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Edited by Ilda Vagge



National Parks and Protected Areas - Conservation, Biodiversity, and Climate Action

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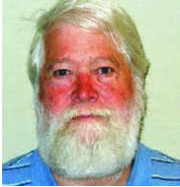
Volume 43

Aims and Scope of the Series

Scientists have long researched to understand the environment and man's place in it. The search for this knowledge grows in importance as rapid increases in population and economic development intensify humans' stresses on ecosystems. Fortunately, rapid increases in multiple scientific areas are advancing our understanding of environmental sciences. Breakthroughs in computing, molecular biology, ecology, and sustainability science are enhancing our ability to utilize environmental sciences to address real-world problems.

The four topics of this book series - Pollution; Environmental Resilience and Management; Ecosystems and Biodiversity; and Water Science - will address important areas of advancement in the environmental sciences. They will represent an excellent initial grouping of published works on these critical topics.

Meet the Series Editor



J. Kevin Summers is a Senior Research Ecologist at the Environmental Protection Agency's (EPA) Gulf Ecosystem Measurement and Modeling Division. He is currently working with colleagues in the Sustainable and Healthy Communities Program to develop an index of community resilience to natural hazards, an index of human well-being that can be linked to changes in the ecosystem, social and economic services, and a community sustainability tool for communities with populations under 40,000. He leads research efforts for indicator and indices development. Dr. Summers is a systems ecologist and began his career at the EPA in 1989 and has worked in various programs and capacities. This includes leading the National Coastal Assessment in collaboration with the Office of Water which culminated in the award-winning National Coastal Condition Report series (four volumes between 2001 and 2012), and which integrates water quality, sediment quality, habitat, and biological data to assess the ecosystem condition of the United States estuaries. He was acting National Program Director for Ecology for the EPA between 2004 and 2006. He has authored approximately 150 peer-reviewed journal articles, book chapters, and reports and has received many awards for technical accomplishments from the EPA and from outside of the agency. Dr. Summers holds a BA in Zoology and Psychology, an MA in Ecology, and Ph.D. in Systems Ecology/Biology.

Meet the Volume Editor



Ilda Vagge graduated with honours in Natural Sciences from the University of Genoa in 1991 and obtained a Ph.D. in “Plant Biology and Ecology in Mediterranean Environments” in 1995. Since 2001, she has been an Associate Professor of Environmental and Applied Botany in the Department of Agricultural and Environmental Sciences at the University of Milan. She coordinates the Master’s Degree Programme in Landscape Architecture and teaches courses on Landscape Analysis and Assessment, Urban Environmental Design, and Plant Species Selection within the Landscape Design Laboratory. Her primary research themes include Geobotany — vegetation and landscape studies integrating geomorphological, pedological, and faunal data; applied Botany and Geobotany; and Landscape Ecology — environmental design, urban green design, and ecosystem services. She collaborates with associations, municipalities, farms, and landscape design studios, has participated in numerous national and international scientific conferences, and has published approximately 80 peer-reviewed articles and 30 books/book chapters.

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Preface

The book *National Parks and Protected Areas – Conservation, Biodiversity, and Climate Action* presents a timely and critical examination of the interplay between biodiversity conservation and climate action within protected areas. Given the escalating threats posed by climate change, this volume highlights the paramount importance of national parks and protected areas in sustaining ecological integrity and safeguarding biodiversity for future generations. As climate change intensifies, national parks and protected areas are increasingly recognised as vital sanctuaries for preserving natural ecosystems and the myriad species that inhabit them. This volume underscores the necessity of these areas not only for environmental protection but also for the resilience of human societies in the face of ecological disruption.

Comprising nine insightful chapters, the book addresses a wide array of challenges and strategies pertinent to conservation in a rapidly changing climate:

Chapter 1, “Five Centuries of Climate History in Cofre de Perote National Park in Mexico”, employs dendrochronology to reconstruct climate histories over the past 600 years, revealing patterns of climate variability and the recurrence of severe droughts, which are crucial for effective park management.

Chapter 2, “Climate-Driven Human-Wildlife Conflict in Mkomazi National Park: The Role of Land-Use Changes and Ecosystem Stressors in Shaping Conservation Challenges”, investigates the intensifying human-wildlife conflicts exacerbated by climate change and land-use changes in Tanzania and advocates for integrated, climate-smart strategies to foster coexistence.

Chapter 3, “Do Current Protected Areas Preserve Soil Health and Ecosystem Resilience? Contributions of Nematodes as Bioindicators in the Souss Massa National Park”, highlights the critical role of soil health and nematodes as bioindicators, underscoring the need to protect biodiversity to enhance ecosystem resilience.

Chapter 4, “Landscape-Environmental Heritage in the Coastal Zone of Guinea-Bissau: Current Trends and Design Scenarios in a Changing Climate”, explores the impacts of climate change on coastal landscapes and proposes management strategies that enhance community safety and ecological integrity through sustainable development.

Chapter 5, “Climate-Resilient Biodiversity Refuges in Biosphere Reserves of the Cantabrian Cornice, Spain”, presents a framework for identifying biodiversity refugia, offering insights into species distribution and climate suitability under future scenarios, thereby guiding conservation priorities.

Chapter 6, “Corridors of Coexistence: Integrating Ecological Connectivity with Local Benefits in Protected Area Management in Central Annamite, Vietnam”, discusses

the management of biodiversity corridors in Vietnam, emphasising the integration of ecological connectivity with local community benefits to enhance resilience against habitat fragmentation.

Chapter 7, “Improving Fruition and Protecting Nature through Landscape Design and Nature-Based Solutions: The Case of West Iceland”, focuses on Iceland and highlights innovative landscape designs that manage tourism while preserving ecological integrity, showcasing nature-based solutions that address environmental challenges.

Chapter 8, “Perspective Chapter: Reshaping Governance at Tram Chim National Park – From Conservation Conflict to Ecological Consensus”, presents a model for an integrated governance approach, demonstrating how ecological consensus can support both biodiversity and sustainable livelihoods.

Chapter 9, “Perspective Chapter: A Judicial Perspective on the Legal Structure of Protected Areas in Turkey”, examines the legal frameworks governing protected areas and advocates mandatory environmental assessments to enhance the effectiveness of conservation efforts.

Overall, this book serves as an essential resource for researchers, policymakers, and practitioners engaged in conservation efforts. It emphasises the critical role of protected areas in combating biodiversity loss and climate change, advocating a proactive, integrated approach to conservation that harmonises ecological health with community needs. As the world faces unprecedented environmental challenges, the insights presented in this volume are vital for informing sustainable conservation practices and ensuring the resilience of our natural heritage.

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Chapter 1

Five Centuries of Climate History in Cofre de Perote National Park in Mexico

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Abstract

The reconstruction of paleoclimate series from tree rings, using the science known as dendrochronology, has allowed the development of climate series spanning several 1000 years around the world and more than 1000 years in Mexico. This technique constitutes an excellent alternative for understanding and analyzing climate variability on a broader scale than that provided by observed records. For the high-mountain forest in Cofre de Perote National Park, *Pinus hartwegii* (Mirb.) Franco trees were selected, and growth samples were extracted using a Pressler increment borer for live trees and a chainsaw for dead trees. The samples were processed and dated using standard dendrochronological techniques. A dendrochronological series was developed spanning nearly the last 600 years (1436–2013). This chronology allowed for the analysis of the annual variability recorded over the last six centuries, as well as the most severe droughts and their recurrence. Severe droughts were observed every mid-century, and droughts recurred every 100 years. Changes in climate variability were also observed over the last century. This type of work provides relevant information that can significantly contribute to better management and conservation of the natural area.

Keywords: dendrochronology, tree rings, climate variability, drought, recurrence of droughts

1. Introduction

Examining alterations in rainfall patterns is a crucial area of interest because human activities are highly susceptible to extreme weather events such as excessive or insufficient rainfall [1, 2]. Drought is a slow-onset natural climate extreme that occurs in most parts of the world and is one of the most complex weather phenomena

affecting millions of people worldwide with severe impacts on nature and human life [3, 4]. Moreover, it tends to spread irregularly in time and space, and its effects are cumulative and can remain even after the event has ended [5]. Therefore, understanding the characteristics and occurrences of droughts are major issues aiming to prevent and mitigate the consequences of future occurrences [3, 6]. Droughts are prolonged periods of unusually low water availability, leading to an imbalance in water availability, quality, and demand [7]. They are a complex hazard, resulting from a combination of climate processes such as lower precipitation, higher evapotranspiration, and anomalous snowmelt, as well as human processes, related to water abstraction and use and land management and use. These processes are a manifestation of natural climate variability, anthropogenic climate change, and unsustainable management of natural resources [8].

No unique definition of drought has been followed globally to characterize and quantify its impact. Drought is commonly defined by taking into account different disciplinary perspectives, which classify it based on specific areas of study or expertise [9]. Droughts are usually classified into four categories, which include meteorological, agricultural, hydrological, and socio-economic. A meteorological drought can be defined as a lack of precipitation over a region for a period of time. An agricultural drought generally refers to a period of reduced soil moisture and consequent crop failure. A hydrological drought can be caused by a deficiency of streamflow and water storage. Finally, a socio-economic drought is associated with the inability of water resource systems to meet water demands, which affects society's productive and consumptive activities [10, 11]. Drought negatively affects the ecosystem services provided by the natural environment and, therefore, the economic value of natural capital. From an environmental point of view, the consequences of drought are diverse: proliferation of herbivorous insects and pathogens in forests [12, 13], decreased river water quality and increased salinity [14], increased tree mortality [15], reduced pollinators, and increased risk of fires [16], all of which affect the provision of ecosystem services. By other hand, drought has also been linked to human migration process [17].

For drought analysis and monitoring, good quality precipitation data are required [18]. Observation-based meteorological datasets offer insights into changes to the hydro-climatic system by diagnosing spatio-temporal characteristics and providing a historical baseline for future projections [19]. However, as in many countries of the world, the density of meteorological stations is not homogeneous in Mexico. This is a significant disadvantage when quantifying the amount of precipitation over a region [20]. Livneh et al. [21] noted a sharp decline of the Mexican station density since 2000, particularly after 2006. Other limitation is the spatial distribution. For instance, in some cases, the area covered by a single station becomes too large for that reading to represent regional precipitation, reducing the level of confidence in reading. While instrumental records provide valuable insights into recent droughts, they only span a rather short time frame, making it challenging to assess long-term drought variability and identify potential patterns [22, 23]. In this context, understanding past drought occurrences and their frequency, intensity, and spatial extent is crucial for predicting future occurrences, identifying trends, mitigating risk, and adapting water management strategies, particularly as climate change intensifies [24].

Therefore, long-term hydroclimatic variability derived from high-resolution paleoclimatic proxy data, like tree rings, is invaluable [25]. Ring widths from climatically sensitive trees provide a means for developing long-duration climate proxies that can extend beyond the instrumental record to encompass several centuries or

even millennia [26]. Tree-ring chronologies can provide an exactly dated, annually resolved extension of the climate record into the centuries prior to instrumental observations to better understand the magnitude and duration of drought and wetness extremes, their frequency of recurrence, and the climate dynamics involved [27]. The objective of the present study was to develop paleoclimatic series based on growth rings of *Pinus hartwegii* (Mirb.) Franco from Cofre de Perote National Park (CPNP) in central Mexico and to analyze the recurrence of severe droughts over the past 578 years.

2. Materials and methods

2.1 Study area

The geographical coordinates of CPNP are 19°25'33" to 19°33'52" N latitude and 97°06'55" to 97°12'52" W longitude. The altitudinal range of Cofre de Perote spans from 3000 m to 4250 m above sea level (masl), making it the seventh-highest mountain in Mexico. In pre-Hispanic times, this mountain was known as "Nauhcampatépētl," meaning "hill of the four sides." It forms part of the Citlaltépētl–Cofre de Perote volcanic range, located at the eastern end of the Trans-Mexican Volcanic Belt (Figure 1).

This mountain range consists of stratovolcanoes, cones, and domes aligned in a northeast-southwest direction, dividing the Mexican Plateau (Serdán-Oriental Basin) from the coastal plains of the Gulf of Mexico [28]. Glaciation during the

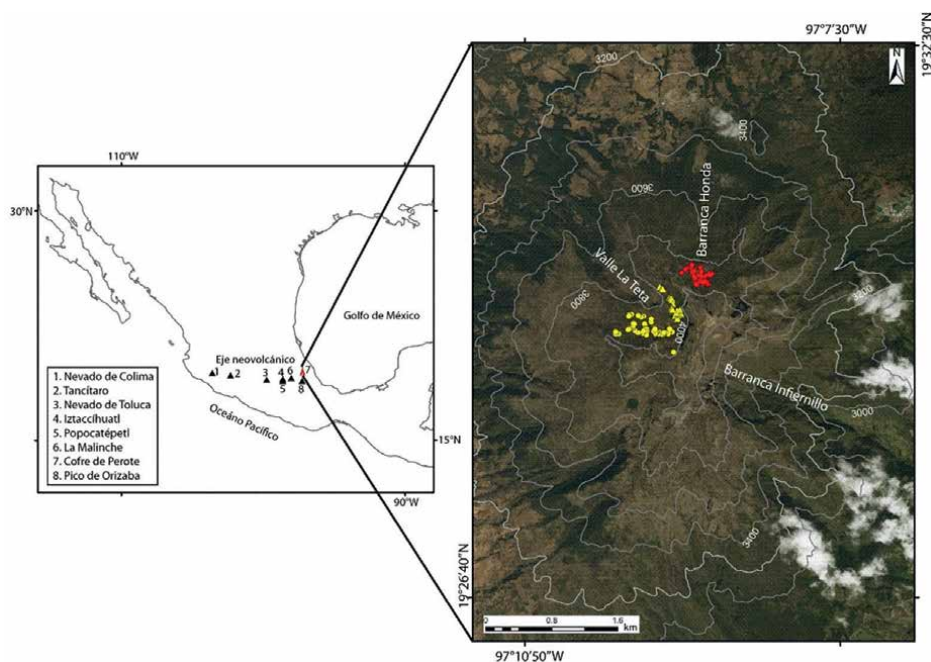


Figure 1. Geographic location of Cofre de Perote National Park within the Trans-Mexican Volcanic Belt and distribution of study sites along the summit under different exposures and moisture conditions on the western slope. Red markers denote Barranca Honda and yellow markers denote Valle la Teta.

Late Pleistocene and Early Holocene shaped cirques and glacial valleys [29], such as La Teta, Barranca Honda, Infiernillo, and El Tigre (**Figure 1**). This area is of great ecological, economic, and social importance for central Veracruz State, and elevations above 3000 m were designated as a “National Park” to protect its forests [30].

The mountain acts as a barrier to the warm, humid winds originating from the Gulf of Mexico, which ascend and cool rapidly upon reaching it, generating fog or rainfall on the eastern slope. As a result, the western slope of the Perote Valley lies in a rain shadow with considerably lower precipitation [31, 32].

In general, the climate within PNCP is classified into two dominant types according to the Köppen system as modified by García [33]. The first, Cb'(m)(f), is a humid, cool-temperate climate dominated by summer rainfall, covering 5338 ha of the study area from the central portion of the park toward the northeast and southeast. The second climatic regime, Cb'(w2), includes at least 10% of its precipitation during winter, maintains a cool-temperate temperature regime, but remains dominated by summer rainfall. This climate covers 6113 ha and extends from the central portion of the park toward the northwest and southwest. Within PNCP, a total of 165 plant species have been documented. The principal vegetation types include alpine scrub (*Juniperus monticola* Martínez), pine forests (*Pinus hartwegii* Lindl.), and sacred fir forests (*Abies religiosa* Kunth Schltdl. et Cham.).

2.2 Field sampling method

Field surveys were conducted to select two study areas (Barranca Honda and Valle la Teta), each dominated by *Pinus hartwegii*. In each site, selective sampling was applied to identify the oldest individuals with the least evidence of disturbance. A total of 35 trees per site were sampled, and two to three increment cores were extracted from each tree using Pressler increment borers (**Figure 2A, C**) of different lengths (45, 55, and 65 cm) and diameters (5 and 12 mm). In addition, whenever possible, cross-sections from dead trees were obtained with the aid of a chainsaw (**Figure 2B**), with the objective of extending the paleoclimatic series further back in time [34].

2.3 Laboratory method

In the Dendrochronology Laboratory of the National Research Center for Water, Soil, Plant, and Atmosphere Relations (CENID-RASPA by acronym in Spanish) of the National Institute of Forestry, Agricultural and Livestock Research (INIFAP by acronym in Spanish), located in Gómez Palacio, Durango, México, the samples were mounted and sanded with progressively finer sandpaper (from 120 to 1200 grit) to enhance the visibility of annual growth structures (**Figure 2D and 3**).

Using a stereomicroscope with a resolution of 10 to 30X, each growth ring was counted, and annual increments were cross-dated following standard dendrochronological techniques [35]. For each growth ring, earlywood, latewood, and total ring widths were measured with a VELMEX sliding-stage measuring system, with a precision of 0.001 mm (**Figure 4**). Dating and measurement accuracy were verified with the program COFECHA [36]. Samples from both sites were integrated into a single database. Biological trends (competition, suppression, and release) and geometric effects (increase in basal area with age and the consequent decline in annual ring width as growth is distributed over a larger surface) unrelated to climate were removed using the program ARSTAN [37]. This was achieved by fitting a curve to the growth series (commonly a negative



Figure 2.
(A) Sampling using the Pressler increment borer, (B) extraction of cross sections of dead trees with the support of a chainsaw, (C) example of the extraction of growth cores, and (D) example of the formation of annual increments (tree rings) and their variability in width, which is an indicator of climatic variability.

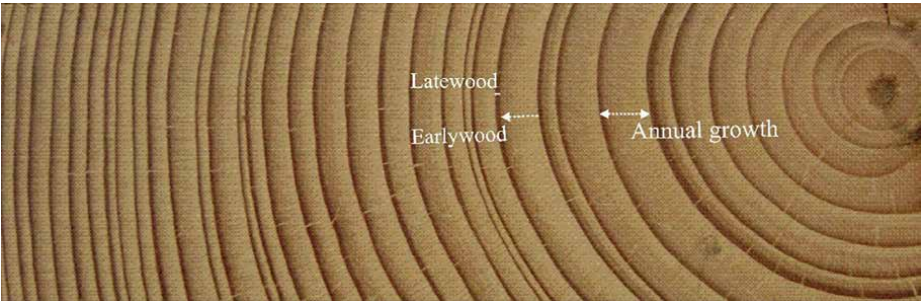


Figure 3.
Cross-section of a *Pseudotsuga menziesii* (Mirb.) Franco tree, showing the annual growth rings; the variability in their thickness indicates the annual climate variation (wide rings represent conditions of good rainfall and thin rings conditions of low rainfall or drought) recorded throughout the life of the tree.

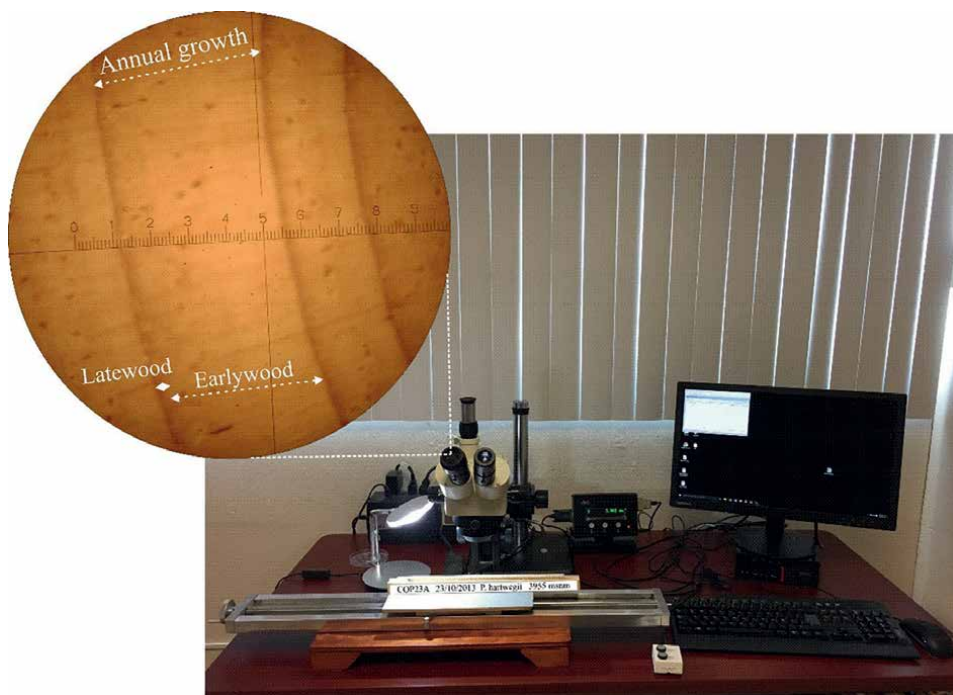


Figure 4. VELMEX measuring system with a sliding phase stage connected to a computer running Measure J2X version 4.2. Using a stereoscope with a graduated reticle, the beginning of the growth ring, as well as the boundaries between earlywood and latewood, are marked. This procedure is repeated for each ring, ultimately generating three databases (total ring width, earlywood, and latewood) that are stored on the computer.

exponential or straight line) and subsequently dividing each annual measurement by the expected value from the curve. This procedure generated standardized index series (chronology) with a mean of 1.0 and homogeneous variance [38].

2.4 Data analysis

The annually resolution chronology, or high-frequency series, was fitted with a flexible decadal curve, representing the low-frequency component, in order to highlight dry and wet events present in the reconstruction. The droughts identified in the chronology were validated using historical documentary sources and dendrochronological studies from central and northern Mexico. Finally, a spectral analysis was applied to the generated chronology, and dominant frequencies or recurrence intervals of anomalies in the paleoclimatic series were identified through spectral density versus frequency plots using MATLAB 6.5 software [39].

3. Results and discussion

3.1 Paleoclimatic series

A total of 94 growth cores (samples) of *Pinus hartwegii* were dated. The intercorrelation between series was statistically significant ($r = 0.418$; $P < 0.01$) (Table 1),

Parameters	Values
Chronology length	578 (1436–2013)
Number of trees (radii)	60 (94)
Average sensitivity	0.253
Correlation between series	0.418
Common chronology interval	150 (1854–2003)
Signal to noise	8.992

Table 1.
Chronology statistics for Pinus hartwegii from Cofre de Perote National Park, Veracruz, Mexico.

exceeding the parameter established by the COFECHA program [36], which establishes $r = 0.3281$ ($P < 0.01$) as the minimum significant correlation between samples. This indicates that the species is highly sensitive to environmental changes and offers potential for generating paleoclimatic series and analyzing regional climate variability.

A chronology with a length of 578 years was generated (**Figure 5, Table 1**), covering the period 1436–2013. The series developed for the center of the country shows high interannual and multiannual variability, which has characterized the climate of the past almost six centuries in this region of Mexico. The extension of this paleoclimate series allows for the analysis of drought occurrence, extent, intensity, and recurrence in the center of the country. It also allows for the determination of the extent of these events, whether severe droughts have spread to other latitudes such as northern Mexico, and the impact they have had on society.

In North America, a network of chronologies has been generated that has allowed us to observe the synchrony of droughts and the variability of their intensity at different latitudes, which shows that climate variability is modulated at extensive geographic scales [40]. In Mexico, paleoclimate series have been developed that have allowed us to analyze climatic variability over the past 1000 years, documenting the

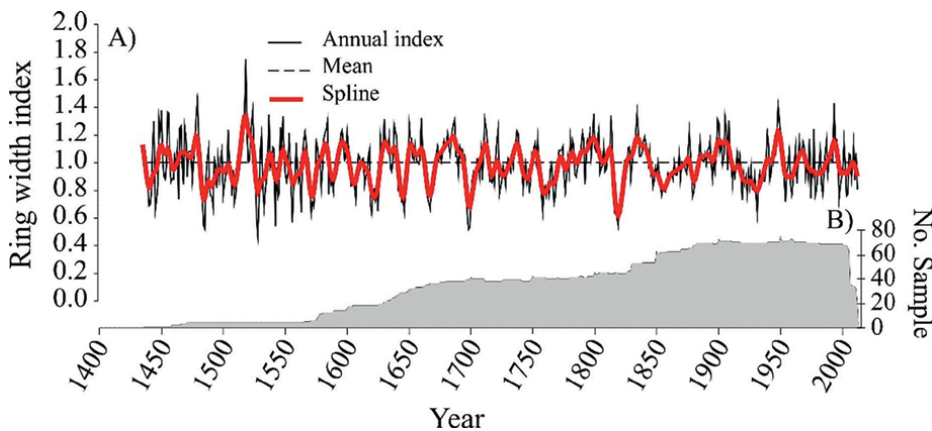


Figure 5.
(A) *Pinus hartwegii* ring-width index chronology for Cofre de Perote National Park in Veracruz. The black line shows the annual variability, the red line shows a 10-year spline that allows a better view of low-frequency variability (droughts and wet periods), and the dotted line represents the mean. (B) The sample size in each segment of the series. The chronology covers the period 1436–2013 (578 years).

occurrence of severe droughts and their relationship to the decline of civilizations such as the Toltec and Aztec [41]. They have also provided insight into the recurrence of severe droughts over the past 600 years in northern Mexico and their impact on society [42]. The application of series developed based on tree rings (dendrochronological series) for the study of past events such as climate, ecology, social, etc., is very broad.

3.2 Drought recurrence

The application of splines or smoothed series of varying amplitudes to the series generated for Cofre de Perote National Park in Veracruz allows us to observe major droughts, events with a recurrence of approximately every 100 years (1450, 1550, 1650, 1750, 1850, and 1950) over the last 578 years (**Figure 6**). Less intense droughts

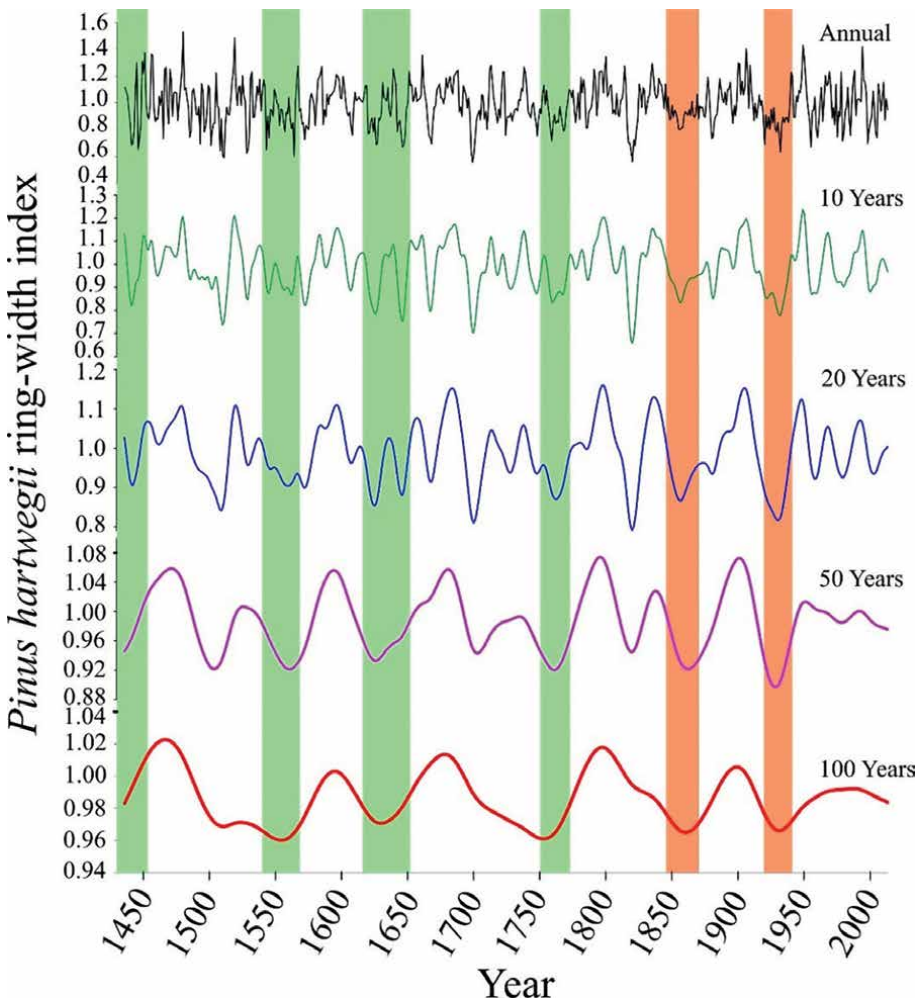


Figure 6. *Pinus hartwegii* ring-width index chronology for Cofre de Perote National Park in Veracruz. Splines of varying amplitudes were applied to the series (from 1 to 100 years) to observe low-frequency events (wet periods and droughts, with a greater emphasis on drought events) and determine their frequency over time for the last 578 years.

have occurred at the end or beginning of the century. Therefore, when considering both frequencies, the events register a recurrence of 50 years on average. However, the most significant or severe events have been recorded approximately every 100 years (every mid-century).

