evolution, and Systematics*, **35**, 557-581. <https://doi.org/10.1146/annurev.ecolsys.35.021103.105711>
- [18] Direction de l'Environnement, de l'Aménagement et du Logement (DEAL) and Direction de la Mer (DM) de la Martinique (2019) Stratégie de gestion du domaine public maritime naturel en Martinique. Préfet de la Martinique. <https://www.dm.martinique.developpement-durable.gouv.fr/strategie-de-gestion-du-domaine-public-maritime-a277.html>
- [19] Scheffer, M., Carpenter, S., Foley, J.A., Folke, C. and Walker, B. (2001) Catastrophic Shifts in Ecosystems. *Nature*, **413**, 591-596. <https://doi.org/10.1038/35098000>
- [20] Scheffer, M., Brock, W. and Westley, F. (2000) Socioeconomic Mechanisms Preventing Optimum Use of Ecosystem Services: An Interdisciplinary Theoretical Analysis. *Eco-*

- systems*, **3**, 451-471. <https://doi.org/10.1007/s100210000040>
- [21] Boon, J.D. and Green, M.O. (1989) Caribbean Beach-Face Slopes and Beach Equilibrium Profiles. *Coastal Engineering Proceedings*, **1**, 1618-1630. <https://doi.org/10.1061/9780872626874.121>
- [22] Fish, M.R., Côté, I.M., Gill, J.A., Jones, A.P., Renshoff, S. and Watkinson, A.R. (2005) Predicting the Impact of Sea-level Rise on Caribbean Sea Turtle Nesting Habitat. *Conservation Biology*, **19**, 482-491. <https://doi.org/10.1111/j.1523-1739.2005.00146.x>
- [23] Fanini, L., Defeo, O. and Elliott, M. (2020) Advances in Sandy Beach Research—Local and Global Perspectives. *Estuarine, Coastal and Shelf Science*, **234**, Article ID: 106646. <https://doi.org/10.1016/j.ecss.2020.106646>
- [24] Grafals-Soto, R., Nordstrom, K.F. and Jackson, N.L. (2019) Differences in Vegetation Characteristics with Shoreline Position on a Tropical Pocket Beach. *Physical Geography*, **41**, 315-331. <https://doi.org/10.1080/02723646.2019.1671298>
- [25] Institut national de l'information géographique et forestière (2022) BD Topo Département 972—Martinique—PVA 2022.
- [26] Institut national de l'information géographique et forestière (2022) BD orthohistorique: Département 972—Martinique—PVA 1951—Projection UTM20W84MART.
- [27] Institut national de l'information géographique et forestière (2022) Le registre parcellaire graphique de l'IGN: Base de données RPG—Région Martinique, édition 2022.
- [28] Germa, A., Quidelleur, X., Labanieh, S., Chauvel, C. and Lahitte, P. (2011) The Volcanic Evolution of Martinique Island: Insights from K-Ar Dating into the Lesser Antilles Arc Migration since the Oligocene. *Journal of Volcanology and Geothermal Research*, **208**, 122-135. <https://doi.org/10.1016/j.jvolgeores.2011.09.007>
- [29] IRD (2006) Base de données Valsol de la Martinique à 1/20 000, d'après Colmet-Daage. 1969. Carte des sols des Antilles: Guadeloupe volcanique et Martinique au 1/20 000.
- [30] UMR GRED-Patrick Gilli-Université Paul-Valéry Montpellier III (2019) Changement climatique et conséquences sur les Antilles Françaises. <https://c3af.univ-montp3.fr/>
- [31] Nachbar, A., Paulineau, M. and Le Roy, M. (2015) Évolution multidécennale (1951-2010) et décennale (2004-2010) du trait de côte de la Martinique. Rapport Final. BRGM/RP-63238-FR.