Paleoclimatic studies covering the last 600 years in the Serra Madre Oriental in northern Mexico have reported similar results: severe droughts occurring mid-century and less intense droughts occurring at the end or beginning of the century [42]. Other studies using ring index series developed for both the Sierra Madre Occidental [43, 44] and the central part of the country [45] have also documented significant droughts with these frequencies.

This type of work allows us to observe the geographic extent of extreme climate events and analyze their intensity in each of the country's different regions. Major droughts have been reported in central Mexico, with significant social impacts [45, 46], which has been corroborated by historical records [47]. Paleoclimatic studies in the north of the country have shown that some extreme events have been more intense in the north, which may give an idea of the damage suffered by society due to the lack of historical information.

3.3 Spectral analysis

Spectral analysis of the ring width index series covering the last 578 years (**Figure 7A**) identified significant frequencies ($p < 0.05$) of extreme events occurring every 50 and 100 years, recurring events over the last nearly 600 years in central Mexico (**Figure 7C**). Time-frequency wavelet spectral analysis shows that the ring width index chronology presents significant areas ($P < 0.05$) that corroborate the frequencies of low-frequency extreme events corresponding to periods of 50 and 100 years (**Figure 7B**). Likewise, biannual, tetra-annual, and 6- to 8-year frequencies were determined, which may be related to general circulation climate phenomena such as the El Niño Southern Oscillation (ENSO), which registers frequencies of two to seven years.

Studies for central Mexico on droughts in the Aztec period through the interpretation of codices have allowed us to understand the great emphasis of Aztec cosmology on predicting natural events in its calendar, assigning a name to an important event, highlighting “The Year of the Rabbit,” an event associated with the presence of catastrophic events such as famine and death, with a cycle identified in its 52-year calendar [45]. During the Aztec Empire, 13 Year of the Rabbit events were identified (882, 934, 986, 1038, 1090, 1142, 1194, 1246, 1298, 1402, 1454, 1505, and 1558) between 882 and 1558. For this region of central Mexico, in the Trans-Mexican Volcanic Belt, the paleoclimate series generated, covering the period 1436–2013, clearly shows a decrease in precipitation in the years 1454, 1505, and 1558 (Years of the Rabbit), which corroborates the ravages of these drought events in the center of the country.

Growth ring index series from both the north [42, 43] and the center of the country [45] indicate that the average value for the years prior to the Year of the Rabbit was significantly lower than normal, indicating drought and poor growth. This is evidence that extreme events such as droughts have not been localized to the center of the country, as this is where the most historical information is available, but rather have extended into northern Mexico, and to date have been recorded over periods ranging from 50 to 100 years (**Figure 6B** and **C**). The significant frequencies ($P < 0.05$) of 2, 3, 4, and 6 years (**Figure 7C**) are associated with the El Niño Southern Oscillation

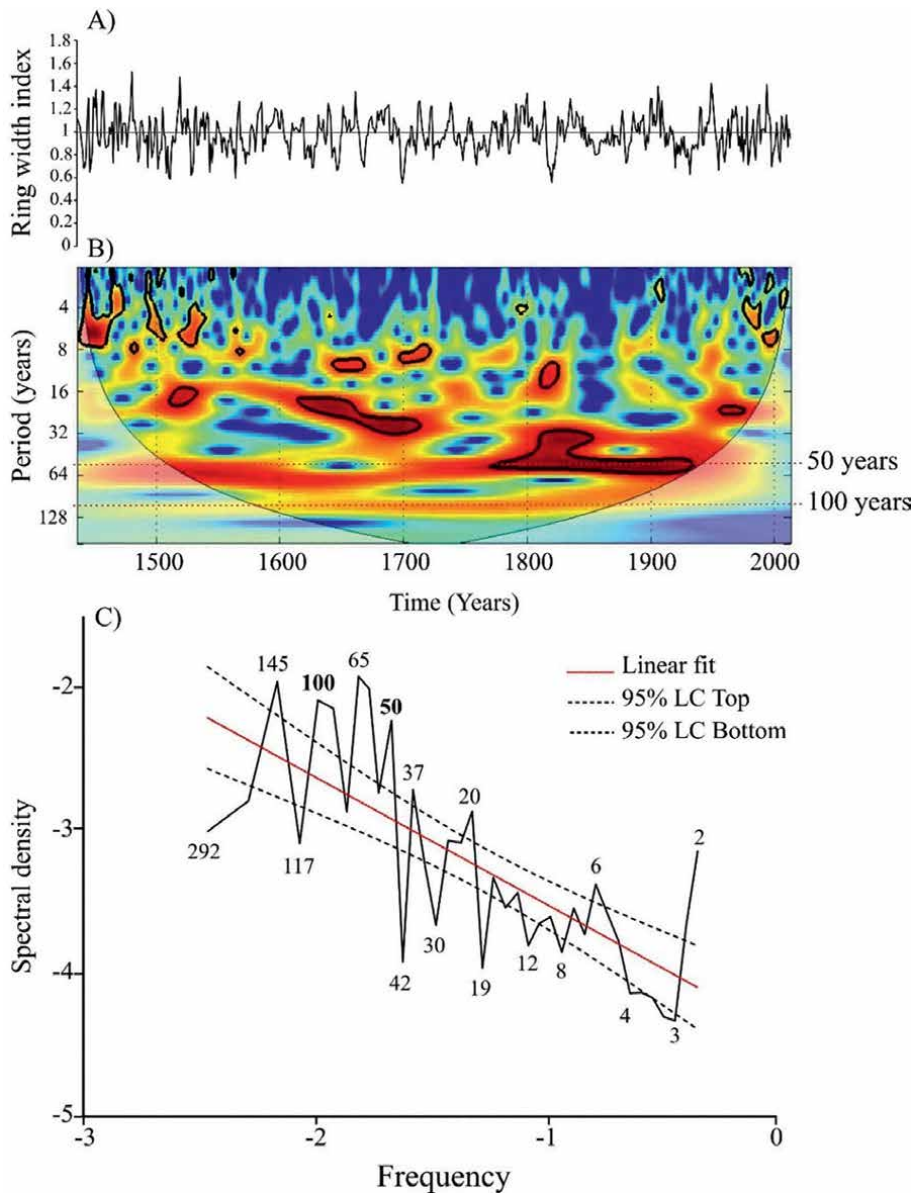


Figure 7. (A) Ring-width index chronologies of *Pinus hartwegii* for Cofre de Perote National Park in Veracruz, showing annual variability. (B) Annual wavelet power spectra of the generated chronology. The red spots are periods with significant frequencies ($P < 0.05$); 50- and 100-year frequencies are shown throughout the entire series. (C) Spectral analysis of the ring-width index series corroborates the significant ($P < 0.05$) 50- and 100-year frequencies in the series over the past nearly 600 years.

(ENSO) phenomenon, as it occurs with an erratic period of 2 to 7 years [48], a phenomenon of global impact that causes drought and floods in different regions when it occurs. In Mexico, it has been documented that this ENSO phenomenon significantly modulates climate variability both in the north [44, 49–51] and in the center of the country [52–55].

4. Conclusions

The paleoclimate series generated from the growth rings of *Pinus hartwegii* in Cofre de Perote National Park shows the climatic variability of the past nearly 600 years in this central region of the country. The importance of this type of study lies in the fact that it allows for the generation of more extensive information than that available with observed data. Over the past nearly six centuries, droughts have been observed to recur every 100 years, with severe droughts occurring mid-century. Events have been recorded as far afield as other latitudes, such as northern Mexico, which demonstrate a common large-scale variability modulated by general circulation climate patterns. Droughts are generally associated with pest outbreaks, fires, tree mortality, and other disturbances. In this context, the information generated from these types of studies provides management tools to support the decision-making of technicians and researchers responsible for the management and conservation of this and other national parks. This is done with the goal of reducing the negative effects of droughts on the ecosystem services they provide to the natural environment and society and ensuring the economic value of the natural capital stored in protected natural areas.

Conflict of interest

The authors declare no conflict of interest.

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Climate-Driven Human-Wildlife Conflict in Mkomazi National Park: The Role of Land-Use Changes and Ecosystem Stressors in Shaping Conservation Challenges

*Kwaslema Malle Hariohay, Alex Wilbard Kisingo,
Emmanuel H. Lyimo, David Castico and Rehema A. Shoo*

Abstract

This chapter explores the intensifying human-wildlife conflict (HWC) in and around Mkomazi National Park (MNP), northern Tanzania, an area of rich biodiversity and regional conservation importance. Over the past two decades, conflicts involving elephants, lions, and other large mammals have escalated due to climate change and rapid land-use changes. Prolonged droughts, erratic rainfall, and increased human pressure on natural resources driven by unsustainable land practices have worsened the situation. Data were gathered through a systematic literature review, key informant interviews (KIIs), focus group discussions, direct field observations, and analysis of satellite imagery (Landsat 7 ETM+, 1994, and Landsat 9 OLI/TIRS, 2024). Results reveal extensive habitat loss and fragmentation due to agricultural expansion, settlement encroachment, and corridor disruption. Climate-induced stressors such as drying rivers, shrinking water sources, and declining forage are pushing wildlife beyond park boundaries, heightening risks to human life and livelihoods. Traditional deterrents are increasingly ineffective, and formal compensation schemes are often seen as inadequate or delayed, leading to retaliatory killings and eroding public support for conservation. While localized interventions such as beehive fences, fortified bomas, and early warning systems (EWS) have shown promise, broader implementation is hindered by financial constraints, weak institutional coordination, and limited community engagement. Current conservation responses remain largely reactive and insufficient to address the scale of climate-driven wildlife displacement. The chapter advocates for integrated, climate-smart strategies, including participatory land-use planning, wildlife corridor restoration, and inclusive governance. Strengthening community resilience through locally appropriate adaptation and cross-sector collaboration is vital for fostering sustainable coexistence in climate-stressed landscapes.

Keywords: human-wildlife conflict, climate change, land-use change, Mkomazi National Park, conservation strategies

1. Introduction

Human-wildlife conflict (HWC) refers to the negative interactions between people and wild animals, often resulting in economic loss, physical harm, or fatalities, and posing a threat to both human livelihoods and wildlife conservation efforts [1–4]. Globally, HWC has become more frequent and severe, driven by human population growth, agricultural expansion, infrastructure development, and the encroachment of human activities into wildlife habitats [5–7]. In Africa, particularly Sub-Saharan regions, these conflicts are more pronounced due to the high dependency of rural communities on natural resources and the continent's rich assemblage of large mammals with expansive home ranges, such as elephants, lions, and hippopotamuses [2, 8–10]. The escalation of HWC in the region is further compounded by poverty, weak institutional frameworks, and poorly planned development initiatives [11]. As a result, Sub-Saharan Africa bears a disproportionate share of global HWC fatalities and economic losses, which in turn fuel retaliatory killings and erode community support for wildlife conservation [12–16]. Climate change has emerged as an additional stressor, exacerbating HWC by disrupting ecological patterns, intensifying competition for dwindling resources, and altering animal behavior and movement patterns, especially in semiarid ecosystems [17, 18].

Mkomazi National Park (MNP), located in the northeastern part of Tanzania bordering Kenya's Tsavo ecosystem, is a critical component of the country's protected area network. MNP represents a dryland savanna biome of global importance and hosts several threatened and endangered species, including the African wild dog (*Lycaon pictus*) and the black rhinoceros (*Diceros bicornis*), reintroduced through international breeding programs. Its landscape serves as a vital migratory corridor and dispersal area for wildlife species moving between Tanzania and Kenya [19, 20].

Despite its ecological importance, MNP has become increasingly vulnerable to human pressures. Surrounding communities rely heavily on subsistence agriculture and pastoralism, with growing demand for land and water resources [21]. The park is particularly prone to conflict involving elephants, lions, and other large herbivores, as these species frequently leave park boundaries in search of food and water during the dry season, often causing damage to crops, property, and human life [21–23]. These conflicts are exacerbated by climate-induced stressors such as erratic rainfall, prolonged droughts, and drying of rivers, factors that force wildlife to range beyond protected areas [24, 25].

This chapter explores the intersections between climate change, land-use transformations, and HWC within and around Mkomazi National Park. Specifically, the chapter aims to analyze the key drivers and patterns of human-wildlife conflict in the region, examine the influence of climate variability and environmental degradation on wildlife behavior and movement, investigate community perceptions, experiences, and adaptive responses to escalating HWC, evaluate the effectiveness of current conservation interventions, highlight policy and institutional gaps, and propose integrated, participatory, and climate-smart strategies to enhance coexistence between humans and wildlife.

This analysis contributes to a deeper understanding of the ecological and social dimensions of HWC in a climate-stressed context, as well as providing practical recommendations for adaptive conservation management. Focusing on Mkomazi, a case representative of many dryland protected areas in East Africa, the chapter offers practical insights for adaptive conservation planning and policy formulation, with implications for regional and global efforts to harmonize human development with wildlife conservation in the era of climate change.

2. Study area description

2.1 Geographic and ecological description

Mkomazi National Park (MNP) is located in northeastern Tanzania within the Kilimanjaro and Tanga administrative regions, bordering Kenya's Tsavo West National Park to the northeast (**Figure 1**). Covering approximately 3245 km², Mkomazi lies between latitudes 3°45' and 4°15'S and longitudes 37°45' and 38°45'E, forming part of the semiarid Acacia-Commiphora bushlands and thickets ecoregion [27, 28]. Its diverse topography includes low-lying plains, undulating hills, and seasonal river systems such as the Uмба and Ruvu Rivers, which are critical for both wildlife and adjacent communities [27, 29].

Climatically, Mkomazi experiences bimodal rainfall with a mean annual precipitation ranging between 400 and 600 mm [30]. Rainfall is erratic and concentrated between March–May and October–December, with long dry seasons dominating the rest of the year [21, 31]. These conditions make the park particularly sensitive to climatic fluctuations, influencing primary productivity and animal movements. Mkomazi is one of the few remaining areas in Tanzania where extensive tracts of dry-land savanna and shrubland ecosystems are still relatively intact and provide habitat for a diverse range of species adapted to arid and semiarid conditions [32, 33].

2.2 Biodiversity importance and conservation status

Mkomazi holds exceptional conservation value due to its location at the intersection of the East African and southern African faunal zones [34]. It supports over 78 species of mammals and more than 400 bird species, many of which are endemic

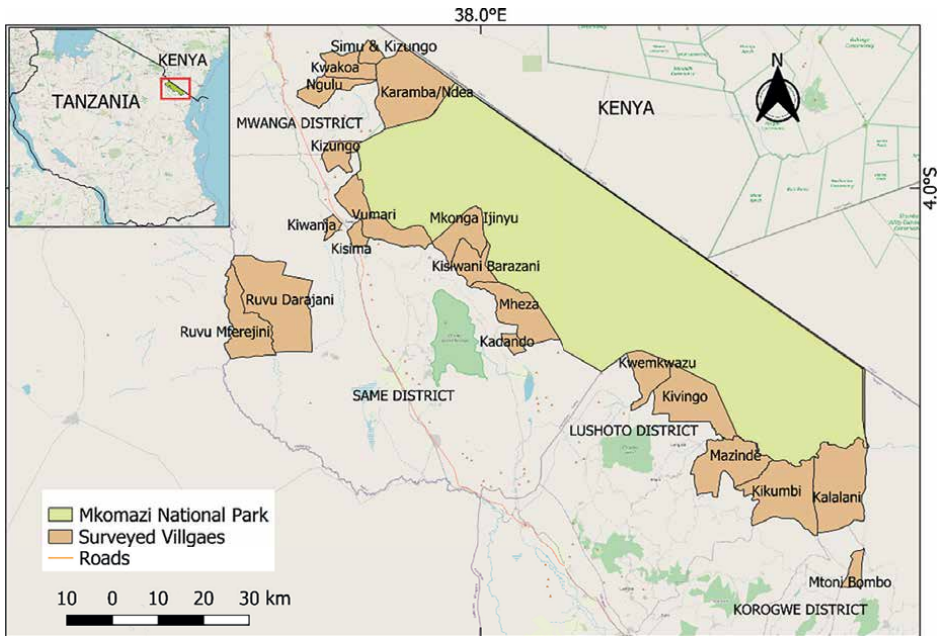


Figure 1.
Map of the study area [26].

or threatened. Notable mammals include elephants (*Loxodonta africana*), giraffes (*Giraffa camelopardalis*), fringe-eared oryx (*Oryx beisa callotis*), gerenuks (*Litocranius walleri*), and lesser kudu (*Tragelaphus imberbis*) [33, 35, 36]. Carnivores such as lions (*Panthera leo*), cheetahs (*Acinonyx jubatus*), leopards (*Panthera pardus*), and African wild dogs (*Lycaon pictus*) are also present, though in varying densities [35, 37].

Of particular conservation significance is the Rhino Sanctuary established within the park, which is part of an international initiative to reintroduce and safeguard the critically endangered black rhinoceros (*Diceros bicornis*). Mkomazi's proximity to Tsavo West enables transboundary wildlife movement, enhancing its ecological integrity as part of the broader Tsavo-Mkomazi ecosystem.

Designated as a Game Reserve in 1951, Mkomazi was upgraded to National Park status in 2008 and is currently managed by the Tanzania National Parks Authority (TANAPA) [35]. Despite this status, the park faces ongoing threats from poaching, habitat encroachment, and weak enforcement in surrounding buffer zones, particularly in areas not demarcated or well-integrated into formal land-use planning frameworks [19].

2.3 Socioeconomic profile of adjacent communities

The human populations bordering Mkomazi are predominantly agro-pastoralists, with major ethnic groups including the Pare, Sambaa, and Maasai. The communities are dispersed across several wards and villages in Same, Mwanga, and Lushoto districts [33, 35, 38]. Livelihoods are heavily dependent on rain-fed agriculture, mainly maize, beans, and bananas, and pastoralism involving cattle, goats, and sheep [35].

Population growth, combined with limited livelihood diversification and weak infrastructure, has led to increasing land pressure and environmental degradation in the park's periphery [33]. Many households rely on forest products, water, and grazing from Mkomazi's buffer zones, creating constant tension between resource use and conservation mandates [37].

2.4 Data collection methods

To ensure triangulation and validation, this study used mixed-methods data collection approaches. The integration of diverse methods was central to capturing the ecological, climatic, and social dimensions of human-wildlife conflict in and around Mkomazi National Park. The systematic literature review served as the conceptual backbone of the study, framing the theoretical lens and identifying research gaps while situating the local dynamics within wider regional and global debates on climate-driven human-wildlife conflict. The remote sensing and land use/land cover change (LULCC) analysis provided empirical evidence of long-term environmental transformations, including habitat loss, fragmentation, and water resource decline. These spatial patterns were not interpreted in isolation but were compared with and contextualized by community narratives and stakeholder insights.

The key informant interviews (KIIs) captured expert-level knowledge on policy, governance, and institutional responses, allowing the study to link ecological changes with management challenges and conservation strategies. Meanwhile, the focus group discussions (FGDs) gave voice to local communities, capturing how farmers, pastoralists, and village leaders perceive, experience, and adapt to climate stressors and wildlife incursions. These social data illuminated the human dimension of conflict, livelihood losses, coping mechanisms, and shifting attitudes, which cannot be derived from biophysical analysis alone.

Finally, direct field observations served as a reality check, validating both remote sensing outputs and community testimonies by documenting tangible signs of conflict such as crop damage, broken fences, livestock depredation, and evidence of elephant movement. This ensured ecological credibility and reduced reliance on perception-based accounts.

2.4.1 Systematic literature review

A structured literature review was conducted to contextualize field findings and support data triangulation. Using the Web of Science as the primary source and Google Scholar as a supplementary tool, a Boolean search string was employed to identify literature linking climate change, land-use transformation, and HWC, especially in protected areas. Search string example: *TS = ((Climate OR “climate change” OR “prolonged drought”) AND (“Mkomazi National Park” OR “protected area”) AND (“land-use” OR “encroachment”) AND (“Human-Wildlife Conflict” OR “HWC”) AND (“animal behavior”) AND (“governance”)).*

A total of 320 articles were initially retrieved. Screening followed two phases: (i) title and abstract review and (ii) full-text screening based on inclusion criteria: Peer-reviewed and open access, published between 2000 and 2025 (with limited exceptions), in the English language, and empirically or conceptually relevant to climate-driven HWC, land-use change, and governance in Africa or Asia. This process yielded 80 final articles for in-depth analysis (**Table 1**).

2.4.2 Focus group discussion (FGD)

FGDs were conducted to gain in-depth insight into climate-driven human-wildlife conflict (HWC) in the study area. A total of 21 FGDs were held across villages, each comprising 6–10 participants. Participants were purposefully selected to represent

Criteria	Inclusion	Exclusion
Document type	Peer-reviewed journal articles, proceedings, and book chapters. Reports that are registered by relevant institutions	Papers, preprints, monographs, proceedings, book chapters, and all documents not peer-reviewed
Accessibility	Articles that are open access only (easy access)	Articles that are not open access
Year of publication	Articles published between 2000 and 2025	Articles published before 2000 and after 2025 were excluded, with a few exceptions
Publication	Articles at the final stage	Articles in the press were excluded
Language	English	Articles used in other languages are excluded
Countries	African countries and Asian countries	Countries affiliated with these two continents were not included
Subject area	Focus on climate-driven HWC, land-use changes, governance of natural resources, and encroachment of the protected areas; discussion of HWC in relation to climate and land-use changes	Articles lacking empirical or conceptual relevance to climate-driven HWC, land-use changes, or governance of natural resources; articles focused on nonconservation-related issues were excluded

Table 1.
Inclusion and exclusion criteria.

a cross-section of the community in terms of age, gender, occupation (e.g., farmers, pastoralists), and community roles (e.g., village leaders, agricultural and livestock extension officers). The FGDs explored issues including climate and land-use changes, HWC drivers and seasonality, livelihood losses and mitigation practices, conflict hotspots, wildlife species involved, and the effectiveness of current strategies. FGDs allowed local voices to directly inform the assessment and served as a key triangulation tool.

2.4.3 Key informant interviews (KIIs)

KIIs targeted individuals with in-depth knowledge of HWC dynamics. A semi-structured interview guide was developed and pretested to gather insights from experienced local stakeholders such as District Game Officers, Mkomazi National Park (MNP) staff, Village and Ward Executive Officers, and Agricultural and Livestock Extension Officers. These informants provided contextual and historical perspectives on conflict drivers, community responses, and governance challenges.

2.4.4 Direct field observation

Field visits were conducted to corroborate information from FGDs and KIIs. Observations focused on signs of elephant presence (e.g., dung, footprints, broken vegetation) and damage to crops, homes, water sources, and livestock enclosures. Existing mitigation measures, such as chili fences and beehive fences (e.g., as seen in Kalalani village, Korogwe district), and patterns of land use near MNP boundaries, including farming and grazing in wildlife corridors, were noted. These observations helped validate community reports and assess conflict intensity and response mechanisms on the ground.

2.4.5 Land use/land cover change analysis (LULCC)

Landsat satellite imagery was utilized to assess land cover changes over a 30-year period (1994–2024) to understand the dynamics of agricultural expansion, encroachment, and vegetation loss in the context of climate and anthropogenic influences. Landsat 7 ETM+ (1994) and Landsat 9 OLI/TIRS (2024) scenes were acquired from the USGS Earth Explorer platform. Both images were preprocessed to Level-1 terrain-corrected products to ensure radiometric and geometric consistency.

Image classification was performed using ArcGIS Pro, employing supervised classification *via* the Image Classification Wizard. Training samples for four dominant land cover classes—agriculture, natural vegetation, encroachment, and bare land—were collected based on visual interpretation, ancillary data, and expert knowledge of the area. The Random Trees classification algorithm was applied due to its robustness in handling mixed land cover types and minimizing overfitting.

Post-classification and accuracy assessment were conducted using a confusion matrix derived from reference points to validate classification performance. Subsequently, pixel-based change detection was carried out using ArcGIS Pro's Change Detection tool, comparing classified outputs from 1994 to 2024. The tool generated a change matrix quantifying land cover transition, enabling the identification of spatial and temporal patterns in land-use change. The results provide a basis for analyzing the effects of land cover dynamics on local climate patterns and human-induced environmental transformation over time.

3. Results and discussions

3.1 Drivers of human-wildlife conflict in Mkomazi

3.1.1 Historical context of land use and resource access

The landscape surrounding Mkomazi National Park has undergone significant socio-ecological transformation over the past century. Prior to the colonial period, the area supported transhumant pastoralism and rotational cultivation practices that allowed seasonal wildlife movements and ecological balance [39, 40]. However, during British colonial rule, conservation and land policies such as the 1951 gazette-ment of Mkomazi as a Game Reserve began to restrict local access to traditional lands [37, 41–43].

Postindependence land reforms and the villagization program of the 1970s (Ujamaa policy) further disrupted traditional land tenure systems and led to concentrated human settlements near the reserve's boundaries. This shift, combined with weak enforcement of land-use zoning, encouraged spontaneous agricultural expansion into former migration routes and buffer zones [44]. In recent decades, rising population pressure and climate-induced livelihood instability have intensified the demand for arable land, pasture, and water, often at the expense of wildlife habitat [43, 45].

The formal upgrading of Mkomazi to national park status in 2008 restricted human activity within park boundaries but failed to address ongoing land tenure conflicts and resource access inequalities in adjacent villages. This legacy of exclusion and inadequate compensation continues to fuel tension between conservation authorities and communities [37].

3.1.2 Key wildlife species involved in conflict

The species most commonly involved in human-wildlife conflict around Mkomazi include African elephants (*Loxodonta africana*). Their wide-ranging behavior and need for large quantities of food and water make them the most problematic species. Elephants frequently raid crops, damage infrastructure such as fences and water tanks, and destroy property during dry seasons or failed rains [21]. Large carnivores such as lions (*Panthera leo*), leopards (*Panthera pardus*), spotted hyenas (*Crocuta crocuta*), and jackals (*Canis spp.*) are also causing human-carnivore conflict in the area. These large carnivores are responsible for the majority of livestock predation incidents. Lions tend to attack cattle in open grazing areas or poorly secured bomas at night, while leopards often prey on goats and sheep [21]. Spotted hyenas and jackals are scavengers, and opportunistic predators are also involved in livestock attacks, especially during periods of food scarcity or drought. Baboons (*Papio anubis*) and warthogs (*Phacochoerus africanus*), though less destructive than elephants, regularly raid smallholder farms, feeding on maize, beans, groundnuts, and root crops [19].

3.1.3 Patterns of conflict

Human-wildlife conflict around Mkomazi follows spatial and seasonal patterns. Crop raiding is most intense during the dry season and at the onset of the rainy season when cultivated fields are maturing and wild forage is scarce. Elephants are known to move out of the park at night and raid nearby farms, often destroying entire fields in a single visit [46, 47].

Livestock predation by lions and hyenas peaks during dry spells when wild prey availability declines. Poorly constructed livestock enclosures and night grazing increase vulnerability [48]. In pastoralist communities bordering the Mwangi and Same districts, retaliatory killings of predators are often reported following such losses, particularly when compensation is delayed or unavailable [37, 49].

While fatalities are less common, human injuries typically caused by surprise encounters with elephants or attacks during nocturnal raids have been recorded, leading to trauma, loss of labor, and hospital expenses [15]. These incidents severely strain relations between communities and park management, with many residents expressing a lack of trust in official responses to conflict events [8].

The cumulative effect of repeated crop losses, livestock depredation, and fear for personal safety has led to a decline in local support for Mkomazi's conservation efforts [37, 47]. Without effective conflict mitigation, this can escalate into widespread resistance to park rules, increased poaching, or encroachment into protected areas.

3.2 Climate change and its impacts

3.2.1 Shifting rainfall patterns, drought frequency, and seasonal variability

Over the past two decades, northern Tanzania, including the Mkomazi landscape, has experienced increasing climate variability marked by erratic rainfall patterns, extended dry seasons, and more frequent droughts [50, 51]. Data from regional meteorological stations indicate delayed onset and early cessation of rains, leading to shorter growing seasons and reduced agricultural productivity [30]. Rainfall distribution, once predictably bimodal, has become highly inconsistent, undermining both crop and pasture regeneration [30].

These patterns are consistent with broader East African trends, where climate models project a future of intensified weather extremes and unreliable intra-seasonal rainfall [52]. Drought recurrence has increased in both frequency and severity, with “once in a decade” droughts now occurring every 2–3 years. Such prolonged water deficits affect not only agriculture but also compromise ecosystem functionality within protected areas [18, 52].

3.2.2 Vegetation and water resource changes within and around the park

Climate-driven stress has altered the structure and composition of Mkomazi's vegetation. The recent supervised land cover classification in the Mkomazi National Park reveals a marked decline in woodland and forest cover, accompanied by an increase in bare land, grassland, and shrubland habitat (**Table 2**). The same analysis also indicated a progressive degradation of key water sources such as pools, permanent rivers, and seasonal rivers (**Table 2, Figure 2**). Seasonal rivers such as the Uмба and Ruvu increasingly dry up before the end of the dry season, while temporary pools that once sustained wildlife during migration have either vanished or become heavily sedimented [30, 51]. Such changes reduce the nutritional quality and availability of forage for herbivores, especially elephants, impalas, and zebras. The scarcity of perennial water points within the park forces animals to travel farther and for longer durations, often into surrounding human-dominated landscapes where water remains accessible in dams, troughs, or agricultural fields [21].

Class	1994 (km ²)	2024 (km ²)	Change (km ²)	Change (%)
Water	52.3	48.7	−3.6	−6.9%
Bare land	125.1	155.4	30.3	24.2%
Woodland	310.8	275.2	−35.6	−11.5%
Forest	280.5	240.9	−39.6	−14.1%
Grassland	195.7	215.3	19.6	10.0%
Shrubland	175.6	185.5	9.9	5.6%

Table 2.
Land cover changes in the Mkomazi National Park (1994–2024).

3.2.3 Implications for wildlife movement and behavior

These ecological stressors are reshaping wildlife behavior in profound ways. Elephants (*Loxodonta africana*), in particular, are altering their migratory routes in response to resource scarcity, moving outside the park in search of water and food, a behavioral shift that increases the likelihood of human-elephant conflict [24, 53, 54]. Similarly, carnivores are increasingly sighted near settlements, drawn by weakened livestock security and declining wild prey availability [55].

Research indicates that under conditions of prolonged drought, wildlife, especially large-bodied species, abandon traditional dry-season refuges and encroach into farmlands and village peripheries [46, 53, 54]. Such movements, often occurring at night, elevate the risk of crop raiding, property destruction, and livestock predation. These behaviors are not arbitrary but adaptive responses to environmental stress that has diminished in-park carrying capacity.

The indirect impacts of climate change on wildlife include increased mortality due to dehydration, heat stress, and reduced reproductive success [56, 57]. Moreover, climate-induced changes in vegetation structure can affect predator-prey dynamics, making it easier for predators to approach livestock undetected in degraded bushland [58].

3.3 Land-use changes and habitat fragmentation

3.3.1 Agricultural expansion and encroachment on wildlife corridors

The areas surrounding MNP have experienced rapid agricultural expansion over the past three decades. Driven by population growth, food insecurity, and unreliable rainfall, communities have converted former grazing lands and wildlife corridors into smallholder farms producing maize, beans, cassava, and sunflower [21, 26]. This land-use transition has significantly narrowed traditional migratory routes used by elephants and other wide-ranging species, especially along the western and southern boundaries of the park [21, 26]. The recent land-use analysis also reveals a drastic increment of agriculture and encroachment over three decades. Both land uses have more than doubled between 2024 and 1994, which impacted natural vegetation on a 10 km buffer from the protected area boundary (**Table 3**).

Historically important wildlife corridors such as the Zirai-Sangaiwe and Kisima-Ndungu routes are now obstructed by farmland and scattered homesteads. These pinch points have become flashpoints for human-wildlife conflict, particularly during the dry season when wildlife is forced to move across these cultivated areas in search

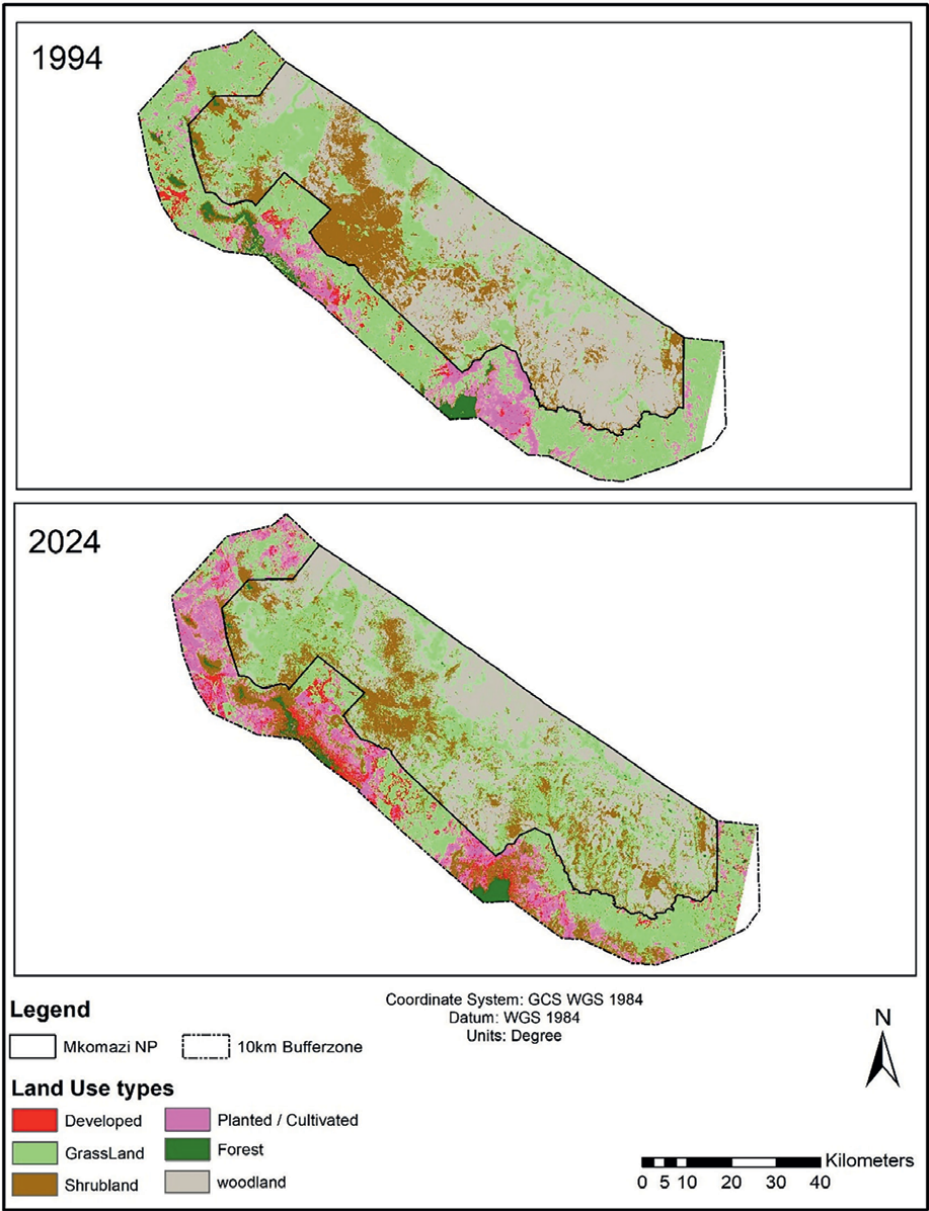


Figure 2.
Land-use changes from 1994 to 2024.

of forage and water. Unregulated land allocation by local village councils, often outside formal land-use plans, has accelerated this fragmentation and undermined previous conservation efforts intended to maintain habitat connectivity [19, 26].

3.3.2 Settlement patterns, livestock grazing pressure, and resource competition

Human settlement around Mkomazi has expanded through both policy-driven initiatives and spontaneous migration. Many villages were established during

Class	1994 (km ²)	2024 (km ²)	Change (km ²)	Change (%)
Agriculture	150.2	320.5	170.3	113%
Encroachment	25.7	68.9	43.2	168%
Natural vegetation	500.1	350.4	-149.7	-30%
Bare land	100.5	120.2	19.7	20%

Table 3.
Land-use change in the 10 km buffer of the Mkomazi National Park (1994–2024).

Tanzania’s Ujamaa villagization program of the 1970s, but since then, informal expansion and new migration into the area, especially from drought-prone areas, have intensified [30]. Newly developed settlements often emerge in unplanned zones, including wildlife dispersal areas and marginal lands near park boundaries (**Figure 2**).

Livestock keeping is the main livelihood for many pastoralist communities, notably the Maasai. As access to traditional grazing lands declines, herders increasingly move their cattle into protected zones or degraded woodlands, sparking tensions with park authorities and exposing livestock to predation [26]. Overgrazing near the park’s periphery has resulted in bush encroachment and the loss of palatable grasses, diminishing the productivity of communal rangelands and further exacerbating resource competition between humans and wildlife [32].

Moreover, many water sources, including seasonal streams and springs, are now shared by people, livestock, and wildlife, especially during the dry season [26, 59]. This overlap in water use intensifies the likelihood of direct encounters, disease transmission (e.g., bovine tuberculosis), and water quality deterioration, posing risks to both ecosystem integrity and human well-being [51, 60].

3.3.3 Degradation of buffer zones and community land tenure dynamics

Buffer zones traditionally serve as ecological and social transition spaces between core protected areas and community lands and have become highly degraded due to unsustainable land use, weak enforcement, and unclear land tenure rights [61, 62]. In theory, these zones are meant to provide multiple-use areas for controlled grazing, beekeeping, and eco-friendly agriculture while allowing wildlife passage. In practice, however, many buffer areas have been cleared, fenced, or subdivided into plots for permanent agriculture or speculative land-holding [47, 62].

Land tenure insecurity is a major underlying factor. In many villages, customary landholding systems coexist uneasily with statutory frameworks, creating legal ambiguities that hinder effective planning [63]. When land is perceived as insecure, farmers and herders are more likely to rapidly exploit it through over-cultivation, charcoal production, or fencing, contributing to fragmentation and ecological degradation [63].

This disintegration of communal land governance, compounded by limited institutional support and political interference in local decision-making, makes it difficult to implement landscape-scale conservation strategies [64, 65]. Wildlife movements, once facilitated by continuous habitat, are now obstructed by patchworks of incompatible land uses, escalating the frequency and intensity of HWC [10, 66].

3.4 Interlinkages: Climate change, land use, and HWC

3.4.1 *Climate stress and intensified resource competition*

The intersection of climate change and land-use transformation has created a high-stress environment in the landscapes surrounding Mkomazi National Park. As rainfall becomes increasingly erratic and temperatures rise, water and pasture resources shrink in both quantity and quality [30]. During prolonged droughts, key water points such as springs, pans, and seasonal rivers dry earlier than expected, leading to acute competition between wildlife, livestock, and humans [45, 50, 57].

Climate variability has also contributed to declining soil fertility, frequent crop failure due to moisture stress, and pest outbreaks, compelling communities to expand farming into marginal lands and former wildlife dispersal zones, further encroaching on natural habitats [52]. Simultaneously, wildlife, especially large herbivores like elephants and buffalo, are driven to these same areas by the lack of in-park forage and water. This overlapping resource dependency creates direct competition, particularly in the dry season, resulting in frequent and sometimes violent human-wildlife encounters [2, 4, 26].

Pastoral communities also face increased risk. As grazing areas within village land are degraded through overuse and drought, herders are forced to move livestock closer to protected areas, leading to contested access to resources and increased conflict with conservation authorities [10, 67].

3.4.2 *Shifts in migratory and foraging behavior of key species*

Under normal climatic conditions, many wildlife species in Mkomazi exhibit seasonal migratory behavior aligned with water and forage availability. However, as these resources become unpredictable, animals are increasingly abandoning traditional migratory routes [26, 44]. For example, elephants, which typically follow well-defined dry-season movement corridors, now make opportunistic incursions into villages as they search for reliable food and water sources, especially irrigated crops or livestock water troughs [24, 26].

Similarly, predators such as lions and hyenas are altering their hunting behavior. Declines in wild prey populations caused by habitat degradation and bushmeat hunting are leading carnivores to target livestock more frequently. This not only disrupts pastoral economies but also erodes the social legitimacy of conservation, as local communities perceive the park as a source of danger rather than a shared resource [16, 26].

These behavioral adaptations by wildlife are not temporary phenomena but rather part of a long-term ecological shift in response to environmental pressures. Without landscape-level planning and adaptive management strategies, these changes will continue to increase the spatial overlap between wildlife and people, escalating conflict frequency and severity [23].

3.4.3 *Increased vulnerability of communities to economic losses*

The combined effects of climate stress and land fragmentation disproportionately affect rural households living near Mkomazi. Most families rely on subsistence farming and livestock as their primary income sources, and repeated losses due to crop damage or livestock predation can push already vulnerable households into deeper

poverty [68]. For example, when elephants destroy an entire maize field overnight or lions kill multiple cattle in a single attack, households lose months of labor investment and face food insecurity, loss of income, and reduced educational opportunities for children. In areas with no compensation or insurance mechanisms, these losses are entirely absorbed by the affected families [1].

The cumulative economic impact of HWC, when added to climate-induced agricultural failures, reduces community resilience, weakens traditional safety nets, and increases hostility toward wildlife. This creates a cycle in which communities disengage from conservation processes, engage in illegal retaliatory actions such as poisoning or snaring, and resist enforcement of conservation laws [69].

The vulnerability is further exacerbated for marginalized groups, especially women, who often bear the brunt of food insecurity and resource collection in times of scarcity [16]. Women are disproportionately affected when water becomes unavailable due to elephant occupation or when they must guard crops throughout the night, exposing them to physical danger [8].

In essence, climate change and land-use changes are not just environmental problems but are deeply interconnected with livelihoods, equity, and social stability [18]. Breaking this cycle requires systemic interventions that address both ecological and human vulnerability in tandem [52, 58].

3.5 Community perceptions and coping strategies

3.5.1 Local knowledge and perceptions of changing wildlife behavior

Communities surrounding Mkomazi National Park have long coexisted with wildlife, developing intricate ecological knowledge passed down through generations [70]. However, local residents report increasingly erratic and aggressive wildlife behavior over the past 15–20 years [26, 45, 70]. In community focus group discussions in Kisima, Ndungu, Kivingo, and Gonja villages, residents described how elephants now raid crops during the day, behavior that was rarely observed two decades ago when elephant incursions were primarily nocturnal [21, 26].

This behavioral shift is attributed to both climate change and habitat loss. Recurrent drought and forest degradation have pushed elephants closer to settlements, where they access irrigated farms and reliable water sources [26]. Similarly, predators such as lions and hyenas are perceived to have become bolder and more persistent in approaching livestock bomas [10]. Community elders note a decline in traditional animal avoidance behaviors, such as elephants retreating at the sound of dogs or drums, suggesting that frequent human-wildlife contact is desensitizing animals to deterrents [21].

Moreover, villagers increasingly view Mkomazi National Park as a threat rather than a benefit. While some residents recognize the park's role in conservation, others feel alienated due to insufficient communication, poor compensation schemes, and exclusion from decision-making processes [16, 37]. This erosion of trust in conservation institutions undermines conflict mitigation efforts and fuels retaliatory attitudes toward wildlife [71].

3.5.2 Traditional and modern conflict mitigation strategies

Communities employ a blend of traditional and contemporary methods to mitigate human-wildlife conflict [26]. Traditional strategies include lighting fires

and banging metal objects to scare away elephants [26]. In some instances, men and youths organize night patrols, guarding fields with flashlights and whistles and building barriers using Acacia thorns and other natural materials to deter herbivores from entering farms [21, 26]. While these practices reflect deep-rooted local resilience, they are often labor-intensive, ineffective against determined wildlife, and expose vulnerable community members, particularly women, children, and the elderly, to risk.

In recent years, several communities have adopted modern deterrents introduced through pilot research projects by nongovernmental organizations (NGOs) [26]. These include beehive fences, which are used around farmlands, particularly in Gonja-Mbweme village, where farmers have successfully deterred elephants using live beehives [26, 72]. Chili-based deterrents are implemented through chili powder mixed with used engine oil and smeared on strings around farms or shaped into “chili bricks” and burned to produce a pungent smoke along elephants’ paths. Some villages have experimented with early warning systems incorporating solar-powered alarms and mobile phone networks to alert residents of approaching elephants. Also, improved livestock enclosures such as reinforced bomas built with chain-link fencing or stone walls reduce predation incidents, especially in Maasai-dominated villages like Kisiwani and Njiro.

In Kisima village, located adjacent to the park’s western boundary, a community-led patrol initiative supported by the Tanzania Wildlife Management Authority (TAWA) reduced crop damage incidents by 35% over a single harvest season [26]. The initiative combined traditional night guarding with scheduled patrols and rapid response to elephant sightings. Despite its success, long-term sustainability remains a challenge due to volunteer fatigue and a lack of incentives.

Adoption of these techniques remains uneven, often constrained by cost, limited technical support, and lack of awareness. In villages where participatory training and follow-up support are provided, however, the uptake is higher and attitudes toward wildlife appear more tolerant [26, 73]. For example, in Kivingo village, a chili and rope fencing project piloted by a local NGO demonstrated initial success but was eventually abandoned after community members were unable to replenish chili supplies or repair damaged ropes [74]. This highlights the importance of linking conflict mitigation tools to sustainable livelihood options or consistent external support mechanisms.

In contrast, Ndungu village has experienced improved outcomes through a hybrid approach combining beekeeping and conservation education. Farmers in the area report not only fewer elephant crop raids but also increased income from honey sales, reinforcing the value of conservation-livelihood synergies to support both wildlife conservation and community resilience [26].

3.6 Conservation responses and policy gaps

3.6.1 TANAPA and government interventions (e.g., fencing, compensation schemes)

The Tanzania National Parks Authority (TANAPA), which manages Mkomazi National Park, has implemented several interventions aimed at reducing human-wildlife conflict (HWC). These include the construction of physical barriers, deployment of rapid response ranger units, and sensitization campaigns in surrounding villages. TANAPA, in collaboration with conservation NGOs, has erected beehive fencing in high-conflict zones such as Kalalani, Kisima, and Gonja to prevent

elephants from entering farmlands. While these fences have been moderately effective, they are costly to maintain and often damaged by floods, vandalism, or elephants themselves [10, 74].

The Tanzanian government has also established wildlife compensation schemes under the Wildlife Conservation Act No. 5 of 2009. Affected households can submit claims for loss of life, crop damage, or livestock depredation. However, the actual implementation of compensation is faced with some challenges, such as delays, bureaucratic hurdles, and inadequate budget allocations [1, 16, 75]. Many community members complain of denied claims or payment delays that stretch over multiple seasons, reducing the incentive to report conflict incidents and increasing the risk of retaliatory action [1, 10].

Ministry of Natural Resources and Tourism (MNRT) efforts to introduce wildlife corridors have been undercut by weak local enforcement, uncoordinated land planning at the village level, and limited financial investment in long-term conflict mitigation infrastructure.

3.6.2 Role of NGOs, research institutions, and community-based conservation

Nongovernmental organizations (NGOs) and research institutions play a critical complementary role in addressing HWC around Mkomazi. Organizations such as the African Wildlife Foundation (AWF), African People & Wildlife (APW), Save the Wildlife and Wildlife Corridors (STWWC), World-Wide Fund for Nature (WWF), Honeyguide Foundation, and various local NGOs and CBOs (community-based organizations) have implemented projects involving participatory land-use planning, habitat restoration, and capacity building for HWC mitigation methods.

One notable initiative is the introduction of beehive fencing, popularized through community demonstration projects and supported by NGOs and researchers from the Tanzania Wildlife Research Institute (TAWIRI). These projects not only deter elephants but also provide communities with alternative income sources through honey production [72]. Similarly, community ranger programs supported by NGOs have enhanced early warning systems, wildlife monitoring, and rapid response to crop raids [21, 26].

Research institutions, including TAWIRI, the College of African Wildlife Management (CAWM), Mweka, and Sokoine University of Agriculture, have also supported conflict studies and developed spatial mapping tools to identify conflict hotspots and migratory corridors [26, 36]. However, research outputs are rarely mainstreamed into district land-use plans or TANAPA's operational strategies due to institutional fragmentation.

3.6.3 Institutional and policy weaknesses in managing climate-driven HWC

Despite national-level commitments to climate change adaptation and wildlife conservation, significant institutional and policy gaps undermine the effective management of climate-driven HWC in Mkomazi. First, poor inter-agency coordination between TANAPA, local governments, district natural resource offices, and land planning authorities creates duplication, policy contradictions, and implementation inefficiencies.

Second, the land use policy framework fails to recognize wildlife corridors as essential ecological infrastructure, treating them instead as vacant land available for agriculture or settlement. This policy blind spot has contributed to corridor degradation and habitat fragmentation [63].

Third, climate change policies in Tanzania remain poorly integrated with conservation planning. The National Climate Change Strategy (2012) lacks specific measures addressing wildlife mobility or HWC mitigation under shifting climate regimes. Similarly, district-level climate adaptation plans rarely consider the ecological dynamics of protected areas like Mkomazi.

Moreover, local governance bodies such as village councils and Ward Development Committees are often under-resourced and lack the technical skills needed to develop and enforce sustainable land-use plans. The lack of legal incentives or funding mechanisms to support corridor protection or climate-resilient infrastructure further limits progress.

3.7 Implications

3.7.1 Integrated land-use and wildlife corridor planning

A key implication emerging from the Mkomazi case study is the urgent need for integrated land-use planning that recognizes and protects wildlife corridors as essential infrastructure for ecosystem connectivity and climate adaptation. The current pattern of unregulated agricultural expansion and spontaneous settlement in corridor zones, such as those linking Mkomazi to Tsavo West and the South Pare Mountains, has critically impaired wildlife movement and increased human-wildlife conflict [19].

Restoring and securing these corridors requires a shift in land governance from reactive enforcement to proactive landscape planning. District-level land-use plans to incorporate spatial data on wildlife movement, community land use, and climate vulnerability. Moreover, wildlife corridors should be legally designated and enforced through the National Land Use Planning Commission and included in village land-use plans (VLUPs) to prevent encroachment and fragmentation [63].

Incentivizing local communities to conserve corridor lands through mechanisms such as payment for ecosystem services (PES), conservation easements, or tourism benefit-sharing will be essential for ensuring sustainable coexistence. Without corridor planning, efforts to address HWC and climate-induced wildlife displacement will remain fragmented and ineffective.

3.7.2 Climate-smart conservation and participatory governance

Climate-smart conservation refers to adaptive management practices that incorporate climate change projections into conservation decision-making [76]. In Mkomazi, this means integrating rainfall variability and drought risk into the park's management plans and infrastructure design [25, 56]. For example, dynamic water provisioning and seasonal ranger stations can help manage dry-season wildlife movements that cause conflict in adjacent villages [27, 30].

Participatory governance is equally vital. Communities living near Mkomazi have demonstrated detailed ecological knowledge and a willingness to participate in conservation when empowered [26, 77]. Strengthening local institutions such as Village Environmental Committees (VECs), Wildlife Management Areas (WMAs), and Joint Park-Community Forums can create platforms for collaborative decision-making. This enhances legitimacy, ensures that local needs are addressed, and improves conflict reporting and response.

Integrating women, youth, and marginalized groups into these governance structures also ensures more inclusive and equitable conservation outcomes [77].

As primary caregivers, natural resource users, and conflict witnesses, women are key stakeholders in resilience building but often remain underrepresented in formal governance systems [77].

3.7.3 Strengthening early warning systems and community-based adaptation

Given the unpredictability of climate shocks and wildlife incursions, early warning systems (EWS) are a critical tool for conflict prevention. Community-led EWS based on radio networks, mobile phone alerts, or real-time tracking of elephants using GPS collars can provide timely information to farmers and herders, allowing them to take protective measures [47, 78]. Successful EWS pilots in southern Kenya and northern Tanzania show that such systems can reduce elephant raids by up to 50% when integrated with local patrols and response teams [47, 79].

However, EWS alone is insufficient without broader community-based adaptation (CBA) strategies. The EWS diversification of livelihoods (e.g., beekeeping, ecotourism, agroforestry) to reduce dependency on high-risk farming, climate-resilient crops, and water harvesting techniques to mitigate drought impact and conflict-sensitive land-use zoning, such as buffer strips between crop fields and wildlife paths [72, 79].