- [32] Blott, S.J. and Pye, K. (2012) Particle Size Scales and Classification of Sediment Types Based on Particle Size Distributions: Review and Recommended Procedures. *Sedimentology*, **59**, 2071-2096. <https://doi.org/10.1111/j.1365-3091.2012.01335.x>
- [33] Saffache, P. and Pelis, Y. (2007) De la lecture des paysages littoraux martiniquais à la définition de leur typologie. *Travaux & Documents. Approches des littoraux réunionnais et martiniquais*, **32**, 131-144. <https://hal.archives-ouvertes.fr/hal-02184460f>
- [34] Dehoorne, O. and Tafani, C. (2012) Le tourisme dans les environnements littoraux et insulaires: Permanences, limites et perspectives. *Études caribéennes*, **19**. <https://doi.org/10.4000/etudescaribeennes.5774>
- [35] Joseph, P., Baillard, K., Claude, J., Abati, Y., Ely-Marius, S., Jean-François, Y., *et al.* (2019) The Main Ecological Characteristics of a Species Introduced to Martinique in a Dynamic of Invasion: *Funtumia elastica* (Preuss) Stapf (*Apocynaceae*). *Journal of Plant Studies*, **8**, 1. <https://doi.org/10.5539/jps.v8n2p1>
- [36] Joseph, P. (2016) The Spatio-Temporal Interfaces within the Lesser Antilles Vegetation (the Example of the Island of Martinique). *OALib*, **3**, 1-17. <https://doi.org/10.4236/oalib.1102463>

- [37] Imbert, D., Labbé, P. and Rousteau, A. (1996) Hurricane Damage and Forest Structure in Guadeloupe, French West Indies. *Journal of Tropical Ecology*, **12**, 663-680. <https://doi.org/10.1017/s026646740000986x>
- [38] Taylor, B.N., Stedman, E., Van Bloem, S.J., Whitmire, S.L. and DeWalt, S.J. (2023) Widespread Stem Snapping but Limited Mortality Caused by a Category 5 Hurricane on the Caribbean Island of Dominica. *Forest Ecology and Management*, **532**, Article ID: 120833. <https://doi.org/10.1016/j.foreco.2023.120833>
- [39] Fournet, J. (2002) Flore illustrée des phanérogames de Guadeloupe et de Martinique. Cirad.
- [40] Sastre, C. and Breuil, A. (2007) Plantes, milieux et paysages des Antilles françaises: Écologie, biologie, identification, protection et usages. Biotope Editions.
- [41] Joseph, P. (1997) Dynamique, écophysio­logie végétales en bioclimat sec à la Martinique. Master's Thesis, Université des Antilles et de la Guyane.
- [42] Yelji, A., Philippe, J., Kevine, B., Jean-Philippe, C., Yanis, J., Severine, E., *et al.* (2020) Some Aspects of the Ecology of a Potentially Invasive Species in Martinique: The Case of *Dichrostachys cinerea*. *International Journal of Sciences*, **9**, 8-26. <https://doi.org/10.18483/ijsci.2242>
- [43] Dobson, A.P., Bradshaw, A.D. and Baker, A.J.M. (1997) Hopes for the Future: Restoration Ecology and Conservation Biology. *Science*, **277**, 515-522. <https://doi.org/10.1126/science.277.5325.515>
- [44] Rousteau, A. (2004) Régénération forestière dans les espaces protégés littoraux: Variété des processus naturels ou anomalies menaçant la pérennité des écosystèmes? *Revue d'Écologie (La Terre et La Vie)*, **59**, 203-211. <https://doi.org/10.3406/rev.2004.6393>
- [45] Smith, J.G., Malone, D. and Carr, M.H. (2024) Consequences of Kelp Forest Ecosystem Shifts and Predictors of Persistence through Multiple Stressors. *Proceedings of the Royal Society B: Biological Sciences*, **291**, Article ID: 20232749. <https://doi.org/10.1098/rspb.2023.2749>
- [46] Dai, L., Vorselen, D., Korolev, K.S. and Gore, J. (2012) Generic Indicators for Loss of Resilience before a Tipping Point Leading to Population Collapse. *Science*, **336**, 1175-1177. <https://doi.org/10.1126/science.1219805>
- [47] Brock, W.A. and Carpenter, S.R. (2006) Variance as a Leading Indicator of Regime Shift in Ecosystem Services. *Ecology and Society*, **11**, Article 9. <https://doi.org/10.5751/es-01777-110209>
- [48] McKenna, P.B., Lechner, A.M., Hernandez Santin, L., Phinn, S. and Erskine, P.D. (2022) Measuring and Monitoring Restored Ecosystems: Can Remote Sensing Be Applied to the Ecological Recovery Wheel to Inform Restoration Success? *Restoration Ecology*, **31**, e13724. <https://doi.org/10.1111/rec.13724>
- [49] Gann, G.D., McDonald, T., Walder, B., Aronson, J., Nelson, C.R., Jonson, J., *et al.* (2019) International Principles and Standards for the Practice of Ecological Restoration. Second Edition. *Restoration Ecology*, **27**, S1-S46. <https://doi.org/10.1111/rec.13035>