Building institutional and technical capacity for CBA must be a national priority, supported by multi-sectoral coordination between TANAPA, TAWA, the Vice President's Office (Environment), district governments, NGOs, and academic institutions. Investing in climate information services, conflict risk mapping, and extension support for community innovations can foster local ownership and sustainability.

Ultimately, the Mkomazi case emphasizes that conflict is not just an ecological problem but a symptom of governance, planning, and adaptation deficits. Long-term coexistence will depend on how effectively climate change, land-use dynamics, and social equity are addressed in conservation strategy.

4. Conclusion

The Mkomazi case provides critical insights into how climate-smart, inclusive, and integrated conservation strategies can address the dual pressures of environmental change and human livelihood demands. Findings reveal that prolonged droughts, erratic rainfall, and declining water and forage availability are increasingly pushing wildlife beyond protected boundaries, while agricultural expansion, settlement growth, and fragmentation of corridors intensify encounters between people and wildlife. These interactions, in turn, deepen economic vulnerability, undermine community support for conservation, and expose the limitations of reactive management responses.

4.1 Strengths of the study

A major strength lies in its multidisciplinary approach, which combines ecological, spatial, and social methods to generate a holistic understanding of the problem. The integration of remote sensing with community-level insights ensured both ecological accuracy and social relevance. The use of triangulated data sources, literature review, satellite imagery, FGDs, KIIs, and direct observation enhanced the reliability and validity of the findings.

4.2 Limitations

Despite these contributions, several limitations should be acknowledged. First, the reliance on Landsat imagery restricted the temporal resolution of land cover change analysis and may have missed finer-scale habitat dynamics. Second, the cross-sectional nature of FGDs and KIIs captured perceptions at a single point in time, which may not fully reflect seasonal or annual variations in human-wildlife conflict. Third, financial and logistical constraints limit the geographic coverage of field observations, potentially underrepresenting conflict hotspots in remote areas. Future research should therefore incorporate higher-resolution satellite data, longitudinal community studies, and broader spatial coverage to capture evolving dynamics more comprehensively.

4.3 Theoretical contributions

The findings contribute to human-wildlife conflict knowledge by illustrating how climate change acts as a multiplier of land-use pressures, reshaping species behavior and intensifying ecological-social interactions. The study underscores the need for integrative frameworks that move beyond ecological determinism to include governance, livelihoods, and social resilience as central elements of conservation theory.

4.4 Practical implications

From a management perspective, the research highlights the importance of shifting from reactive to proactive conservation strategies. Practical measures include legally securing and restoring wildlife corridors, embedding climate risk assessments into park management plans, and strengthening community-based governance platforms. Moreover, the study reinforces the necessity of aligning local livelihoods with conservation outcomes, for example, through payment for ecosystem services, honey production from beehive fences, or participatory land-use planning. These approaches can enhance both ecological sustainability and social legitimacy, which are essential for long-term coexistence.

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Conflict of interest

The authors declare no conflict of interest.

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Do Current Protected Areas Preserve Soil Health and Ecosystem Resilience? Contributions of Nematodes as Bioindicators in the Souss Massa National Park

Obidari Tayeb, Abdallah Zoubi, El Mousadik Abdelhamid and Mayad El Hassan

Abstract

Soil health underpins terrestrial ecosystems, agriculture, and global food security, yet its role as a biodiversity hotspot and carbon is often overlooked in policymaking. Alarming, 70% of global soil biodiversity hotspots remain outside protected areas. Soil health is shaped by biological, chemical, and physical properties that sustain life above and below ground. Among biological indicators, nematodes are highly valuable due to their functional diversity and sensitivity to environmental changes. They contribute to soil quality by mineralising nutrients and enhancing plant availability. In this review chapter, we studied the extent to which protected areas safeguard soil health and ecosystem resilience based on our published works and bibliography. Overall, results demonstrated that protected areas effectively preserve soil health and functioning. Nature conservation enhances nematode biodiversity and soil food webs complexity, with taxa characteristic of undisturbed soils serving as indicators of disturbance. Moreover, *Meloidogyne* spp., a phytoparasitic nematode of major economic importance, was absent in protected areas, suggesting improved regulation of soil organisms and stronger ecosystem resilience. On the other hand, predator and bacterivore nematodes supported soil carbon storage by transforming organic matter into biomass, highlighting their role in carbon cycling under conservation measures. As a conclusion, soil biodiversity protection requires strict preservation of sensitive ecosystems and delving into agroecological cropping that mimic natural undisturbed systems. No nature-based solution can succeed without explicitly considering soil biodiversity, which is central to climate change mitigation, sustainable development, and restoration of degraded ecosystems.

Keywords: biodiversity, soil functioning, ecosystem service, policymakers, global change

1. Introduction

Conserving nature, and hence nature's contributions to people, is the goal of many conventions and agreements [1, 2]. About 700 Multilateral Environmental Agreements (MEAs) have been adopted between 1868 and 2011, around 150 of which are related to nature [3], for example, the World Heritage Convention (adopted in 1972, 186 parties), the Ramsar Convention (adopted in 1971, 159 parties), and the Convention on Biological Diversity (adopted in 1993, 193 parties) [4]. Nevertheless, when it comes to determining global conservation priorities, CBD takes the most comprehensive approach, with one of its three main objectives being “the conservation of biodiversity” [4].

The Post-2020 Global Biodiversity Framework (GBF) of the Convention on Biological Diversity (CBD) is the latest global scale, multi-lateral policy initiative that seeks to improve the development of policies and strategies to conserve biodiversity and manage ecosystems in a sustainable manner [5]. The Post-2020 GBF was developed following a comprehensive and participatory process between signatory countries to the CBD and other stakeholders (governments, Indigenous people, local communities, women and youth groups, and scientific community) [6] in order to achieve four goals that are supported by 23 targets to be completed by 2030 [7]. The main goal was to boost the protection of terrestrial, inland water, and marine areas to a minimum of 30%, which is a significant increase from the previous targets of 17% for terrestrial and 10% for marine areas. Additionally, the goal included restoring 30% of the Earth's degraded terrestrial, inland water, marine, and coastal ecosystems and ensuring ecological connectivity across landscapes and seascapes to support essential ecological processes, such as meta-population viability and successful species migration [5, 8].

With increasing population growth, the demand for farmland and housing space is also growing, and consequently, land use is expanding [9]. Urbanization and agriculture drive natural habitat loss and threaten biodiversity, especially soil biodiversity [10, 11]. Soils harbor a significant terrestrial biodiversity, which has recently begun to be recognized as a crucial and irreplaceable part of ecosystem health, providing benefits for human wellbeing [12, 13]. Unfortunately, soil biota are threatened by several land-use change such as cropping, urbanization, desertification and deforestation [14]. For instance, changing land-use from natural to agro-systems enhanced bacterial diversity due to fertilization effects [15]. In another study, urbanization can negatively impact soil nematodes [16]. Furthermore, the effects of land use intensity on soil biodiversity might be reflected by cascading effect on plant diversity, which is the main driver of soil organism biodiversity in forests [17].

Studies about the relationships between nature conservation and soil biodiversity under land use intensification are scarce [18–20]. Therefore, it is important to investigate if current protected areas may protect soil health and functioning. To answer this relevant question, we used our previous published results and bibliography in this review chapter.

2. Methods

The present chapter builds primarily on our previous research, which looked at how nature conservation affects soil organisms and soil health [21, 22]. In addition to these findings, we conducted an extensive review of the literature to integrate and

synthesize studies addressing the relationship between protected areas and soil biodiversity. This combined approach allows us to gain a comprehensive understanding of how conservation practices contribute to sustaining soil ecosystems and enhancing their ecological functions. Our study was carried out in the National Park of Souss Massa region (SMNP), a protected zone with national and global significance, especially for migratory birds (**Figure 1**) [23]. Situated in central western Morocco since 1991, the park has a variety of plant life, including around 300 vascular plant species, 13 of which are only found in Southwest Morocco. It is also home to a highly diverse fauna and qualifies as an international biodiversity hotspot [24]. The park has a mean annual temperature of 19.8°C and mean annual rainfall of 300 mm [24]. Nevertheless, the park is situated in the Souss-Massa region, one of the most dynamic and affluent regions in Morocco [25]. Previous studies focused on studying the aboveground biodiversity in the SMNP [23, 24, 26–28]. However, no study has been carried out in the park about the belowground biodiversity. The conservation approach adopted in the park involves dividing its territory into three zones: core zones (protect sensitive biological resources and shelter mammals introduced for restoration), buffer zones (slightly disturbed by grazing), and transition zones (slightly disturbed by grazing and organic farming) (**Figure 1**). Our study is based on a comprehensive field survey, encompassing 180 samples of the soil collected from three distinct zones within the SMNP in central Morocco (core, transitional, and buffer zones) and from an unprotected zone outside the park, heavily disturbed by intensive farming and urbanization.

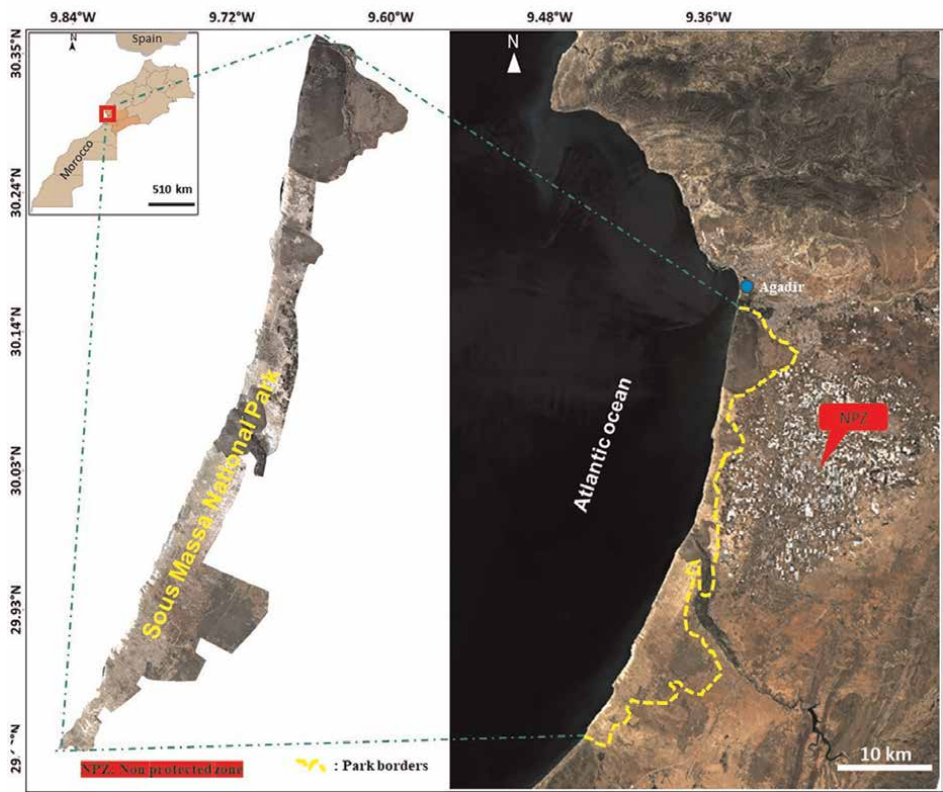


Figure 1.
Map of the Souss Massa National Park in Morocco. The white spots in the non-protected zone indicate greenhouses used for intensive cropping [21, 22].

3. The concept of soil health and ecosystem resilience

The concept of soil quality has emerged from our understanding of soil diversity and its functions. It is defined as “its ability to function within a given ecosystem to support biological production, maintain environmental quality, promote plant and animal health, and support human health and habitation” [29]. Soil quality is determined by three principal components: biological, chemical, and physical properties. Biological properties are directly determined by the soil’s organisms. In agricultural terms, the state of soil properties has given rise to the concept of “soil health,” a good state of health being generally linked to nutrient cycles, high stability (resistance) or resilience capacity) and a high level of variability in its biological components [30].

The concept of soil suppressiveness has emerged from soil health [31], which is not a recent soil characteristic. Indeed, suppressive soils has been defined as those that does not allow the growth or survival of pathogens, or they may develop but cause only limited or no symptoms [32]. The presence of disease suppression is a sign of healthy soil [31]. There is a significant correlation between soil suppressiveness and both soil biodiversity and soil food web complexity [33]. For example, the prevalence of predator nematodes in the soil enhances soil disease suppression by predation on phytoparasitic species [34, 35]. Disease suppression also relies on the antagonistic actions of specific microbial communities in the plant’s rhizosphere [36]. Therefore, disease suppression is due to antagonistic activities of specific microbial communities in the plant rhizosphere [36].

The status of soil organisms can be used as an indicator of specific environmental conditions, such as pollution and microclimatic changes. Therefore, these organisms can serve as bio-indicators of the soil health state, as each organism has its own ecological niche (physico-chemical, biological, and environmental requirements) [37]. Therefore, the right choice of bio-indicator to assess soil health depends on a clear understanding of the systematics, physiology, ecology, and interactions of these organisms. In the following section, we will show that nematodes (the model of our study) are excellent bio-indicators of the state of the soil food web and soil health.

4. Nematodes as bioindicators of soil health and functioning

In the soil, nematodes are among the most common and diverse organisms [38]. They are found in almost every type of ecosystem and exhibit a variety of behaviors, including parasitism of plants, predation, fungivory, and feeding on bacteria (**Table 1**) [39]. In addition, they drive various ecosystem functions in the soil, including organic matter decomposition, carbon and nutrient cycling, soil fertility and stability and the regulation of soil microorganism populations (**Table 1**) [38, 40]. Furthermore, nematodes are highly sensitive to physicochemical variations in the soil ecosystems and thus considered as bioindicators [41]. Several studies reported the negative impact of intensive farming on nematodes’ biodiversity [42–45], and other recent studies delved into the negative impacts of land use change for urbanization and farming on nematodes biodiversity [10, 16]. The composition of soil nematode communities, due to their pivotal role within the complex network of the soil food web, acts as an indicator of the soil ecosystem’s overall structure, which is closely linked to soil health and has a significant influence on ecosystem functioning [46, 47]. Phytoparasitic nematodes (PPNs) represent the entry point of carbon into the soil,

Feeding type	Feeding habits	Rol/ecological impact
Bacterivores	consume bacteria	Participate in the degradation of organic matter and the release of available nutrients (mineralization), stimulate bacterial growth, and serve as indicators of nutrient enrichment and land-use changes
Fungivores	consume fungi	Release nutrients beneficial to plants, stimulate fungal growth, are abundant in uncultivated soils, and may indicate soil acidity
Herbivores	Feed on plant roots	Cause direct damage to roots, reduce crop yields, trigger secondary infections, and transmit viruses to plants.
Predators	consume other nematodes and small soil organisms	Control the populations of phytoparasitic nematodes, provide insights into the condition of the soil food web, and are sensitive to disturbances.
Omnivores	Feed on a variety of organisms (bacteria, fungi, other nematodes, protozoa, algae)	Nutrient recycling, reflects a diverse and stable soil food web, they are sensitive to soil disturbances

Table 1.
Nematodes trophic groups and their role in the soil.

whereas free-living nematodes contribute to the decomposition of organic matter, nutrient cycling, and soil mineralization. They also play an important role in disease suppression [39, 48–50]. The structure of nematode communities and their functional shifts under different levels of soil disturbance can be quantitatively assessed using ecological indices based on nematode functional diversity [51]. This approach enables the use of nematodes as an effective bioindicator for monitoring soil health [45, 48].

5. Results and discussion

Including soil organisms in biodiversity surveys improves our understanding of interactions between above- and belowground ecosystems, enabling us to develop effective management strategies for natural ecosystems [30]. It further enables us to understand the impacts of human-induced ecological shifts on soil biodiversity and natural ecosystem functions [52], hence developing more effective strategies for soil management in anthropogenic ecosystems [10]. Furthermore, as our spatial understanding of the Earth’s biosphere continues to advance, our capacity to manage natural resources in a more effective and sustainable manner also increases [38].

While protected areas have made significant strides in preserving aboveground biodiversity, there is a pressing need to focus attention on belowground soil organisms and their conservation within these established zones to ensure a more holistic approach to biodiversity preservation. Notably, despite the identification of global soil biodiversity hotspots in previous studies, an alarming 60% of these hotspots remain uncovered by protected areas [12]. This substantial coverage gap raises concerns about the conservation of these vital belowground ecosystems. Furthermore, the evaluation of the effectiveness of conservation strategies implemented within protected areas specifically targeting soil biodiversity remains largely overlooked.

The soil ecosystems, hosting a quarter of global biodiversity, are fundamental to our planet's health [53, 54]. Our research underscores this by documenting a substantial variety of nematode taxa within the SMNP, echoing the global trend of higher nematode densities in higher latitudes compared to those at lower latitudes [38]. The cataloging of 75 nematode taxa represents a significant advancement in nematode biodiversity knowledge and provides an invaluable reference for global nematological research (**Table 2**) [21]. The variations observed relative to other regions [55] underscore the influence of local ecological variables [56].

Our findings indicate that conservation strategies significantly shape nematode communities, with the protected area enhanced nematode biodiversity (**Table 2**) [21]. This aligns with the paradigm that unmanaged forests with high organic carbon inputs foster rich microbial communities and nematode abundance [57, 58]. The prevalence of the Cephelobidae family across all zones (**Table 2**) reflects its resilience to environmental stressors [59], while the absence of higher trophic level nematodes in disturbed areas reflects their sensitivity to anthropogenic land transformation [60]. Occurrence of specific genera exclusively within core zones might suggest unique environmental conditions and the potential of sensitive nematodes to serve as bioindicators for ecosystem health (**Table 2**) [61]. We noted that the conservation strategies employed in the SMNP are generating a positive impact on the soil ecosystems, as evidenced by high maturity and structure indices (**Table 2**). We observed also a high abundance of fungivore, predator, and omnivore nematodes within the protected zones (**Table 2** and **Figure 2**). Our findings align with Duarte et al. [18] when studying the impacts of nature conservation on soil biodiversity in Portugal (**Figure 3**). On the other hand, natural forests are more effective in maintaining soil biodiversity and ecological functioning and should therefore be prioritized in nature conservation strategies. In another study, Varela-Benavides et al. [20] showed that the mean values of biodiversity (generic richness), abundance, and biomass are comparatively high in nematode communities in tropical protected soils.

To achieve integrated protection of both aboveground and belowground organisms, conservation strategies must take into account the impacts of management practices on soil biodiversity and ecosystem functioning [18]. Therefore, studying the ecology of sensitive nematodes of high trophic groups within the context of conservation can provide essential insights to guide the management and the conservation strategies of sensitive ecosystems. Our findings indicate distinct nematode communities fostered by different soil management (**Table 2**). Notably, phytoparasitic nematodes such as *Heterodera*, *Pratylenchus*, *Rotylechus*, and *Meloidogyne* recognized for their significant agro-economic impact [62] were exclusively observed in more anthropogenically influenced soils, indicating negative impact of soil use on organism communities (**Table 2**). Prior research has suggested that shifts in soil nematode assemblages are often correlated with alterations in the soil food web structures, thereby affecting ecosystem services like disease suppression and nutrient cycling [51]. Furthermore, the disturbed relationships between nematodes and other soil antagonistic organisms can lead to rapid development of opportunistic nematodes especially PPN [22], that hence compete with other persistent species [63–65].

The structure (SI) and maturity (MI) indices showed lower values in the non-protected sites (NPZ) (**Table 3**). By contrast, MI and SI were higher in the park sites. Consequently, nematode communities in protected zones became more complex, exhibiting a well-developed trophic structure. The more structured soil food web is indicative of enhanced soil health, ecological stability, and increased resistance to biological invasions [35, 66]. The Chanel Index (CI) indicated higher fungal

Family	Genera	SMNP's zones				Family	Genera	SMNP's zones				Family	Genera	SMNP's zones			
		CZ	BZ	TZ	NPZ			CZ	BZ	TZ	NPZ			CZ	BZ	TZ	NPZ
<i>Seiura</i>	Aphelenchoideidae	—	—	+	—	<i>Chiloplacus</i>		+	+	+	+	Plectidae.sp		—	+	—	—
<i>Aphelenchoides</i>		+	+	+	+	<i>Zeldia</i>		+	—	—	—	<i>Plectus</i>		+	—	—	—
<i>Aphelenchus</i>	Aphelenchidae	+	+	+	+	<i>Nothacrobates</i>		+	+	+	+	<i>Pratylenchus</i>	Pratylenchidae	—	—	+	+
<i>Alaimidae.sp</i>	Alaimidae	+	+	+	—	<i>Paracrobates</i>		+	+	+	—	Prismatolaimidae.sp	Prismatolaimidae	+	+	+	—
<i>Alaimus</i>		—	—	+	—	Cephalobidae.sp		+	+	+	—	<i>Mesodorylaimus</i>	Qudsianematidae	+	—	+	—
<i>Aulolaimus</i>	Aulolaimidae	—	—	+	—	<i>Disocriciconemella</i>	Criconematidae	+	—	—	—	Qudsianematidae.sp		+	—	+	+
<i>Anguinidae.sp</i>	Anguinidae	+	—	+	—	<i>Criconematoides</i>		+	—	—	—	<i>Carcharolaimus</i>		+	—	+	—
<i>Ditylenchus</i>		+	+	+	+	Cyatholaimidae.sp	Cyatholaimidae	+	—	—	—	<i>Eudorylaimus</i>		+	—	+	—
<i>Nothotylenchus</i>		—	+	—	—	Dolichodoridae.sp	Dolichodoridae	+	+	+	—	<i>Koehinema</i>		—	—	+	—
<i>Aphanolaimus</i>	Aphanolaimidae	+	+	+	—	<i>Diplogasteriana</i>	Diplogasteridae	+	—	—	—	<i>Microdorylaimus</i>		+	+	+	—
<i>Paraxonchium</i>	Aporcelaimidae	+	—	+		Discolaimus	Discolaimidae	+	+	+	—	<i>Discolaimoides</i>		+	+	+	—
<i>Aporcelaimellus</i>		+	+	+	+	<i>Heterodera</i>	Heteroderidae	—	—	+	+	<i>Rhabditis</i>	Rhabditidae	+	+	+	+
<i>Aporcelaimus</i>		+	+	+	—	<i>Hoplolaimus</i>	Hoplolaimidae	+	—	+	—	<i>Mesorhabditis</i>		+	—	—	—
<i>Tylenchorhynchus</i>	Belondaiminidae	+	+	+	+	<i>Helicotylenchus</i>		+	+	+	—	<i>Rotylenchus</i>	Rotylenchidae	—	—	+	—
<i>Morinitus</i>		+	—	+	—	<i>Longidorus</i>	Longidoridae	+	—	+	—	<i>Prodorylaimus</i>	Thornemenatidae	+	—	—	—
<i>Axonchium</i>	Belondiridae	+	+	+	—	<i>Xiphinema</i>		+	+	+	—	Thornemenatidae.sp.		+	—	—	—
<i>Acrobates</i>	Cephalobidae	+	+	+	+	<i>Meloidogyne</i>	Meloidogynidae	—	—	—	+	<i>Trichodorus</i>	Trichodoridae	+	+	—	—
<i>Acrobeloides</i>		+	+	+	+	Microalaimidae.sp	Microalaimidae	+	—	—	—	<i>Tripyla</i>	Tripylidae	+	+	—	—
<i>Cephalobus</i>		+	+	+	+	Mononchidae	Mononchidae	+	—	—	—	<i>Thobritus</i>	Thobritidae	+	+	—	—
<i>Cervidellus</i>		+	+	+	—	Monhysteridae.sp	Monhysteridae	—	+	+	—	<i>Tylencholaimus</i>	Tylencholaimidae	+	+	+	—
<i>Eucephalobus</i>		+	+	+	+	Neodiplogasteridae.sp	Neodiplogasteridae	—	+	—	—	<i>Malenchus</i>	Tylenchidae	+	+	—	+
<i>Heterocephalobus</i>		+	+	+	—	Nygotalaimidae.sp	Nygotalaimidae	+	—	+	—	<i>Filenchus</i>		+	+	+	—
<i>Pseudacrobates</i>		—	—	+	—	<i>Panagrolaimus</i>	Panagrolaimidae	+	—	+	—	<i>Tylenchus</i>		+	+	+	+
<i>Seggella</i>		+	+	+	—	<i>Anaplectus</i>	Plectidae	—	+	—	—	Tylenchidae.sp		+	—	+	+

Family	Genera	SMNP's zones			Family	Genera	SMNP's zones			Family	Genera	SMNP's zones		
		CZ	BZ	TZ			CZ	BZ	TZ			CZ	BZ	TZ
<i>Sigaelletina</i>		+	+	+	Nygalaimidae.sp	Nygalaimidae	+	–	+	<i>Neothada</i>		+	+	+
<i>Tylocphalus</i>		+	–	+						<i>Boleodorus</i>		–	+	–

Table 2.
Nematode taxa detected across sampled locations in the Souss Massa National park and in non-protected zone [21, 22].

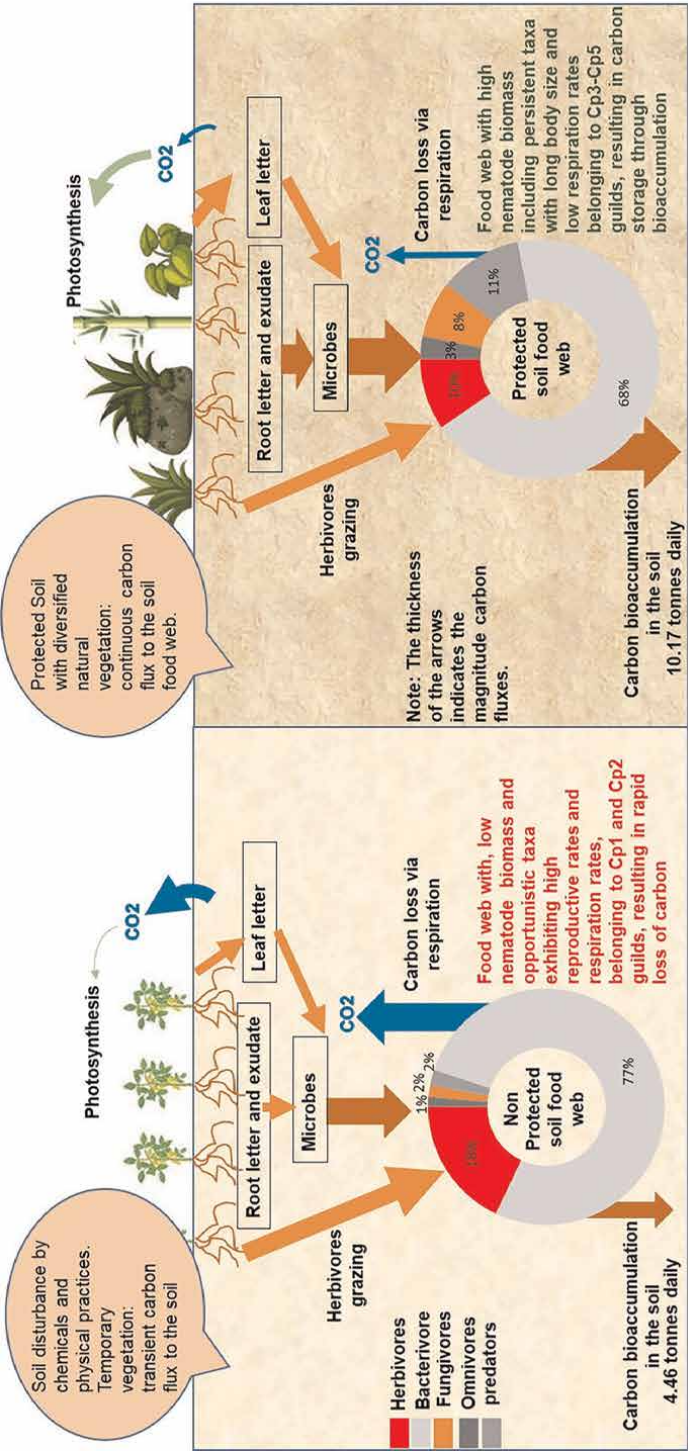


Figure 2.

The impact of soil protection on the complexity of the soil food web and carbon storage by soil nematodes. The figure is generated based on the findings of Obidari et al. [21, 22]. The figure compares carbon flux dynamics between protected and non-protected soils. In protected soils, diversified natural vegetation supports a stable soil food web, with higher nematode biomass, functional diversity, and efficient carbon storage. This leads to greater bioaccumulation (10.17 tonnes/day) and reduced carbon loss. In contrast, non-protected soils, disturbed by chemicals, tillage, and degraded vegetation, show a simplified food web dominated by fast-reproducing opportunistic taxa. This results in lower carbon storage (4.46 tonnes/day) and rapid carbon loss through respiration. Overall, soil protection and vegetation diversity are key to maintaining soil health and carbon sequestration.

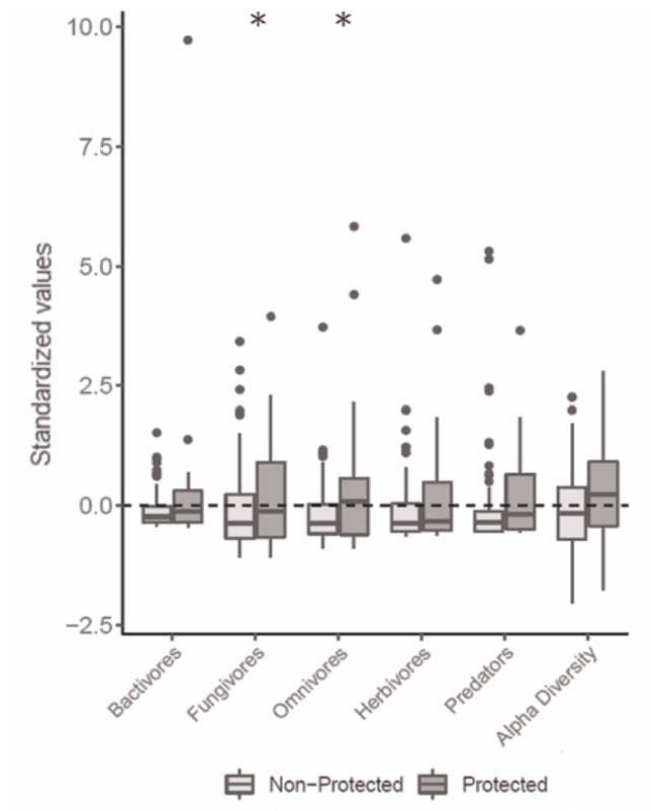


Figure 3.
The abundance of nematodes trophic groups in protected and non protected zones in Portugal [18].

decomposition in both the buffer and transition zones (**Table 3**). The enrichment index points to high nutrient concentration in the soil, which was indicated by the high density of opportunistic nematodes belonging to bacterivore group in the NPZ [51].

Soils represent one of the largest carbon sinks on Earth [67]. The main carbon inputs to the soil are the root exudates and plant litter [68]. The processing and assimilation of plant-derived carbon (C) by soil food networks contribute to its accumulation and storage in the soil [69]. The ecological functions performed by soil food webs depend on the diversity, relative abundance, and interactions among their constituent organisms [48]. The soil food web is threatened by intensive agriculture, pollution, urbanization, deforestation, soil compaction, acidification, climate change, and invasive species [70]. The soil food web encompasses a wide variety of soil organisms distributed across multiple taxa and trophic levels [71]. Nematodes represent a significant component of the soil animals, occupying a crucial part in various ecological processes, including nutrient recycling, decomposition, nutrient regulation, carbon storage, energy transfer, and population regulation [38, 40].

Our findings showed that nematode assemblages within the Souss Massa National Park contribute approximately 10.17 tonnes of carbon (biomass) per day,

	Maturity index	Phytoparasitic index	Basal index	Channel index	Structure index	Enrichment index
Core zone	2.13b	2.612 b	45.84 b	29.24 c	37.65 a	28.66 a
Buffer zone	2.347 a	2.62 ab	55.41 ab	58.47 ab	40.91 a	8.394 b
Transition zone	2.329 ab	3.111 a	52.84 ab	71.98 a	41.37 a	16.27 b
Non protected zone	1.896 c	2.409b	61.22 a	44.15b c	9.816 b	33.29 a
<i>P value</i>	0.0013	0.011	0.0065	0.0083 e-5	0.0021 e-5	0.0037 e- 3
F	5.47	3.832	4.219	13.19	14.36	10.07

F is *F*-value of one-way ANOVA. Different letters among different columns indicate significant difference between zones based on the TukeyHSD Test [21, 22].

Table 3.
Maturity index, plant parasite index, basal index, channel index, enrichment index, structure index of soil nematodes in the studied zones.

corresponding to an annual production of around 3662 tonnes, whereas production was 56% lower in the NPZ (**Figure 2**) [21]. In comparison, the annual carbon storage by nematode communities in the park represents about 24.4% of Morocco's total transport-related carbon emissions in 2011 [72]. The environmental conditions brought about by nature conservation, such as soil moisture and less fluctuation in temperature, can influence how carbon is allocated between respiratory and productive processes [73]. Furthermore, carbon fixation by soil microbial communities increased with increasing nematode abundance and diversity [74] because nematode predation can enhance bacterial abundance, leading to positive sequential effects on carbon sequestration [75].

6. Conclusion

The present chapter suggested that nature conservation enhances abundance and nematode functional diversity, and this could contribute to soil health improvement and the enhancement of ecosystem functions performed by the soil, such as nutrient mineralization, increased carbon sequestration, and disease suppression. It would also reverse the disadvantages of intensive farming in reducing carbon stock by the protection of functional diversity and the activity of soil organisms. Results showed that it is possible to restore the soil's health and functioning. This necessitates stringent safeguarding of vulnerable natural resources and a conversion to agroecological cropping aiming to recreate an environment similar to undisturbed natural sites. These findings emphasize the importance of conservation initiatives in fostering beneficial nematode communities, enhancing soil health, and pest control. Practical and theoretical implications for ecosystem management are highlighted. Future research should focus on experimental interventions to investigate the impact of protected areas on soil nematodes and their interactions with other soil organisms. Considering that studies on the conservation impacts on soil organisms are scarce, more comprehensive studies across multiple seasons and involving various soil organisms would be necessary to evaluate the impact of biodiversity conservation strategies in protected areas at a global scale, which currently constitute 17% of the Earth's surface. This

knowledge is crucial for policymakers in designing nature conservation programs, developing sustainable land-use strategies, and addressing the challenges posed by global change, such as the recently launched EU 2030 Biodiversity Strategy [76].

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Landscape-Environmental Heritage in the Coastal Zone of Guinea-Bissau: Current Trends and Design Scenarios in a Changing Climate

Elio Trusiani and Giorgio Caprari

Abstract

The paper presents a study on the landscape system, understanding the landscape in the broadest sense of heritage and common good, with a focus on the identification, analysis, and critical evaluation of the coastal Landscape Systems (LSs) of Guinea-Bissau (GB) in north-western Africa. It examines the major spatial and temporal transformations of a rapidly evolving landscape, particularly in recent years, due to socio-economic dynamics and the impacts of climate change, including a specific assessment of climate change effects on coastal landscape quality. The analysis was conducted at the geographical-territorial scale using the traditional landscape approach in order to highlight homogeneous landscape systems and subsystems, and to propose a coastal perimeter for landscape management in at-risk areas of GB. The research aims to protect and enhance the GB landscape, as well as to manage the territory and its botanical-ecological and historical-cultural heritage. Specifically, it supports coastal-landscape planning towards climate resilience and the safety of communities in the coastal area, from the perspective of sustainable development, which in this context is particularly significant given the widespread poverty, administrative-financial and socio-health challenges, as well as the absence of up-to-date data, studies, or projects on the coastal landscape. The study further develops two complementary GIS-based scenarios: one describing socio-cultural and spatial trends in the absence of planning initiatives, and another resilience-oriented scenario focused on coastal safety, the enhancement of natural and cultural heritage, and the improvement of quality of life.

Keywords: Guinea-Bissau, landscape analysis, landscape planning, urban planning, heritage, natural heritage, GIScience, climate change, sustainable development

1. Introduction

This research examines the coastal Landscape Systems (LSs) of Guinea-Bissau (GB), in north-western Africa (**Figure 1**), emphasising recent spatiotemporal dynamics influenced by socio-economic and political drivers, as well as the impacts of climate change in an area already critical due to geopolitical-geographical reasons [1, 2]. This study is part of a broader framework of research and technical-scientific consultancy activities supporting the development of Guinea-Bissau [3]. These efforts are carried out by international organisations (e.g., UN-Habitat, FAO), NGOs (e.g., Tiniguena, the Organisation for the Protection and Development of Wetlands in Guinea-Bissau—ODZH, the International Union for the Conservation of Nature—IUCN, etc.), specialised companies, and independent researchers. Specifically, this study—following the most up-to-date regulations and strategies in terms of land use and urban planning in GB—provides a multidisciplinary knowledge base to improve and implement coastal land-use planning tools in Guinea-Bissau, ensuring their relevance and applicability [4].

Key priorities include territorial safety and climate adaptation, which are essential pillars for Guinea-Bissau’s future [5]. Equally critical are the preservation of heritage in all its forms and the enhancement of the quality of human and natural landscapes. These goals are addressed through measures to ensure the safety and resilience of basic infrastructures, the availability of public services, and the creation of spaces for social interaction, with particular attention to communities living along the coastline and its tributaries.

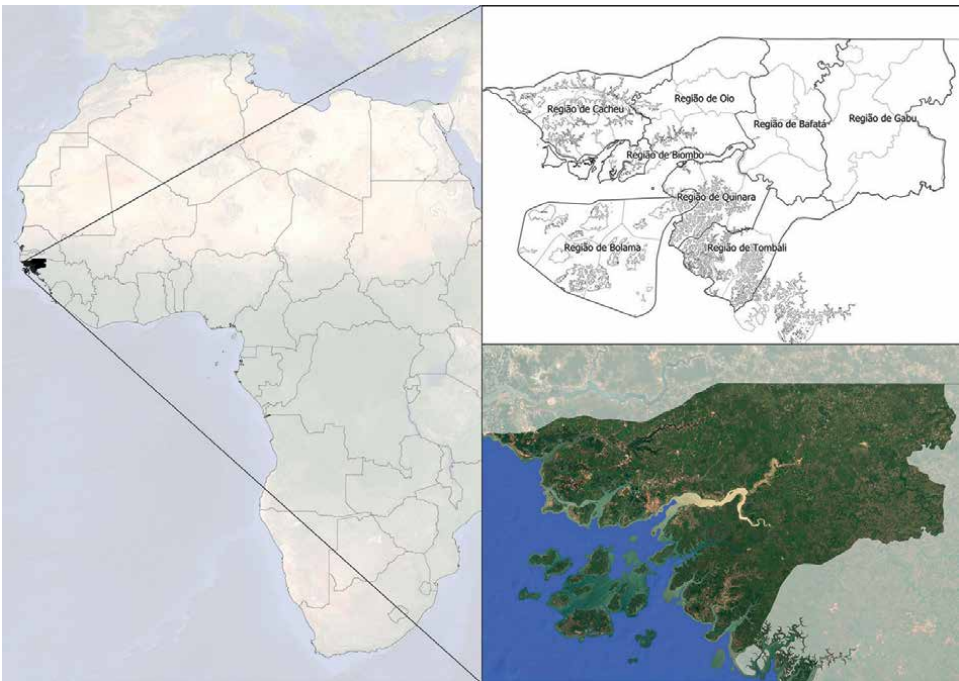


Figure 1.
Geographical context and administrative division (Regions and Sectors) of Guinea-Bissau (Google © 2025 and OpenStreetMap). Edited by the authors.

The climatic and spatial dynamics are particularly important for GB, which sustains itself mainly through its fishing and agro-industrial economy, that is, for a country dependent on the territorial and subsistence economy and the quantity/quality of productions [4].

In this context, unsustainable agricultural practice has been explored in recent years due to the declining productivity of the 'bolanhas' (i.e., rice cultivation close to mangroves) and the 'rural exodus' to Bissau, or to areas with a high concentration of forestry for agro-commercial purposes (i.e., wood energy or valuable wood for the Chinese market, i.e., Pô-de-Sangue or *Pterocarpus erinaceus*). In this sense, the abandonment of coastal crops impact on the overuse of natural resources and forest products. Uncontrolled logging and the increased need for cropland or grazing land directly impact forest biomass, which degrades in terms of biodiversity, area, and vegetation composition, as well as the loss of ecosystem services (i.e., supporting, cultural, regulation, production).

As confirmed by scientific discourse, including the IPCC (Intergovernmental Panel on Climate Change) reports [6, 7], human environment interactions significantly contribute to climate change on both spatial and temporal scales. These anthropogenic influences, often referred to as the human footprint, are currently affecting territories worldwide, including GB. Indeed, the coastal zone experiences different phenomena, including heatwaves, flooding and river overflows, sea-level rise, rainfall instability and low rainfall, prolonged drought, etc., which exacerbate the criticality of fires fuelled by dry winds or intentionally set for agricultural and production purposes. In addition, climate and weather variability affect the timing of harvests and sowings due to seasonal changes, with relative uncertainty of food productivity in rural areas [8, 9]. The climate scenarios derived from the Regional Climate Models of the CORDEX Project (Coordinated Regional Climate Downscaling Experiment) predict significant changes in the climate of Guinea-Bissau [9].

- 2016–2045: Temperature increases are projected between 1.2°C (RCP4.5) and 1.3°C (RCP8.5) for the coastal zone and between 1.4°C (RCP4.5) and 1.5°C (RCP8.5) for the inland areas. Average daily precipitation may increase slightly by 3% (RCP4.5) or remain stagnant (RCP8.5), except in the Southwest and the Bijagós Archipelago, where increases between 5 and 10% (RCP4.5) and 2–5% (RCP8.5) are anticipated;
- 2046–2075: Projected temperature increases range from 1.5°C (RCP4.5) to 2.9°C (RCP8.5). Average daily rainfall is expected to increase by 5–10% (RCP4.5) and 2–5% (RCP8.5) in the southern regions, while northern areas, such as Cacheu, may experience slight decreases in rainfall of –2 to –5% (RCP4.5) or –2 to –10% (RCP8.5).

These scenarios, characterised by rising temperatures, declining or irregular precipitation, rising sea levels, and coastal erosion, pose significant threats to groundwater resources—the primary source of drinking water for the population. Additionally, these changes are likely to intensify malaria transmission and facilitate the spread of waterborne diseases. Prolonged droughts may further increase the risk of meningitis outbreaks, potentially leading to infections and epidemics [8].

Climate instability represents a critical challenge for several climate-sensitive sectors that are vital to Guinea-Bissau's economy and have serious implications for public health [9, 10]. In this context, landscape and urban planning play a crucial role in managing, protecting, and enhancing GB's natural and cultural heritage, particularly

within the coastal zone, which hosts a large part of the inhabitants and the largest amount of natural and economic resources, and currently faces the most severe impacts of climate change. However, the topic remains insufficiently explored, with a notable lack of up-to-date data, studies, and projects addressing these challenges.

Based on this framework, the second section of the paper (Section 2) presents the data collected and used for the development of thematic maps and the identification of the study area (Subsections 2.1 and 2.2). It also includes critical and evaluative discussions on the topics of landscape, climate change, and cultural heritage (Section 2.3 and related subsections), which represent the main technical-scientific contribution to the study of the coastal landscape in Guinea-Bissau.

The final sections aim to summarise the key findings (Section 3), present the main results of the research (Section 4), and provide a general overview of the current state and future advancements in the research (Section 5).

2. Data and methods

2.1 Data

The landscape-environmental heritage analysis was conducted through an integrated reading of the major physical-naturalistic and anthropic phenomena in the area, in order to identify so-called Landscape Systems (LSs). To achieve this objective and to establish a foundation for further studies on Guinea-Bissau, all research outputs were developed within a georeferenced environment (i.e., QGIS), utilising and generating geospatial data through GIScience methodologies and applications [11–13].

Despite a general absence of local data, all the geospatial open data information relevant to the study was collected and systematically organised. These were sourced from publicly accessible national and international databases, offering varying degrees of spatial detail, as well as from technical-scientific documents and reports or cartographic resources developed by international bodies (i.e., UN-Habitat). Additionally, studies and datasets produced during the same period by sector-specific partners were integrated into the analysis.

The following open-access geospatial datasets were utilised directly/indirectly in this study:

- OpenStreetMap (OSM) Geodata – Available for Guinea-Bissau through Geofabrik: *Geofabrik Download Server*
- Global mangrove watch (2020) – Mangrove extent dataset provided by UNEP-WCMC: *Ocean Data Viewer*
- Geospatial data and web-GIS platforms by UN biodiversity lab (UNBL) and UNDP – Developed in collaboration with the Biodiversity Centre UNEP-WCMC, accessible at: map.unbiodiversitylab.org/location/UNBL/guinea-bissau
- Copernicus digital elevation model (COP-DEM) – 30 m resolution, provided through Digital Earth Africa: *dem_cop_30 whole collection*
- Population census data – Guinea-Bissau census dataset (2009), available at: *Guinea Bissau Census Data, 2009 - Guinea-Bissau Data Portal*

- ICPAC (IGAD climate prediction and applications centre) data – Climate and environmental datasets accessible through the ICPAC Geoportal: <https://www.icpac.net/open-data-sources/>.

Building on these data, the following paragraphs critically examine the landscape scale recent and ongoing changes in land use and land cover within the maritime landscapes and seascapes area. The analysis considers the region's geography, key settlements, and the complex interdependencies between land, natural ecosystems, human activities, and climate change.

2.2 Rationalising the coastal perimeter

The first step identifies the study area, considering, on the one hand, the delimitation of coastal and inland areas already identified by competent national authorities [10] and, on the other hand, the administrative subdivision into coastal and inland areas commonly accepted by local entities. The former comprises the regions of Bolama, Cacheu, Quinara, and part of Tombali; the latter comprises the regions of Bafatá, Oio, and part of Tombali, with the exception of the administrative region of Gabu.

The values that guided the choice of the perimeter can be summarised as:

- recognisability of the boundary;
- areas most exposed to coastal impacts/effects of climate change;
- areas with a higher concentration of village and/or rural/urban-coastal settlements.

In addition, the physical-naturalistic (forest, agricultural crops, etc.), anthropic (settlements, main roads, etc.), and legal-administrative (national, regional, and/or local sector limits) aspects were considered.

The inland part encompasses flat terrain crossed by a minor hydrographic network, but it has no contact with the ocean or the coastal and deltaic landscape, and lacks large river sections except for a short stretch of the Rio Cacheu and the Rio Geba. Beyond the coastal perimeter, the altimetric profile rises significantly, with elevations of 60–90 metres a.s.l. in the northern and eastern sectors and up to about 270 metres a.s.l. in the Gabu region towards Guinea. Moreover, the settlements in this area do not resemble coastal settlements in terms of location, urban development, dependence on coastal marine activities, and so on. They are away from major water bodies and mainly concentrated in areas adjacent to major road intersections and extensive forest or shrub reserves.

If on the one hand the morphological and hydrological aspect (large rivers, delta or estuary river mouths, low altitude) appears dominant in the coastal landscape of the GB (average altitude within the coastal perimeter: 8,7 m a.s.l.), on the other hand it is not the only discriminating factor considering that the entire country is crossed by a dense hydrographic system and is mostly flat (national average altitude 17,5 m a.s.l.) with the exception of a few areas, especially in the east as mentioned (**Figure 2**).

On this basis, the final boundaries (i.e., coastal area) (**Figure 3**) can be summarised and described as follows:

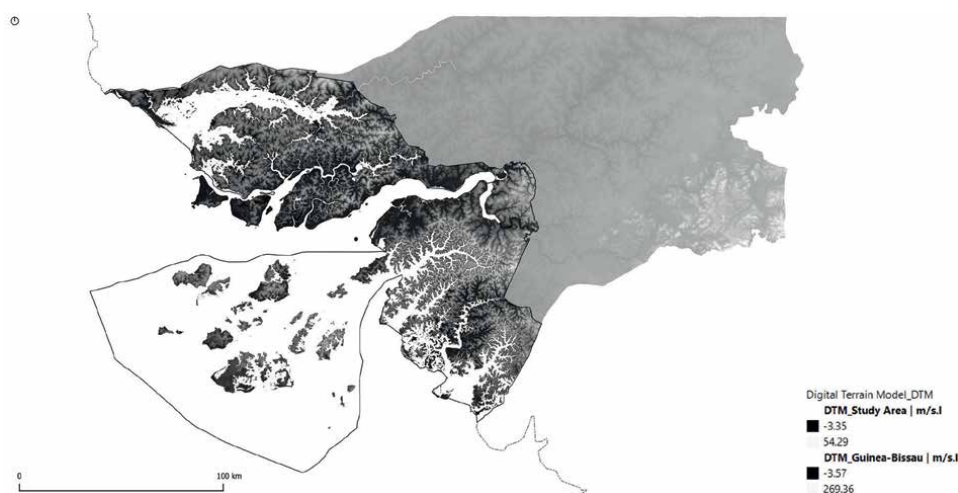


Figure 2.
The morphology of the coastal study area compared to the national altimetry (COP-DEM, 30 m/px). Edited by the authors.

- to the north and south, the perimeter lies on the limits of the neighbouring countries, Senegal (to the north) and Guinea (to the south) respectively;
- to the west (continental slope), the boundary considers the national border of GB, along the coastline;
- to the east (continental slope), the boundary instead follows several limits, mainly anthropic, such as some main roads, the boundaries and potential expansions of the major fringe settlements (Ingoré, Bissorã, Mansoa, Bambadinca, Xitole), some river bends (Río Geba, Río Corubal), and only partially the administrative limits between the various regions;
- to the south (ocean side), the boundary considers the boundary of the Bijagós Archipelago Biosphere Reserve as recognised by UNESCO (United Nations Educational, Scientific and Cultural Organization) in 1996 [14].

Defining a perimeter based on specific criteria helps to overcome the uncertainty regarding the actual extent of Guinea-Bissau's coastal zone, which is commonly delineated as the territory within a 150 km inland buffer from the shoreline—corresponding to the maximum inland reach of the country's major rivers.

In the following paragraphs, a landscape assessment by the so-called LSs (paragraph 2 et seq.) and its impacts on future work in coastal planning adaptation are in-depth described.

2.3 Decomposing and recomposing the landscape: A critical reading by landscape systems

In landscape planning, Landscape Systems (LSs) are defined as areas characterised by a high degree of homogeneity across all landscape elements—biotic and abiotic, visible and intangible—that influence human presence, activities, and natural

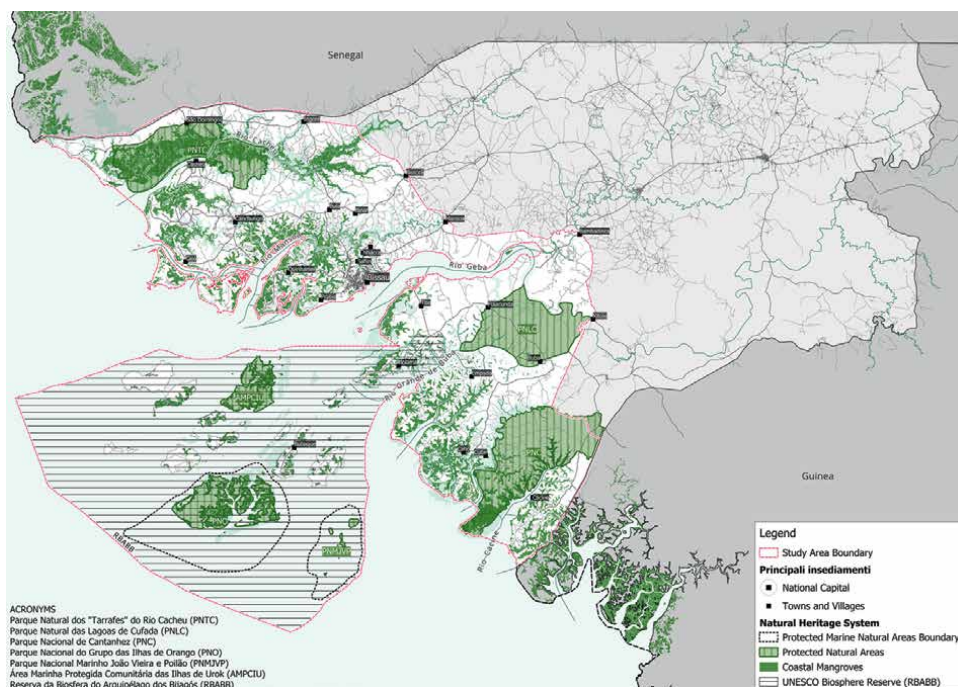


Figure 3.
 The perimeter of the coastal study area, its main cities, as well as the system of natural heritage and national protected parks. Edited by the authors.

dynamics [15, 16]. These systems are also subject to evolving and interacting conditions, whether driven by human or natural factors [17].

Each LS within a given territory represents a conceptual synthesis of these elements and their relationships. To this aim, the research guiding criteria refer to the traditional approach of the study of the landscape at the various scales, its character-vocations, its transformations, and its different functionalities [18, 19]. This means a critical evaluation of the analysed territory, divided into two large systems or 'reading categories' that include within them different subsystems or 'layers': the physical-naturalistic system (morphology, hydrography, natural and semi-natural environments, etc.), the anthropic-settlement and infrastructural system (settlements, roads, infrastructures, etc.). Moreover, traditional art and customs were considered an integral part of GB's heritage, closely tied to animist religion and rituals. Art functions as a medium of communication with the Irãs (deities) and ancestors, fostering a connection to the supernatural. These cultural expressions often manifest in sacred sites, particularly within forests. Consequently, the concept of cultural heritage, typically viewed through a Western lens, is expanded here to include various forms of intangible heritage, warranting equal protection and preservation.

Adopting this analysis framework, the study identifies and evaluates key climate-altering processes (e.g., land use) and climate-affected changes (e.g., land cover transformation) within all LSs as identified through three basic components/criteria: (i) the morphology of the territory; (ii) the prevailing land cover and land use; and (iii) the dynamics of transformation that, in some cases, characterise their environmental and landscape arrangements.

The analysis of climate vulnerabilities, that is, impending and ongoing hazards, as well as the areas most exposed to climate change phenomena, was conducted with a cross-sectional analysis of some of the most recent texts and dossiers produced [8, 9, 20–22] for Guinea and/or in the African coastal area.

Within the identified perimeter of coastal areas (see **Figure 3**), the following four LSs have been identified (**Figure 4**).

- *LS no.1. The coastal wetlands system:* the boundaries consist of the coastline and the boundary identified by the cartography; within this perimeter, oceanic coastal areas, mangrove systems, and coastal areas along rivers near the estuary itself are recognisable;
- *LS no.2. The agroforestry and fringe settlement system:* the boundaries consist of the inner boundary of the wetlands and mangrove system. It is basically a filter area between the inner boundary of the wetlands and the larger system of inland areas towards the north of the country;
- *LS no. 3. The urban system of Bissau:* the country's capital is the only major urban settlement, such that it constitutes a system in its own right, as also documented by the transformation and development dynamics identified in the Strategic 2030 study [23], and for this reason it was deemed appropriate to take the perimeter of the entire municipality as the boundary, and to which the northern expansion area was added;
- *LS no. 4. The Bijagos Archipelago system:* it is classified as the Reserva da Biosfera do Arquipélago Bolama Bijagós (RBBB), where there are three protected areas: Parque Nacional do Grupo das Ilhas de Orango (PNO), Parque Nacional Marinho João Vieira e Poilão (PNMJVP), and the Area Marinha Comunitária de Ilha de Urok (AMCIU); the boundaries of this system consist of the institutional perimeter of RBBB.



Figure 4.
The four landscape systems. Edited by the authors.

Once the LSs had been identified and mapped out, as a metaproject action, the main critical trends, the most severe impacts, and the effects of these on land use and landscape and urban dynamics were analysed and reported for each LS, as follows.

2.3.1 *The coastal wetlands system*

LS no.1 (**Figure 5**) is an easily recognisable system, as it mainly follows the main-stream hydrographic network. The boundary was produced by relating, in the GIS environment, the geometric boundaries of wetlands from OSM data with the most recent ones provided by Global Mangrove Watch (2020). It is characterised by the wetlands system and, in particular, the mangrove forest system. In general, mangroves form the dominant land cover of the GB maritime interface and perform important ecosystem services: protection from coastal erosion, food security and medicinal purposes for local communities, carbon uptake, and refuge areas for biodiversity (terrestrial and fish fauna) [24, 25]. According to some estimates, mangroves cover approximately 8% of the national territory and their concentration within the study area is prevalent in the northern sector of the study area at the ‘Tarrafas do Rio Cacheu National Park’ (approximately 40% of the park area) and in the south within the ‘Cantanhez National Park’, as well as along all the main river loops (Rio Cacheu, Rio Mansoa, Rio Tombali, Rio Combidjam, Rio Cacine, Río Geba) up to the limit of the wetland-pluvial forest [26]. In addition to the two protected national reserves mentioned, this LS also includes the natural park ‘das Lagoas de Cufada’, in the centre-south, between Buba, Xilotè, and Calafunda villages, and two islands between the Canal de Jata and the Rio Mansoa (to the north) and the island Ilhéu de Melo (to the south), also predominantly covered by mangroves and wetlands.

The concentration of reserves and consolidated parks reflects the ecological and landscape importance of this LS, where mangroves are considered a natural and socio-economic heritage, given the ecosystem benefits they provide to the population. Although some local differentiations, it appears homogeneous and entirely naturalistic, where the landscape is structured by a main and secondary hydric-morphological

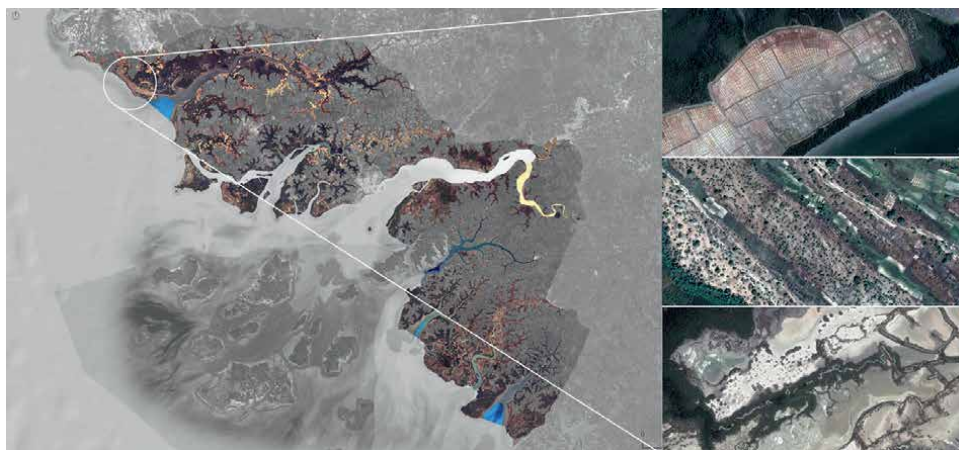


Figure 5.
LS no.1: Coastal wetland system. On the right, from top to bottom, the three LSSs: Rice paddies (‘Bolanhas’) and a strip of coastal savannah in the Varela area; a patch of coastal halophytic vegetation. Credits: Google Maps. Edited by the authors.

system, an altitude of no more than 20–25 metres a.s.l., the massive presence of mangroves, and the agricultural system of rice paddies. The vegetation aspect is therefore the most relevant, and in detail, it is possible to distinguish several Landscape Subsystems, LSSs, with naturalistic and/or productive dominance, including:

- LSS no. 1.1. *The 'bolanhas'*: these are lowland agricultural areas devoted to rice cultivation that are mainly developed on mangrove soils by means of anti-salt dykes and water retention systems. This land use determines a seascape mosaic of 'cells/chambers', whose tesserae are perfectly recognisable both in their overall configuration and in their internal compositional rules;
- LSS no. 1.2. *Coastal shrub savannas*: this LSS is found on soils with low fertility and a sandy texture, the result of the evolution of marine sediments. Its physical-vegetational composition is simple: a predominantly herbaceous layer (1-2 m), and a sparse shrub layer;
- LSS no. 1.3. *The 'tannes'*: these are salt flat areas of bare ground with halophilic and hydrophilic herbaceous vegetation associated with mangroves and can be found at the edge of coastal herbaceous savannas, recognisable because they are clustered in islets between mangroves, especially in the Cacheu areas but also near Cumbidja and Cacine.

Land use and land-change nowadays evolve due to social and economic needs, making the boundary between wetland-mangroves, wet forest, and wooded savannah more discontinuous. Furthermore, sea-level rise and increased temperature of sea and delta waters are damaging coastal soils and shoreline erosion with consequent loss of riparian-dunal biodiversity, shoreline modification, and excessive salinisation of wetlands and 'bolanhas'. These trigger indirect effects, such as the decrease/modification of fish stocks, the abandonment of rice fields, food insecurity of coastal areas, the degradation of mangroves, and, in general, the modification of the composition/structure of marine species, as well as their route/direction within watersheds, affecting fisheries. The degradation of mangrove ecosystems is primarily driven by unsustainable commercial logging activities, unregulated artisanal mining, the conversion of mangrove forests into agricultural plantations, and the extraction of timber for construction and fuelwood [27].

At the end, this LS includes several small settlements and villages along the Varela area (northern border with Senegal), as well as Cacheu (north) and Cacine (south), and other scattered villages throughout the area. These are generally linearly located along the river-coastal limits and mangrove boundaries, in close contact with the water resource on which they depend for their daily subsistence (see Appendix A). Varela areas differ from other sites by a humid and dense secondary coastal forest with a predominance of palm groves, subject to a strong erosion phenomenon.

2.3.2 Agroforestry and fringe settlement system

This LS (**Figure 6**) is based on the limits of the wetland and mangrove area and expands inland, up to the eastern limit of the study area, which can be identified along the main N-S crossing road on which minor urban-rural settlements linearly develop. Among these are those of São Domingo, Bissora, Ingorè (north), Mansoa, Bambadinca, Xitole (centre), Buba (south), as well as a series of more inland

settlements. Others, such as Canchungo, Bula (north), Quinhameil, Falacunda, Tite (centre), Empada, and Cufar (south), to name but a few, develop linearly along the internal E-W roads, that is, in the filter areas between the LSs no. 1 and 2 (see Appendix B).

Most of the settlements are in areas slightly elevated from the coastal plain, especially those in the linear ‘crown’ along the continental limit of the study area, to the east. The LS no. 2 has an elevation between 25 and 50 m a.s.m., characterised by slight foot-hill relief and a ridge to the south, at the edge of the ‘Rio Grande de Buba’. Furthermore, the entire LS has a forest and agro-sylvo-pastoral vocation, dotted with small rural centres mostly dedicated to subsistence farming, cashew monoculture, and the felling of specific tree-vegetable species, which on the one hand are among the most profitable activities in the country but on the other threaten the forest ecosystem, that is, the dominant landscape matrix [28]. The rainforest today appears more dense and homogeneous in the southern area, in the Tombali region (i.e., Cantanhez forest), where it is associated with the mangrove system and, to a lesser extent, with the ‘bolanhas’ rice fields.

It is an LS in transformation to meet the needs of local rural communities where (i) cashew monoculture, (ii) socio-economic pressure due to marked poverty, and (iii) the continuing lack of control and enforcement of environmental matrix laws, are severely threatening the stability and regenerative capacity of the present natural heritage and the biodiversity/heterogeneity of the natural landscape.

Despite its morphological and agro-ecological homogeneity, the LS can be read through three main LSSs (**Figure 6**).

- LSS no. 2.1. *The edge rainforest*: it is located at the mangrove margins and is dominated by humid and dry forest, depending on the different locations and climatic-pedological conditions. The dry forest is more present in the protected area ‘das Lagoas de Cufada’, while the main patches of humid forest are found in the south, where rainfall regimes are more consistent (e.g., Cantanhez forest). The natural park is part of this area as the main centre of biodiversity for aquatic and terrestrial fauna,

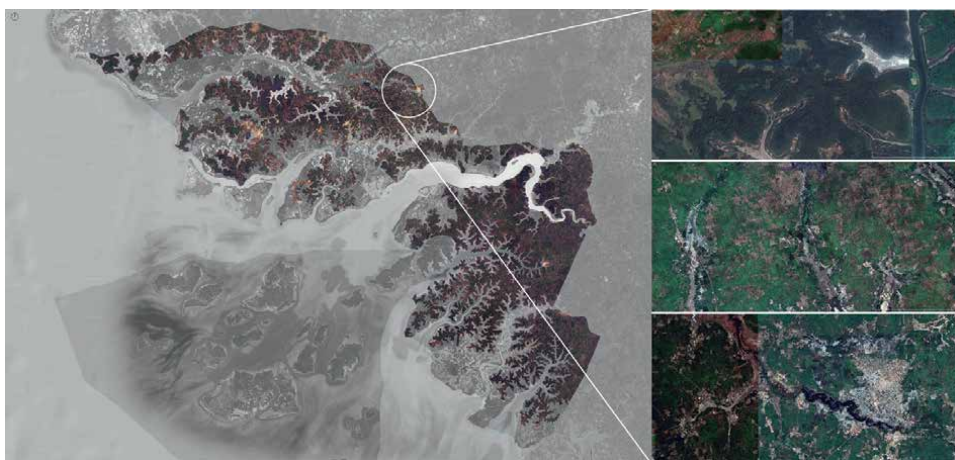


Figure 6.
 LS no. 2: agroforestry and fringe settlement system. At the right, from top to bottom, the three LSSs: the edge rainforest, inland areas with an agro-sylvo-pastoral matrix, and the system of minor rural-urban settlements (Bissorã area). Credits: Google Maps. Edited by the authors.

and at the same time hosts all the typical vegetation formations of this LSS: dry and semi-dry forest, humid forest, sub-humid and humid savannah;

- LSS no. 2.2. *Inland areas with an agro-sylvo-pastoral matrix*: this area, with different land uses and cover, consists of forest vegetation and annual and semi-permanent crops as well as extensive pastures. It is also characterised by so-called itinerant farming ('mpam-pam') and cashew fruit farming (especially in the northern area of Biombo and Oio, and in Cacheu, and Quinará).
- LSS no. 2.3. *The system of minor urban-rural settlements*: the LSS, despite its apparent discontinuity/fragmentation, develops linearly along the main roads connecting the various local communities. In some cases, these centres present a semi-urban or village-like character, particularly along the north-western border of the study area and close to the wetland hydrographic system (i.e., Bissorã, Mansoa). These predominantly residential areas maintain a close link with the natural heritage and its resources, which sustain the economy. Examples are Canchungo and Quinhamel (approximately 43,000 inhabitants each), Mansoa (46,000), Empada and Buba (17,000 each).
- Last but not least, the LS includes intangible heritage sites, such as sacred areas within the Colage forest in the northwest, revered by local ethnic communities as spaces for initiation, knowledge transmission, and the preservation of community traditions [29].

2.3.3 Urban system of Bissau

The LS of the country's capital, Bissau (**Figure 7**), unlike the others, is characterised by its urban-settlement matrix (approximately 500,000 inhabitants). The city is located in the central coastal area of GB, and is characterised by a very low altitude (approximately 39 m a.s.l.). The morphology, albeit slightly, changes within the compact city and along the northern expansion axis, where the terrain is slightly raised. The vegetation, in general, belongs to the sub-Guinean type of landscape, consisting mainly of rainforests, mangroves, and vegetable-cereal crops. The territory is marked by a low plain and by slight depressions in the river area of the Rio Geba and to the east in the Safim area; the prevailing destination is agricultural and rice-growing, almost always obtained in deforested areas. Nevertheless, there is an observable reduction of agricultural areas and a process of abandonment of rice fields along the wetlands due to water salinisation and acidification. This entails a transformation of the peri-urban agricultural landscape with a reduction in the size and quality of forest areas due to generalised urban sprawl and agro-food production.

Even so, Bissau presents socio-health criticalities due to territorial fragilities (i.e., flooding and river overflows), the uncontrolled expansion or compaction of the city and its forms/materials (i.e., heat island phenomena) [22]. Other studies highlight that there are potential increases in malaria cases caused by the proliferation of mosquitoes in marshy areas due to the lack of rainfall and rising temperatures, which will increase according to trend scenarios [1].

On this basis, three LSSs can be identified within the LS no. 3:

- LSS no.3.1. *The compact urban-metropolitan landscape*: the central and heavily urbanised area of Bissau is subdivided into four districts, which represent

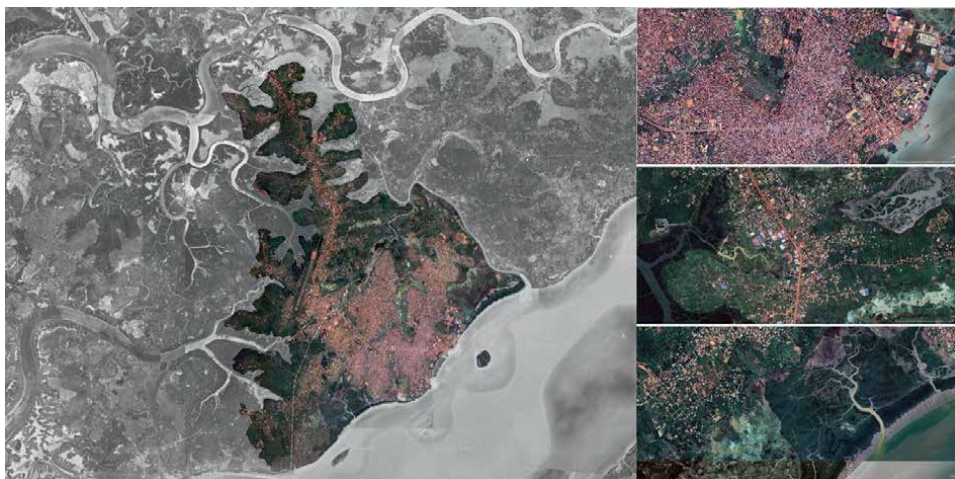


Figure 7.
 LS no. 3: Urban landscape of Bissau. From top to bottom, the three LSSs are the compact urban landscape of Bissau, the changing peri-urban landscape, and the agroforestry edge landscape. Credits: Google Maps. Edited by the authors.

different land-use categories, such as (i) a mixed urban fabric with varying densities, between the city centre and the rest of the urbanised residential area, (ii) agricultural areas located mostly on the city periphery and near the coastal areas, (iii) existing and expanding port and industrial areas, on the edges of the city, and iv) wetlands, which characterise both the mangrove and rice-growing coastal landscape both the edges of settlements;

- LSS no.3.2: *The changing peri-urban landscape*: the urban sprawl of Bissau develops linearly (i) in a northerly direction towards Safim, along a main road/morphological ridge on which several expanding internal roads are located; (ii) in a south-westerly direction along the coast towards Prabis. This dynamic entails significant ecological and environmental impacts but also reflects the contemporary demand for land and the metropolitan expansion of Bissau along the N-NW axis.
- LSS no. 3.3. *The agroforestry landscape on the margins*: forested areas on the edge of the compact and diffuse urban fabric are located along wetlands and dominant hydrological and morphological systems. In contrast, denser and more compact development is found along the E-W coastal zone and the central areas of the city, crossed by multiple river tributaries. Here, vegetation prevails, surrounded by extensive rice fields or various agricultural fields that support food subsistence.

The boundary of LS no. 3 is based on the administrative perimeter of the city and the urban expansion areas that reflect a recognisable LS (predominantly urban-residential) with three LSSs strongly dependent on each other. Although with a different vocation/use inside the areas, those cannot be separated from the dynamics of urbanisation, evolution, and transformation of Bissau that cross its administrative boundaries.

Especially in the latter two LSSs, there are phenomena typical of the urban fringes of large cities, that is, linear expansion dynamics close to the main roads, along higher-level facilities (airport and port) and along watercourses, with a relative decrease in agricultural and/or forest land of landscape value.

The urban centre of Bissau is characterised by a lack of urban identity and the presence of unregulated construction projects. The central area, generally identified as the urban zone surrounding the presidential palace, consists of multi-story residential buildings interspersed with low-rise structures (one to two stories), predominantly residential, some of which exhibit architectural influences from the colonial period. These buildings are mostly two-storey structures with a high ground floor, typically used for commercial purposes such as shops or warehouses, while the upper floor serves as housing [30]. Similarly, administrative, political, and institutional headquarters (e.g., embassies, ministries) are concentrated in this area. In contrast, the neighbourhoods near Bissau's harbour, historically characterised by colonial architecture (i.e., 'Old Bissau'), are in an advanced state of decay (**Figure 8**). Only a few buildings have been recently renovated for residential use or, more commonly, converted into commercial spaces on the ground floor. In recent years, the municipality has promoted the enhancement of certain public urban spaces—such as the central axis connecting the presidential palace to the port—and the restoration of both public and private buildings, including hotels, schools, and ministerial offices. However, as one moves away from the city centre, informal settlements become predominant, housing the majority of Bissau's urban population.

Finally, the geostrategic position of the city makes it an attractive pole for the inhabitants of the rural area and for investors. This gives and will give rise to migratory phenomena and the related increase in demand for land acquisitions, new realisations, and/or increase in industrial areas, such as to promote processes of urban development and landscape transformation along the city's fringes, where such phenomena are already found. This process is resulting in spontaneous urbanisation and the 'metropolitanization' of Bissau, characterised by continuous built expansion and sprawling developments lacking services, infrastructure, and adequate social housing. For all these reasons, the capital, like other cities and villages in GB, is the focus of plans and strategies developed by NGOs and international actors [23] aimed at guiding urban and building development, managing land use, and regulating various sectors that impact the quality of places, natural environments, and public health. This is particularly crucial in contexts where planning tools are either entirely absent or exist but remain unimplemented.

2.3.4 Bijagos archipelago system

The landscape system of the Bijagós archipelago (**Figure 9**), due to its overall forest homogeneity and insularity, is considered unique here and corresponds to the limits of the Biosphere Reserve [31]. It is worth noting that of the four identified LS, this is the only one to have an accepted management strategy and, in the near future, could be managed by an integrated management plan, currently ongoing on the basis of previous studies [32].

The Bijagos is the only active deltaic archipelago on the Atlantic coast of Africa and is morphologically made up of islands and islets separated from each other by a network of channels of varying width and depth. The size of the archipelago is approximately 85 km in diameter from east to west and 65 km from north to south. Administratively, it is divided into four distinct sectors, namely Bolama and Bubaque, which are the main urban-coastal centres (see Annex A), and Uno and Caravela, with a total emerging surface area of approximately 900 km².

The maritime interface and the marine areas around the landmasses, that is, channels and shallow areas characterised by the retreat of waters by the tides, characterise



Figure 8.
'Bissau Velha': selected views of the colonial-era urban fabric near the port area of Bissau (February 2025). Edited by the authors.

more than 85% of the Biosphere Reserve's surface area and are one of the dominant seascape elements of the entire system that are associated with the 'mudflats' complex. The latter represent a dynamic and changing element of the landscape perception, since when the tide is low, almost a third of the archipelago dries up, while when the tide is high, only the islands emerge in their scenery of beaches or mangroves. Taken together, these two elements constitute two subsystems in their own right of significant ecological-naturalistic value.

Within the LS thus described, two prevailing LSSs can be traced:

- *LSS no.4.1, the forest system:* is the dominant landscape matrix within the entire system. It dominates the landscape of all the islands with the exception of a couple of cases where the dense forest cover gives way to wooded savannah and areas with irregular and sparse tree cover. This subsystem is characterised by the

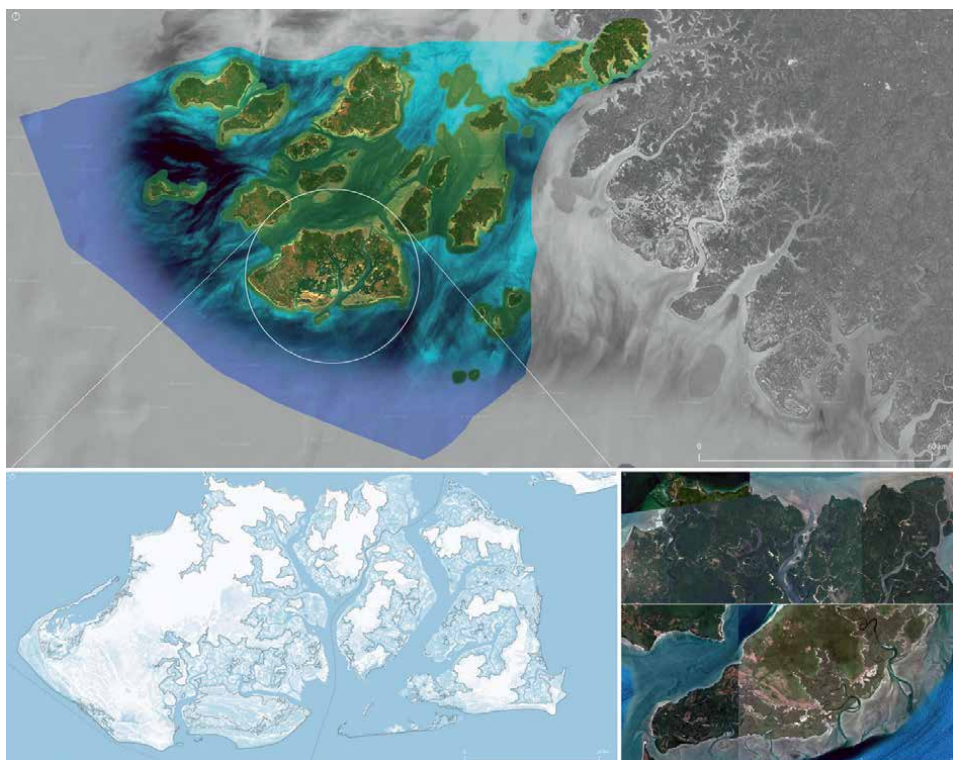


Figure 9.

LS no. 4: Bijagos Archipelago system. Below, the blue scale, limited to 10 m a.s.l., reflects the system of wetlands and dynamic mudflats as an added system beyond the national perimeter (in hatching). On the right, from top to bottom, the two LSSs: the forest system between the 'Ilha de Orango' and the 'Ilha de Bubaque', and the coastal and mangrove system on the coast of the 'Ilha de Carache'. Credits: Copernicus, COP-DEM, and Google Maps. Edited by the authors.

presence of the three protected areas consisting of the 'Orango Islands National Park', the 'João Vieira e Poilão National Marine Park', and the 'Urok Islands Community Protected Marine Area'. Many of these areas are considered sacred and have a cultural-historical and identity value safeguarded by the strategies and policies on the subject and, before that, by the inhabitants themselves. The settlement component in these areas is limited to small inland or coastal villages, devoted to fishing and agro-sylvo-pastoral activities, and interconnected by a network of roads and paths that follow the morphology of the terrain.

- *LSS no.4.2, the coastline and mangrove system:* this subsystem is landscape-dominated by mudflats, mangrove-dominated wetlands, coastal marine areas, and the minor hydrographic network. It is affected by tidal dynamics and thus by the immersion/emergence of land. Here too, mangroves have priority ecological and morphological importance, and are mostly concentrated in the central-southern island complex of the reserve. In close contact with the marine-coastal areas, on the other hand, are the two settlements of Bolama and Bubaque, which emerge as the only urban centres in the Archipelago. Around these two areas, other small rural settlements are developing, linked by a network of connections that appears to be expanding.

The social and economic life of the archipelago, based on traditional relational structures, customary rights, and a degree of self-sufficiency, is fundamental for the present/future management of the entire LS. Bijagós communities are able to meet almost all their needs independently; agriculture and animal husbandry are conducted without special recourse to imported products, and society is not dependent on state subsidies or services [33]. This model has a very low environmental impact on the landscape, reinforcing the broader concept of landscape as a social product of the people who inhabit it, design it, manage it, and perceive it over time [34, 35]. A traditional community model has the effect of protecting resources and biological diversity, which are closely linked to the daily rituals and practices of the inhabitants. For instance, each island has sacred forests reserved for male/female initiation ceremonies and other religious-magic ceremonies. These customs and traditions, within the context of a vast flora and fauna heritage protected by UNESCO, constitute a widespread intangible cultural heritage that must be preserved. Examples of these sites are found in the Bijagos Islands (especially in Orango, Uno, or Soga islands).

The zoning of the reserve, inspired by this community model, protects the various forms of sociality in line with the traditional organisation of the space. This orientation, in general, has guided the creation of the two national parks and the marine protected area mentioned above. Indeed, the strong cultural sense gives a high level of protection, allowing the preservation of the natural heritage and the regulation of the use of resources available to the inhabitants [32].

This level of protection restricts agro-productive activity (e.g., in Rubane, Tufo, Maju-Inorei, Maju-Anchorupe, Ebenga, João Vieira, Meio, Cavalos, Poilão, and Cute) and prohibits ploughing and tree cutting in some areas. These traditional management measures reflect the cultural and identity aspects of the place and the more noble and broader meaning of cultural heritage.

On the contrary, different climatic and land-use dynamics are affecting the LS [36]. The development of cashew cultivation (as in other areas of GB) threatens the community/natural environment relationship and is transforming the relationship of the islanders with their land, which is generally managed communally for rice production and food subsistence. At the same time, increased temperature and ocean salinisation are destined to reduce agricultural productivity and land and marine biodiversity. Nevertheless, coastal flooding and coastal erosion, as well as salinisation of water, evapotranspiration, changes in moisture levels, and reduced precipitation affect the LSSs. In particular, the eastern part of Formosa and the eastern islands of 'Orango Park', which are the most populated, have to be focused on. The impacts of climate change in a humid territory such as Bijagos will increase the transmission of diseases such as malaria, meningitis, and other infections.

3. Discussion of the coastal landscape analysis

Critically examining the interim results achieved through landscape analysis, it is possible to briefly highlight and summarise the direct/indirect impacts/effects of climate change on the coastal area and the relative soil/land-use changes described.

The main threats to the coastal landscape are:

- rising mean sea level and coastal erosion;
- heat waves and thermal stress;

- intensification of extreme flooding phenomena;
- prolongation of aridity/drought periods;
- increase in mean sea/river and estuarine temperatures.

Due to these climate-related phenomena, two key dynamics emerge. On one hand, there is the spatial transformation and reconfiguration of degraded, hazardous, or unproductive landscapes, including their use and abandonment. On the other hand, there is a continuous search for arable land and economic resources to sustain a growing population, manifested in rural migration and the process of Bissau's 'metropolization'.

Linked to these aspects, the following cause-and-effect relationships characterise the study area:

- *Coastal flooding and consequent salinisation of 'bolanha' and coastal crops*: this problem is exacerbated by rural exodus, inadequate maintenance and infrastructure, and the widespread presence of coastal settlements in areas of high flood risk;
- *Nutrient depletion and soil compaction due to prolonged drought*: these problems are intensified by soil depletion due to monoculture and socio-productive practices, exacerbated by sewage problems in settlements and poor management of waste that flows into cultivation areas;
- *Coastal erosion*: this is the result of rising sea levels, tidal phenomena, and ocean wave dynamics (i.e., Varela). Erosion drives the search for cultivable land and leads to the abandonment of crops and improperly built coastal structures.
- All these aspects individually serve as analytical criteria and synthetic qualitative-quantitative indicators used to study each Landscape System (LS). They are then compared and systematically organised in a matrix table (**Table 1**).

As highlighted in this study, the coastal study area, as well as Guinea-Bissau as a whole, possesses a significant natural and cultural heritage, deeply intertwined with site-specific social customs and sacred or spiritual values.

By categorising Guinea-Bissau's heritage into tangible and intangible dimensions, we can state that:

- The natural heritage is predominant and holds clear economic, socio-cultural, and ecological value [37], responding to the needs of local inhabitants while also mitigating the impacts of contemporary climate change. Furthermore, it has a crucial cultural significance, as these landscapes are inhabited by diverse communities whose knowledge, traditions, and ways of life are intrinsically connected to them. Socio-ethno-anthropological practices—such as religious beliefs, tribal customs, and initiatory rites—find spatial expression within various 'sacred sites' and protected forests (e.g., Cobiana, Colage).
- Heritage sites and architectural structures, on the other hand, are primarily concentrated in historic centres, such as Bolama, Bubaque, and Bissau, though they remain widely dispersed. These constructions reflect the colonial Portuguese

Indicators and analysis criteria	LS no. 1	LS no. 2	LS no. 3	LS no. 4
<i>Geomorphology</i>	Very low elevation and flat ground	Low elevation, flat ground, and light slopes	Low elevation and predominantly flat ground	Very low elevation and flat ground
<i>Elevation (metres a.s.l.)</i>	min: -2.32 mean: 0.35 max: 34.74	min: 0 mean: 3.71 max: 68.77	min: -0.02 mean: 6.84 max: 55.80	min: 0.0 mean: 1.55 max: 47.47
<i>Main land cover</i>	Mangroves, coastal savannahs, and rice fields	Humid forests and agro-mosaic	Urbanised environment and agroforestry mosaic	Forest, mangroves and coastal mudflats
<i>Natural protected areas</i>	yes (PNTC, PNLC)	yes (PNTC, PNLC)	no	yes (PNO, PNMJVP, RBBB, Ilhas Urok)
<i>Degree of transformation</i>	medium	medium	high	low
<i>Human impact</i>	high	high	high	low
<i>Cultural-identity values</i>	yes	no data	no data	yes
<i>Diffuse Urban/rural settlements</i>	yes	yes	no	yes
<i>Main urban settlements</i>	no	yes	yes	no
<i>Urban planning tools</i>	no	no	yes (not applied)	yes
<i>Climate change impacts</i>	Sea level rise, coastal flooding, coastal erosion, extreme weather phenomena, rising sea/river temperatures	Extreme weather phenomena, droughts, heat waves, and rainfall instability	Extreme weather phenomena, sea level rise, coastal flooding, heat waves, heat islands, rainfall instability, droughts	Sea level rise, rising sea/river temperatures, evapotranspiration, and changes in humidity levels

Table 1.

Critical summary of the main indicators and qualitative-quantitative analytical criteria for each LS.

architectural style—characterised by concrete blocks and tiled or fibre-cement panel roofs—or serve as examples of post-colonial African architecture [30]. In Bissau, the degradation of urban buildings, coupled with a housing deficit and a massive influx of impoverished rural migrants, has led to unplanned urban expansion and low-quality living conditions [30]. In Bolama, buildings of great historical interest are entirely neglected, lacking maintenance and facing the risk of collapse. In other coastal urban and rural settlements, which constitute a significant portion of inhabited areas within the LSs, architectural forms and materials reflect a traditional-vernacular style. Traditional dwellings, historically built with rammed earth or adobe walls and thatched straw roofs, are now undergoing a gradual shift towards zinc sheet roofing [38];

- While tangible heritage is fragmented and deteriorating—partly due to its association with a historically contentious colonial period—intangible heritage remains extensive and deeply tied to natural landscapes [39], as previously noted.

The natural and human-induced phenomena discussed in Sections 2 and 3 define GB's landscape systems and subsystems that are largely undergoing transformation. In general—and particularly evident in Bissau (LS no. 3)—population growth and the demand for new spaces for residential settlements, productive activities, and subsistence agriculture are driving the transformation of urban, rural, and peri-urban areas, along with their associated landscape resources. These dynamics are exacerbated by the absence or non-implementation of urban and territorial plans, the accelerating impacts of climate change, and the interlinked challenges of demographic growth and widespread poverty. All these factors, combined with institutional fragility, governance disorganisation, and the inefficiency of responsible bodies, contribute to environmental degradation and the progressive fragmentation of the coastal and inland natural landscape [40].

4. Results

The rationalisation of the coastal perimeter (see **Figure 3**) is the first outcome of this research, as it highlights the area most exposed to climate-coastal challenges, which is the focus of specific international projects to which this study has contributed directly as applied research [3]. This area establishes a clearly defined and recognisable boundary, anchored to known or easily identifiable territorial markers. Defining such a perimeter can provide clarity regarding the zones subject to future plans and projects, thus preventing or at least reducing confusion among competent land-use planning and management authorities. In this regard, delineating the coastal zone constitutes a fundamental outcome, instrumental for both the research presented here and future studies on this topic.

The identification of LSs and LSSs serves as both a methodological approach to landscape analysis and a planning tool for homogeneous spatial units. These units can support strategies and projects with either similar or differentiated characteristics and functions, depending on the specific context. Thus, LSs and LSSs represent the second research outcome, offering a framework that can be further developed, monitored, and updated both spatially and in terms of content.

The social, economic, cultural, and ecological functions of the four LSs, along with the spatiotemporal dynamics of land use and resource consumption in the coastal area, as presented in Section 2, have been spatialised into a critical up-to-date GIS-based map of coastal resources and vulnerabilities. This constitutes one of the two key outcomes, synthesising ongoing territorial trends and representing the 'business-as-usual reality' (i.e., 'Scenario 0') (**Figure 10**). This baseline scenario (i.e., scarce effectiveness scenario) illustrates the expected developments in the absence of intervention [41].

In particular, the map highlights the previously discussed aspects, emphasising the natural heritage (e.g., terrestrial and marine protected areas, mangroves, traditional agricultural systems) and cultural heritage (e.g., sacred sites, colonial-era historical centres). At the same time, it illustrates the range of observable impacts threatening their integrity and landscape quality as highlighted in Section 3 (e.g., sea level rise, coastal salinisation, monoculture expansion, urban sprawl).

Based on this analytical framework, nine objectives and nineteen strategies have been defined, collectively shaping the planning scenario for the coastal area (i.e., 'Scenario 1') (**Table 2**). This represents the key outcome and the main objective of the research that is based on the principles of 'Integrated Coastal Zone Management', 'Sustainable Land Management', 'Land Degradation Neutrality', and 'Climate Adaptation' [4].

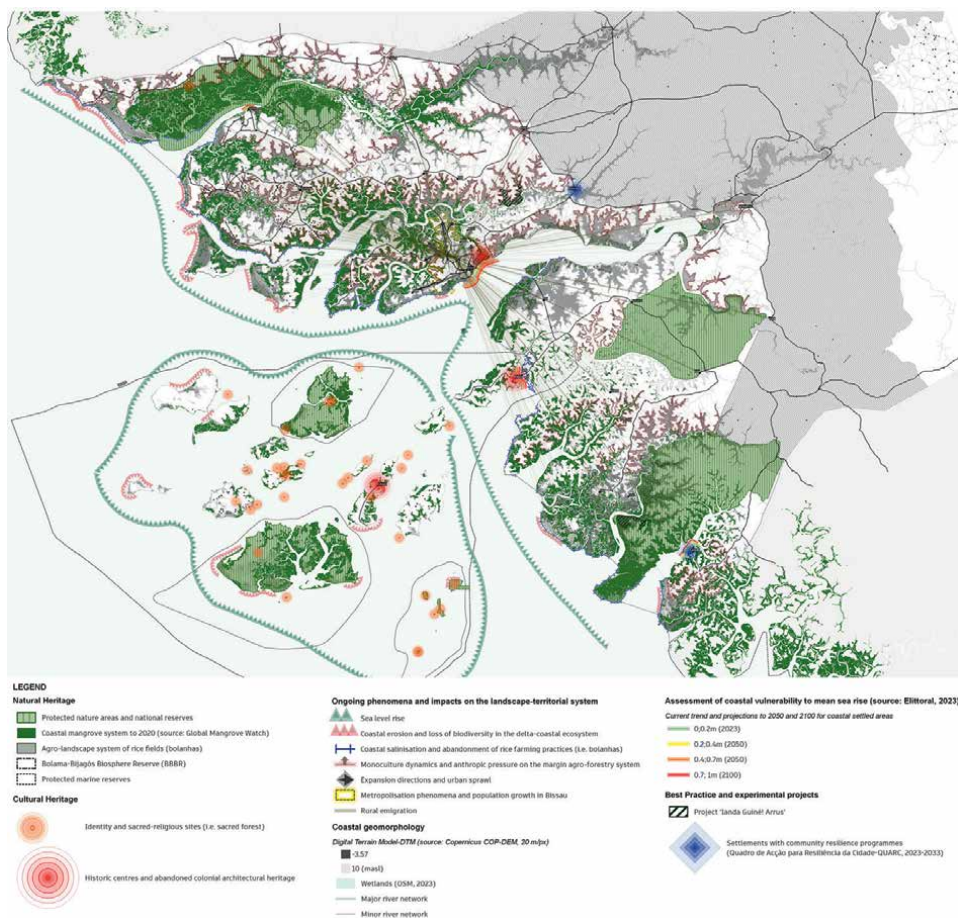


Figure 10.
'Scenario 0 - baseline scenario'. An updated overview of the criticalities and strengths of the GB coastal landscape and related LSs and LSSs. Edited by the authors.

These guidelines align with the landscape study presented while also adapting to the existing national legislative framework [41–46]. Furthermore, they draw upon the extensive fieldwork and research experience of a portion of the research team. Additionally, the proposed actions specifically target urban and landscape planning, as well as cultural heritage enhancement. They take into account ongoing projects (e.g., Project 'Ianda Guiné! Arrus', Quadro de Acção para Resiliência de Cidade, QUARC) and active strategies [23, 36, 47, 48].

The proposed scenario (i.e., cost-effectiveness scenario) (**Figure 11**) identifies objectives and actions to ensure adequate levels of liveability, territorial security, and environmental quality, in line with local socio-cultural traditions. It also aims to strengthen technical-administrative and political-institutional capacities [4, 49, 50] and align with national strategic policies [51, 52].

This initial set of strategies (i.e., environmental system) can be incrementally implemented in the short, medium, and long term, following a strategic vision that enhances: (i) the country's natural heritage, (ii) the quantity and quality of ecosystem services available to local populations, and (iii) the biophysical resilience (e.g., vegetation-soil systems) of landscape elements in response to extreme events and

Sl. No	Objectives				
1	Ensuring sustainable use of coastal natural resources				
2	Conservation of critical habitats				
3	Land degradation neutrality				
4	Strengthening coastal communities’ resilience				
5	Adapting land use and protecting critical public assets and services				
6	Ensuring resilient economy through inclusive development				
7	Ensuring effective planning and implementation through prioritization and continuous monitoring				
8	Protecting indigenous cultural heritage				
9	Increasing the available funds for local communities and institutions, by leveraging financial values of coastal ecosystems (climate finance)				
Strategies					
Environmental and landscape system		Historical-cultural and settlement system		Governance	
1	Preservation of the protected areas	9	Promotion of social and agro-productive projects for food security and landscape enhancement (i.e ARRUS Project)	18	Strengthening the governance of coastal and metropolitan areas
2	Extension of the National System of Protected Areas (SNAP)	10	Mainstreaming landscape enhancement, biodiversity conservation and climate change adaptation in the tourism sector	19	Developing and implementing climate finance mechanisms
3	Protection of the sacred areas	11	Strengthening the adaptation and resilience capacity of coastal communities to the climate change impacts		
4	Strengthening the ecological connectivity	12	Promoting active safeguarding of intangible identity heritage and traditional culture		
5	Protection and conservation of carbon sinks (mangroves, other forest, seagrass, ecc.)	13	Urban and architectural recovery of minor historic centers and widespread assets		
6	Reforestation of bare / sparse areas of the mangrove system	14	Containment of land take and urban sprawl and urban regeneration interventions		
7	Securing the coastal strip in response to climate change effects (sea level rise, coastal erosion, floods, etc.)	15	Coastal settlements’ adaptation to climate resilience projects		

8	Landscape enhancement through the recovery and diversification of subsistence agro-forestry pastoral activities and the reforestation of the sparse rainforest	16	Update of existing plan (Bissau) and development of urban plans for the main centers
		17	Development of urban planning tools for climate-environmental sustainability and community resilience

Table 2.
Objectives and project strategies, adapted from SETIN and PD consult [4].

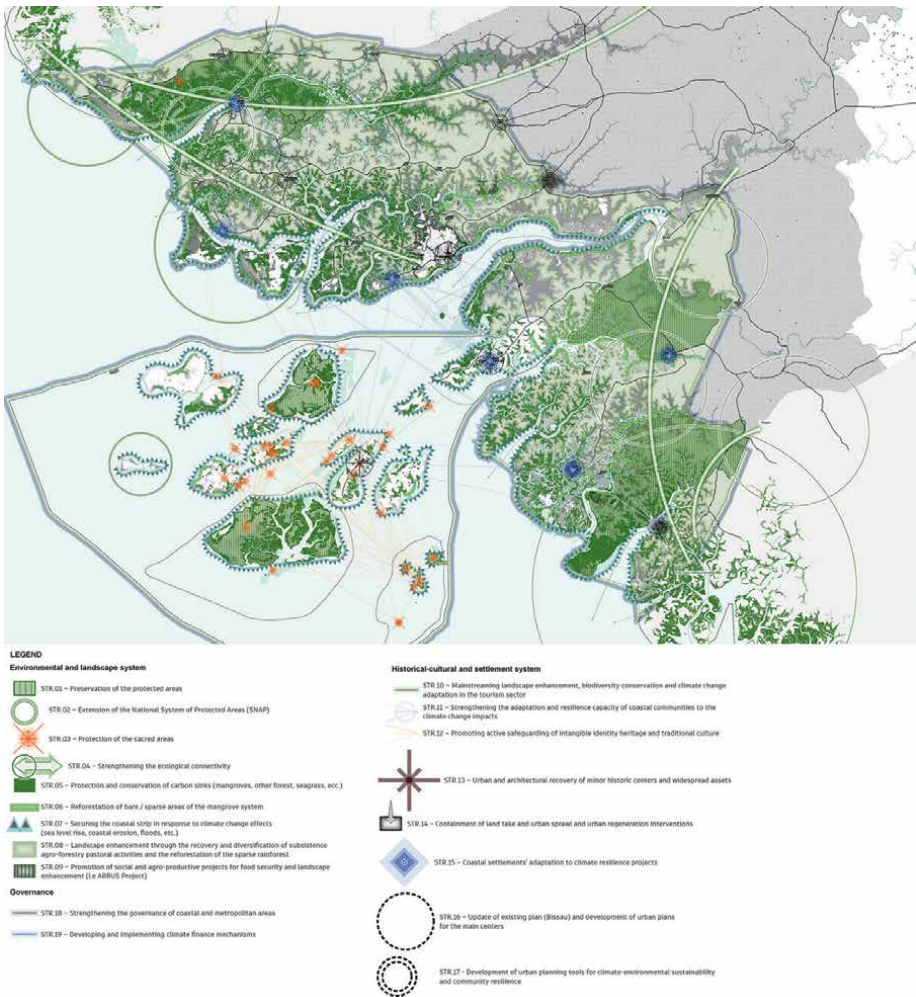


Figure 11.
'Scenario 1 - coastal resilience scenario'. The nineteen spatialised strategic goals. Edited by the authors.

ongoing environmental transformations. Conversely, safety measures function as a cross-cutting strategy affecting both the physical and infrastructural systems and coastal communities. These measures provide tools, viable alternatives (e.g., adaptation and resilience projects), and awareness-raising activities. Such guidelines could lead to a network of informed and equipped coastal communities capable of adapting to global and local changes while maintaining their strong connection with the deltaic and fluvial settlement patterns that characterise GB's seascape.

While natural heritage serves as a 'resilient infrastructure' in response to ongoing transformations, adaptive capacity cannot be fully realised without the implementation of (i) land and landscape governance tools, (ii) climate-proof urban plans, and (iii) recovery, restoration, and renovation plans for housing and historical architecture, particularly in historical centres. Planning instruments can address housing and social demands, particularly in Bissau, while simultaneously tackling contemporary challenges (e.g., climate, habitability, employment, resources, energy). These goals can be achieved through citizen engagement and a top-down/bottom-up approach (i.e., information-knowledge-planning). Where possible, these strategies could also support ecologically and culturally sustainable tourism.

The strategic scenario envisions a renewed coastal-landscape system for Guinea-Bissau, where both residents and institutions play a key role in responding to contemporary issues impacting the sustainability of coastal communities and their heritage.

5. Conclusions

The study contributes to the disciplinary debate on updating and developing knowledge frameworks in the era of climate change and multiple transitions, particularly in a region where updated data and applied research are critically scarce. The findings advance disciplinary approaches within the context of climate change, offering methods and insights to support coastal landscape planning, strengthen climate resilience, and promote sustainable development in West Africa. Conversely, the critical-evaluative analysis presented here is based primarily on indirect sources (e.g., reports, publications). This limitation may be addressed in the continuation of the research through field missions and the collection of specific data, which will support the development of analytical and strategic scenarios at the appropriate scales.

Given the interconnected dynamics between human activities (e.g., subsistence, mobility, trade, and production) and the quality of landscape primary elements—particularly soil and water, which are fundamental to human well-being—territorial governance plays a crucial role. In this context, identifying LSs and LSSs is a key step in advancing landscape knowledge and planning (protection, valorisation, and management). It provides a foundation for managing landscape quality and guiding transformations over time, both within and beyond formal landscape planning frameworks. As previously noted, defining these coastal landscape units is not a theoretical exercise. The four LSs represent the minimum landscape units at the macro scale, for which—while maintaining flexibility and allowing for finer-scale adjustments—specific planning guidelines can be established. These guidelines can then be refined at the micro scale for technical and design-oriented applications. The LSs and their respective LSSs are therefore instrumental in achieving the ultimate objective: adapting the coastal area to ongoing and projected climate impacts, considering cultural and natural diversity as well as the economic needs.

The establishment of a clearly defined coastal perimeter, the LSs approach, the 'baseline' and 'resilience' scenarios, and the broader reflections presented here serve as a

foundation for future work on Guinea-Bissau's maritime landscapes and seascapes or to other areas that present similar characteristics of transformation due to natural causes, human intervention, or both. This work must be carried out in collaboration with competent institutions and local communities to achieve landscape quality objectives while ensuring public safety and protecting both natural and cultural heritage.

While those and/or other strategies have yet to be implemented, it is important to underline that coastal landscape and urban planning is today a matter of significant interest for both the government and professionals in Guinea-Bissau (e.g., Law for Territorial and Urban Planning - 'Lei do Ordenamento Territorial e Urbano-LOTU'—currently a Draft Law pending approval by República da Guiné-Bissau (RGB)). In this regard, it is hoped that the research will be further developed, with a focus on high-priority intervention areas, through a downscaling approach applied to selected pilot areas.

In conclusion, the current trends and challenges are already affecting Guinea-Bissau's coastal area, local communities, and economic sectors due to weak planning capacities, lack of funding, limited human resources, and difficulties in implementing the extensive range of national and local strategies and programmes. In addition to these critical issues, there is a need to build an up-to-date knowledge base for coastal and urban planning processes, with a particular focus on: (i) establishing and regularly updating a multi-scale territorial topographic database using GIS-based techniques and geospatial tools (e.g., photogrammetry and drone mapping); (ii) exploiting existing and emerging satellite data archives to implement remote sensing analysis for environmental monitoring (e.g., through machine learning and geo-AI); and (iii) systematising existing knowledge and historical-archival sources in open-source geospatial formats, where possible (e.g., through WebGIS platforms). These ICT-oriented strategies can play a key role in supporting the management of spatial transformations and the conservation of natural and cultural heritage, particularly in view of future opportunities to develop predictive models based on temporal dynamics and time-series data.

Addressing these challenges requires political stability, capacity-building initiatives, and a comprehensive review of governance processes related to urban and landscape planning at all levels, taking into account site-specific issues. While these aspects extend beyond the scope of this paper, they are fundamental to ensuring that the proposed strategic objectives translate into concrete actions and become integral to the everyday management of Guinea-Bissau's landscape-environmental heritage.

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Conflict of interest

The authors declare no conflict of interest.

Appendix A

See **Figure A1**.



Figure A1
Other important coastal urban-rural settlements. From top to bottom, Cacheu and Cacine within LS no. 1, and Bolama and Bubaque within LS no. 4, are both in close contact with the coastal wetland system. Credits: Google Maps. Edited by the authors.

Appendix B

See **Figure B1**.

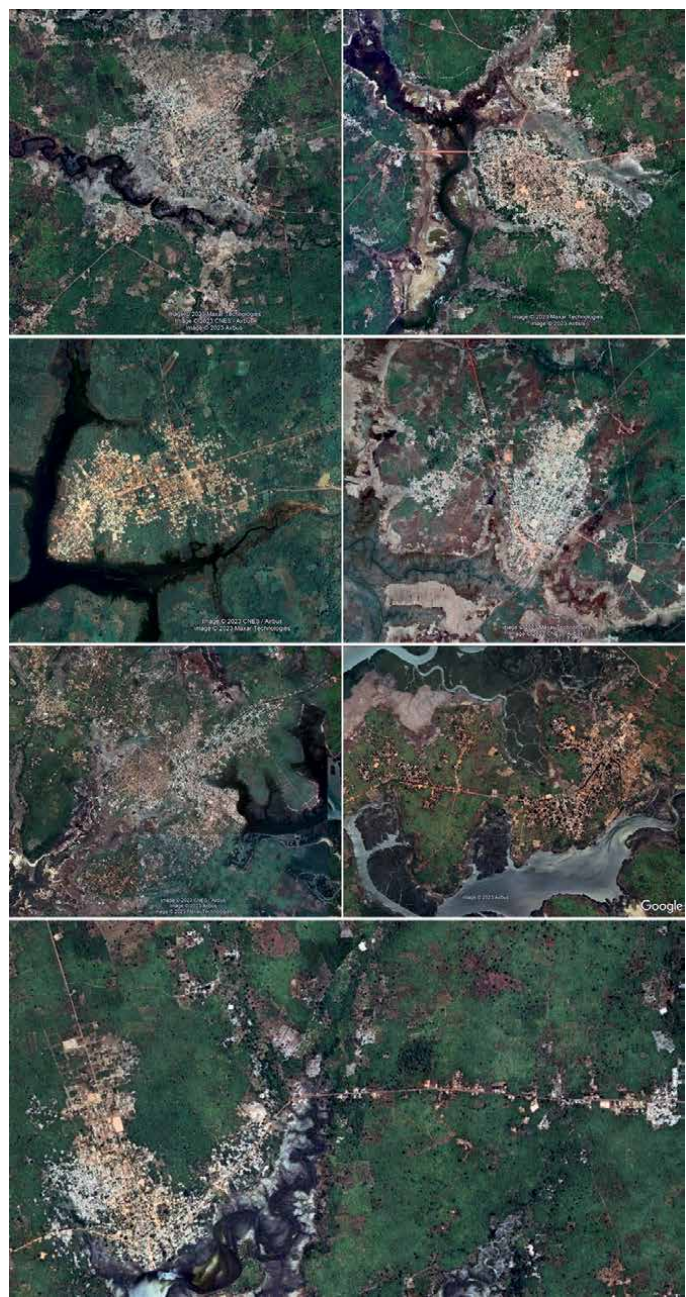


Figure B1.
Some of the urban-rural fringe settlements within LS no. 2 are in close contact with major rivers and the agroforestry landscape. From top to bottom: Bissorã, Buba, Canchungo (left side), Ingoré, Mansôa, São Domingos (right side), and Quinhamel (bottom). Credits: Google Maps. Edited by the authors.

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Climate-Resilient Biodiversity Refuges in Biosphere Reserves of the Cantabrian Cornice, Spain

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Abstract

This chapter presents a spatially explicit, climate-informed framework for identifying biodiversity refugia in two northern Spanish Biosphere Reserves—Picos de Europa and Urdaibai—under future climate scenarios. Using ensemble species distribution models (SDMs) for 58 species, we projected suitability across three future periods and four shared socioeconomic pathways (SSPs), employing downscaled outputs from ten general circulation models (GCMs) at 250 m resolution. We incorporated climatic, edaphic, and topographic predictors, including non-traditional variables such as evapotranspiration, to enhance ecological realism at local scales. Model outputs were synthesised using the Percentage of Climate Models Predicting Suitability (PCM-PS), a probabilistic metric that captures uncertainty and model agreement. We identified four types of refugia—retention, migration, transitional, and loss zones—offering a typology for conservation prioritisation. Results showed consistent warming trends (+1.4 to +4°C by 2100), with associated shifts in suitability, especially for mid-altitude and lowland species. Picos de Europa retained more areas of climatic persistence than Urdaibai, which faces greater risk of complete species loss due to its limited elevational buffering. The maps and classifications developed were co-produced with reserve stakeholders and are already being applied in spatial planning and restoration initiatives. Our approach aligns with emerging best practices in adaptive conservation, offering a replicable methodology for anticipating biodiversity change and guiding proactive management in mountainous Mediterranean systems. By integrating high-resolution climate projections, ensemble modelling, and stakeholder engagement, this work advances the operationalisation of climate-resilient biodiversity refugia in conservation planning.

Keywords: climate-resilient refugia, habitat suitability model, Cantabrian range, biodiversity refugia, climate change, biosphere reserves, adaptive conservation

1. Introduction

The interlinked crises of climate change and biodiversity loss represent two of the greatest environmental challenges of the twenty-first century. These dual threats are no longer considered isolated issues but rather interconnected phenomena that amplify each other's impacts. The Intergovernmental Panel on Climate Change (IPCC) and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) have clearly demonstrated how climate change affects ecosystems, disrupts species distributions, and alters essential ecosystem services, including water availability, carbon storage, and food provision. Against this backdrop, climate change adaptation has emerged as a fundamental pillar of conservation strategies at both global and local scales [1–4].

This chapter advances the concept of climate-resilient biodiversity refugia as a forward-looking strategy to enhance biodiversity conservation in the face of accelerating climate change. It explores how the integration of downscaled climate projections, habitat suitability modelling, and spatial analysis of ecological connectivity can inform adaptive conservation [5, 6]. Climate refugia are defined as areas that remain relatively buffered from climate extremes, serving as safe havens for species persistence and ecosystem stability. These zones function as “slow lanes” for biodiversity, enabling species and communities to endure and potentially adapt amidst accelerating environmental change [7–9]. Their significance is heightened in topographically complex regions, such as the Cantabrian Mountains, where a mosaic of microclimates supports diverse and often endemic biota.

Our analysis focuses on two emblematic protected areas in northern Spain—Picos de Europa and Urdaibai—both designated Biosphere Reserves. These areas represent contrasting ecological settings and altitudinal ranges, allowing a comparative exploration of climate-driven biodiversity dynamics. While protected, these reserves are not always aligned with future species range shifts, underscoring the need to revise static conservation boundaries through the lens of climate resilience [10–12].

To address this challenge, we employ a methodological framework that integrates downscaled projections from ten CMIP6 global circulation models (GCMs) under four Shared Socioeconomic Pathways (SSPs). These projections were regionalised to 250 m resolution using the FICLIMA approach to capture localised climate heterogeneity relevant to ecological processes [13]. This spatial framework enables the assessment of future suitability patterns for 58 plant species selected in collaboration with reserve managers.

Nested species distribution models (N-SDMs) were employed to estimate current and future habitat suitability, using ensemble modelling and a comprehensive set of 29 environmental predictors—including climatic and edaphic variables—following best practices in nested species distribution modelling [14, 15]. These projections were summarised using the Percentage of Climate Models Predicting Suitability (PCM-PS), which quantifies model consensus and supports robust identification of potential refugia.

In parallel, we incorporated principles from landscape ecology to characterise the spatial context of refugia, particularly in relation to ecological connectivity and fragmentation. This allowed us to identify areas not only of climatic stability but also of strategic importance for species movement and persistence [16, 17]. Our framework builds on the climate-smart conservation standards, a participatory and evidence-based approach for integrating climate adaptation into biodiversity strategies [18–20]. These standards guided the classification of refugia into four main types—retention, migration, transitional, and loss zones—each carrying distinct implications for

conservation and restoration actions. This holistic approach integrates ecological science, climate modelling, and stakeholder engagement to build adaptive capacity within protected areas.

Finally, we introduce the notion of biodiversity refugees—species or communities whose current habitats are projected to disappear entirely, necessitating active intervention such as assisted migration. While controversial, this approach may be essential to support species with limited dispersal capacity or those confined to climate-exposed lowlands. As such, climate-resilient refugia are not only conservation anchors but also dynamic platforms for adaptation, restoration, and the reconciliation of biodiversity and climate agendas in Mediterranean mountain landscapes.

2. Methods

2.1 Study area

The study was conducted in two Biosphere Reserves (BRs) located in the Cantabrian region of northern Spain: Picos de Europa and Urdaibai (**Figure 1**).

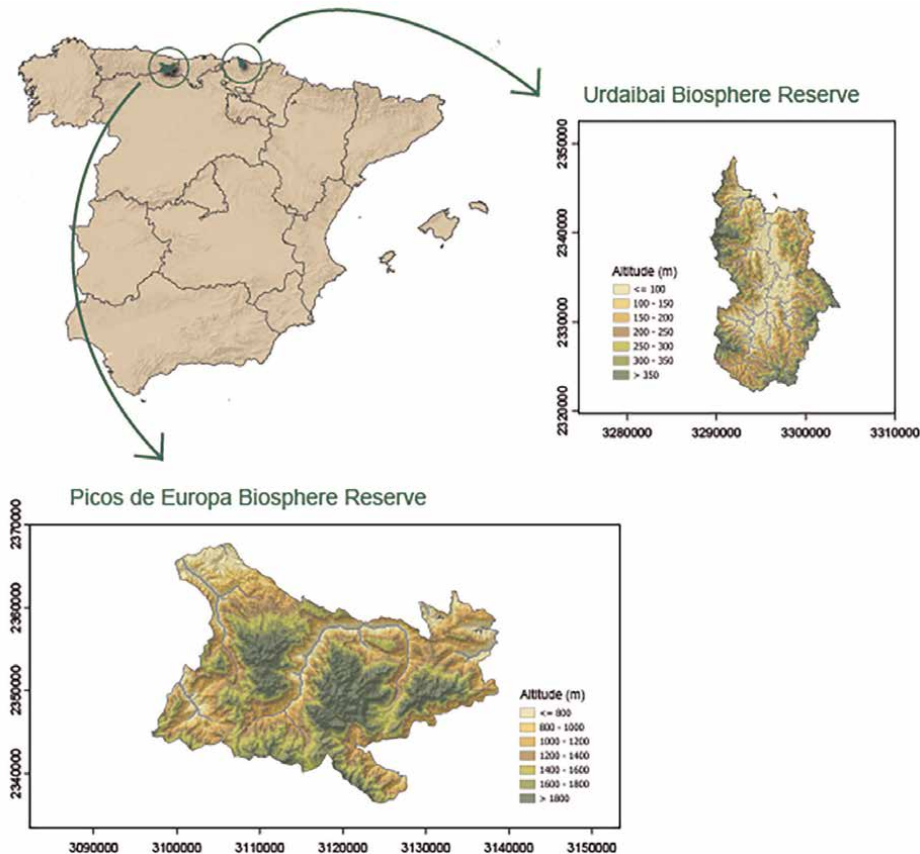


Figure 1.
Location of the biosphere reserves Picos de Europa and Urdaibai within the Spanish context.

These areas span several administrative regions, including the Autonomous Communities of Asturias and Cantabria, the Province of León in Castilla y León, and the Province of Biscay in the Basque Country. Together, the study area encompasses 31 municipalities, approximately 90% of which have fewer than 2000 inhabitants. Spanish Biosphere Reserves collectively cover 60,713 km², representing around 12% of the national territory. Specifically, Picos de Europa extends over approximately 646 km² (64,660 ha), while Urdaibai covers 220 km² (22,000 ha).

2.2 Data processing

2.2.1 Species data

The analysis began by delineating the study areas within each Biosphere Reserve and at the peninsular scale (**Figure 2, I.1**). A total of 58 species were selected through a participatory process involving reserve managers, who contributed expertise on ecologically and conservation-relevant species—particularly those that are threatened, endemic, montane, or water-dependent. Species were chosen based on data availability, ecological relevance, and modelling feasibility, with a focus on those with sufficient georeferenced records at both local and peninsular scales. This multi-scale selection enabled robust projections across contrasting biogeographic contexts [21]. Occurrence data were compiled from Global repositories (e.g., Global Biodiversity Information Facility, Botanical Information and Ecology Network), institutional inventories, Spanish National Forest Inventory, and local monitoring records, ensuring spatial completeness and ecological coherence. All data were standardised at 250 m resolution using raster formats to capture fine-scale variability and ensure compatibility with modelling tools. Harmonisation and preprocessing procedures ensured spatial alignment between species data and environmental layers.

2.2.2 Environmental variables

To support the identification of climate-adaptive biodiversity refugia, high-resolution climate scenarios were developed for the Picos de Europa and Urdaibai Biosphere Reserves (**Figure 2, I.2**). Baseline conditions (1985–2014) were defined using national meteorological records, ERA5 and ERA5-Land datasets, with quality control and homogenisation procedures applied to ensure reliability [22]. Future climate projections were derived from ten CMIP6 global climate models (GCMs) across four SSPs—SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 [2, 23]—and downscaled to 250 m resolution using FICLIMA, a two-step statistical methodology that combines analogue stratification with regression and probabilistic techniques [13]. This framework enabled the generation of daily projections for three timeframes: 2021–2050, 2041–2070, and 2071–2100.

For each reserve, spatial layers were produced for 40 scenario combinations (10 GCMs × 4 SSPs), including monthly climate means and derived indicators such as PET, SPI, SPEI, and over 25 bioclimatic variables (see Appendix 1) [24, 25]. These data supported subsequent ecological and hydrological modelling. A total of 29 predictors were selected for species distribution modelling: 11 temperature-related, eight precipitation-related, six linked to evapotranspiration, and four soil variables (e.g., pH and organic carbon)—including soil organic carbon, nitrogen, pH, and sand content—were selected for their physiological relevance. All layers were resampled to 250 m using bilinear interpolation for continuous variables and nearest-neighbour

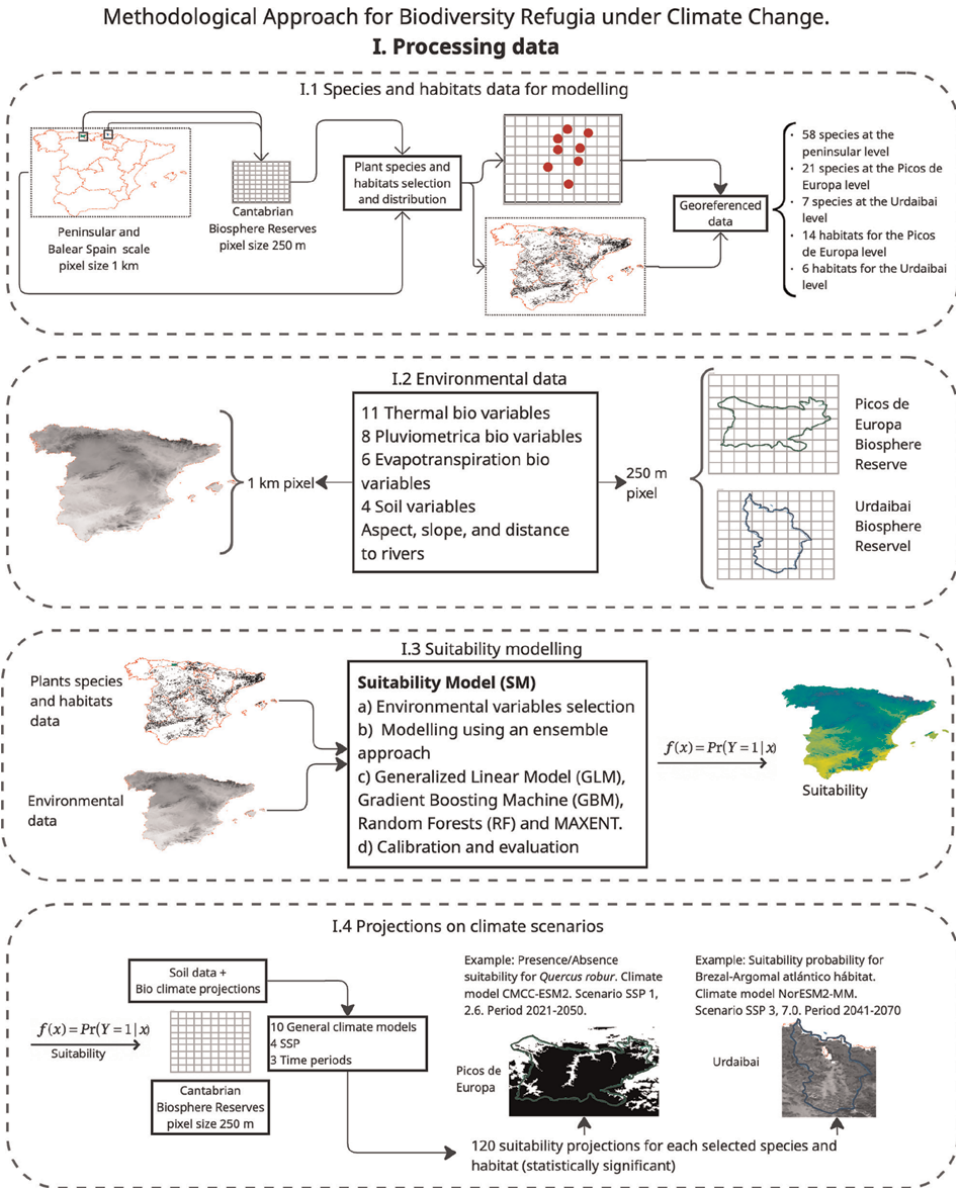


Figure 2.
This infographic summarises the data processing steps.

methods for categorical ones. Climate data originated from downscaled CMIP6 projections developed in the FICLIMA project (AEMET), while soil variables were sourced from SoilGrids v2.0 [26], and variable definitions from [27].

2.2.3 Species distribution modelling

To assess the impacts of climate change on biodiversity in the Picos de Europa and Urdaibai Biosphere Reserves, we implemented a multi-scale modelling framework (Figure 2, I.3) aligned with the conceptual structure of the ForesteCCo and

ReBioCCAN projects and grounded in recent advances in species distribution modelling [15, 28]. The models were calibrated at the peninsular scale using species records from Spain's, then reprojected at higher resolution for each reserve, capturing broad ecological gradients while refining predictions at local scales [28].

Environmental predictors, including bioclimatic and soil variables, were screened for multicollinearity and ecological relevance [29]. Models were calibrated through an ensemble approach combining GLM, RF, and GBM algorithms [30, 31], implemented using the *sabinaNSDM* R package [21, 32]. Occurrence records were complemented with pseudo-absences generated *via* random sampling background correction, and spatial filtering to reduce sampling bias and clustering artefacts [33–35]. Each algorithm was run 10 times with 80:20 train-test splits and fivefold cross-validation. Performance was evaluated using AUC, TSS, retaining only models with $AUC \geq 0.8$ [36]. Reserve level downscaled predictions were obtained through nested species distribution models (N-SDMs), in which peninsular-scale models were refined using covariate-weighted ensembles and multiplicative integration, thereby enhancing spatial precision and reducing overprediction [28]. All steps were executed in automated, version-controlled workflows, with outputs stored in GeoTIFF format, enabling reproducibility and future updates. This framework supports robust future suitability projections and informs spatial conservation planning under climate change.

2.2.4 Projected suitability under future climate scenarios

Future climate projections for the Picos de Europa and Urdaibai Biosphere Reserves each suitability model was projected under the full combination of GCMs, SSPs, and time slices, resulting in a total of 120 future scenarios per species. To synthesise these outputs, we calculated the Percentage of Climate Models Predicting Suitability (PCM-PS) for each grid cell and scenario. This metric represents the proportion of GCMs that agree on suitable conditions for a given species under a specific SSP and time horizon. Maps of PCM-PS provide a clear visualisation of climate model agreement, highlighting areas where future suitability is consistently predicted across multiple climate models.

This approach supports adaptive conservation planning by emphasising zones of potential persistence or emergence of suitable conditions under climate change [28, 37]. By focusing on PCM-PS, it avoids the complexity of additional certainty indices while maintaining transparency and interpretability for managers and decision-makers. These synthesised suitability maps provided the foundation for defining and classifying biodiversity refugia under future climate scenarios.

2.3 Definition of biodiversity refugia

To delineate areas with the potential to support biodiversity under changing climatic conditions, we integrated current suitability distributions with projections across multiple future scenarios (**Figure 3**). A central element of this process was the use of the Percentage of Climate Models Predicting Suitability (PCM-PS), calculated as the average across the four Shared Socioeconomic Pathways (SSPs) for each time horizon, thereby providing a robust synthesis of model agreement across contrasting emission trajectories. This methodology facilitated the identification of zones where multiple climate models converge in predicting sustained suitability across time periods and socioeconomic contexts. By coupling baseline and future suitability maps within a spatially explicit framework, we established a classification system for

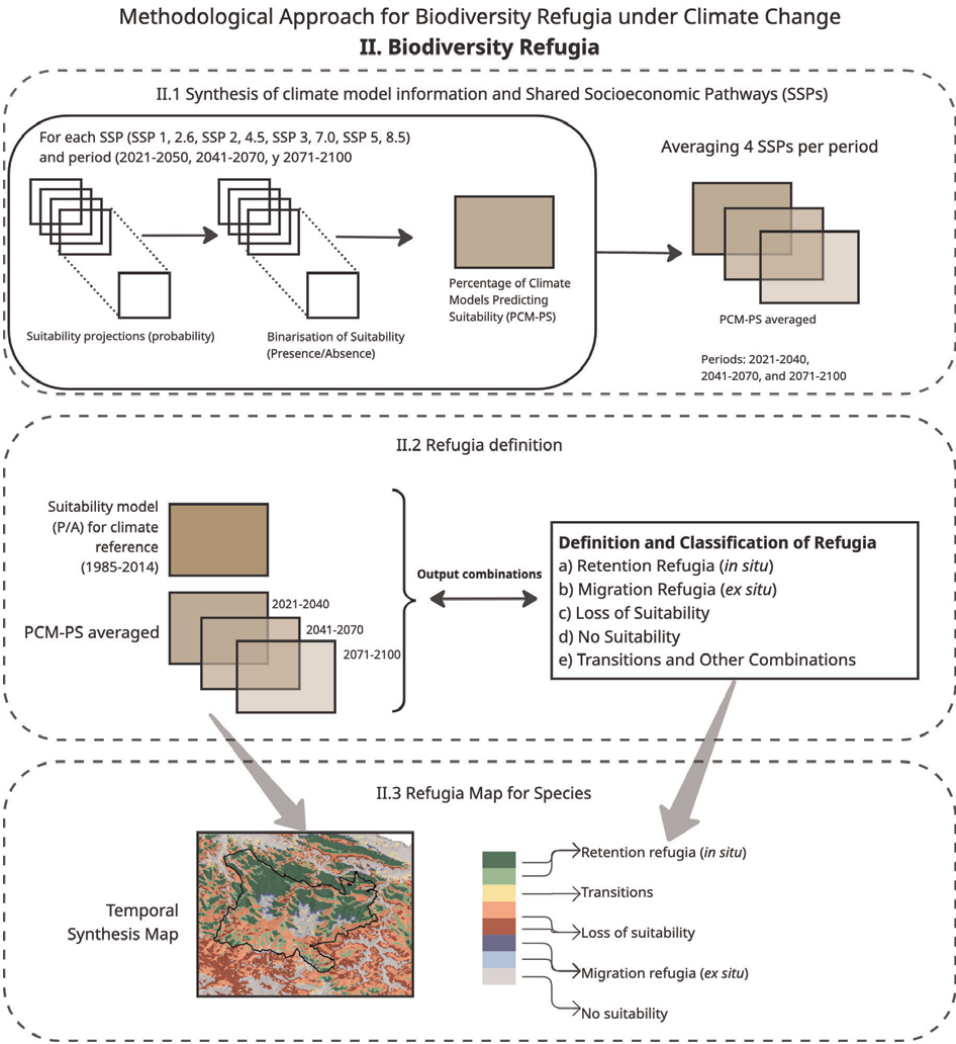


Figure 3.
This infographic summarises the biodiversity refugia.

biodiversity refugia and other areas of interest, enabling targeted conservation planning and adaptive management in the face of climate change (**Figure 3, II.1**).

Refugia were conceptualised as areas that either maintain suitable conditions over time, become newly suitable in the future, or serve as transitional spaces where suitability fluctuates (**Figure 3, II.2**). Specifically, we defined retention refugia as locations that are currently suitable for a given species and are projected to remain so throughout the twenty-first century. These areas, characterised by high PCM-PS values across all scenarios and time periods, are considered critical strongholds for *in situ* conservation, providing stability amid climate-driven environmental shifts [7, 8].

In contrast, migration refugia, sometimes referred to as emerging refugia, are zones that lack current suitability but are projected to develop favourable conditions in future decades. These areas represent opportunities for proactive management, such as habitat restoration or assisted colonisation, to facilitate biodiversity adaptation as climate envelopes shift [38, 39].

We also recognised transitional areas, where suitability does not follow a linear trajectory but instead varies across time slices and scenarios. These zones may reflect ecological thresholds, microclimatic heterogeneity, or model variability, and they could function as stepping stones or temporary refuges that support species movement through fragmented landscapes.

Additionally, we identified zones of lost suitability, where currently suitable conditions are predicted to disappear entirely under all future scenarios. These areas may hold limited long-term conservation value for the target species or habitats but could still serve important roles for other ecological functions.

Finally, non-refugia were defined as areas that remain unsuitable across all periods and scenarios, indicating low potential for climate-driven colonisation or persistence.

3. Results

This section summarises the key results, including projected climate changes, suitability patterns, and biodiversity refugia. Given the extensive number of environmental and biological datasets, the complete outputs are available online (URL). The online repository includes interactive maps and downloadable datasets to support further analysis and conservation planning. Selected examples are presented here to illustrate the main patterns.

3.1 Future climate in the biosphere reserves

3.1.1 Reference climate (1985–2014) and projected future climate

For each of the Biosphere Reserves, future climate projections were computed using 10 general circulation models (GCMs) [37], across all SSPs and climate periods, resulting in a total of 120 projections. Each projection includes 29 environmental data layers as previously described.

As an example of the climate projections, **Figure 4** shows the annual mean temperature for the Picos de Europa Biosphere Reserve. The figure illustrates changes and increases in temperature across the three time horizons for two contrasting SSPs

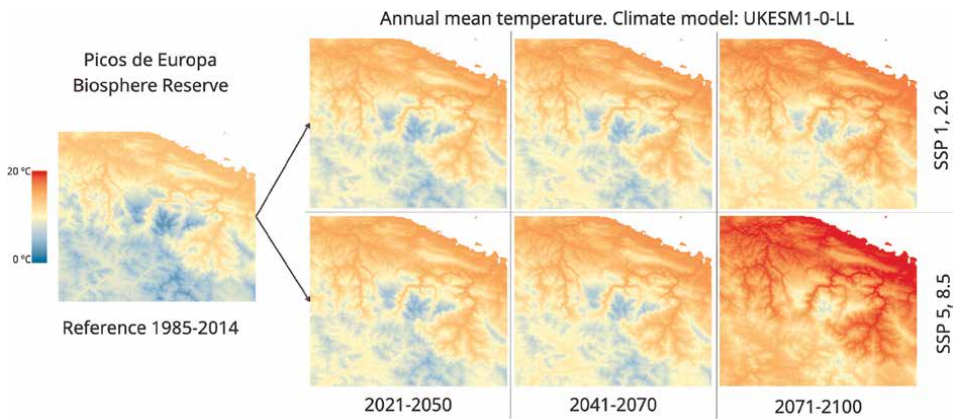


Figure 4. Annual mean temperature in the Picos de Europa biosphere reserve, based on the UKESM1-0-LL climate model, for SSP1-2.6 and SSP5-8.5 across three future climate horizons.

(SSP1-2.6 and SSP5-8.5), relative to the baseline period. For both SSPs, differences are minimal during the first climate period (2021–2050); however, a pronounced increase in temperature is evident by the final period (2071–2100). This pattern highlights the increasing divergence between low- and high-emission pathways over time.

These changes and differences between SSPs, incorporating outputs from 10 climate models, can be visualised through a comparative graphical analysis. **Figure 5** presents boxplots for four key climate variables—annual mean temperature, total annual precipitation, total annual evapotranspiration, and minimum temperature of the coldest month—for both Biosphere Reserves. Each boxplot displays the median, the 10th and 90th percentiles, and outliers of the variable’s frequency distribution. Boxplot colours indicate the SSPs, while line patterns (solid, dashed, and fine-dashed) denote whether changes relative to the baseline period are statistically significant.

Although Picos de Europa and Urdaibai differ markedly in altitude and topography, the four climate variables display broadly similar temporal trends in both

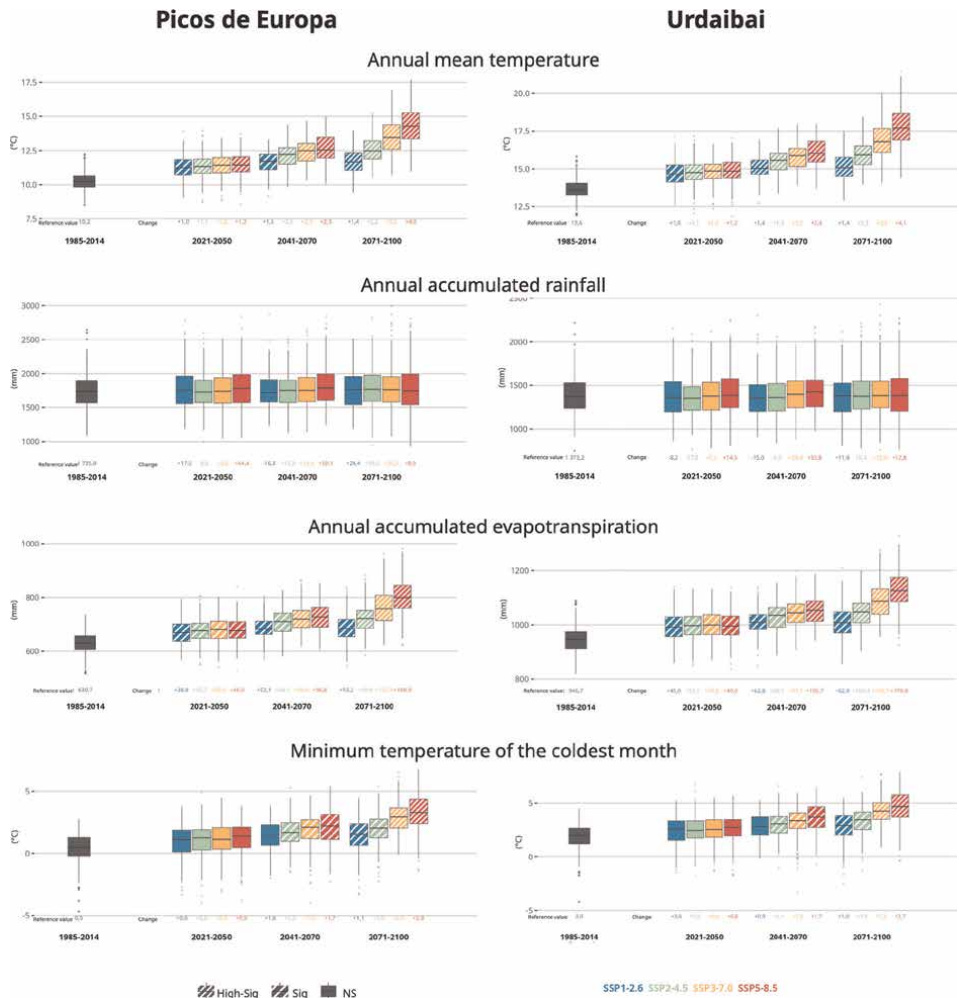


Figure 5. Comparative boxplots of four key climate variables—annual mean temperature, total annual precipitation, total annual evapotranspiration, and minimum temperature of the coldest month—for the Picos de Europa and Urdaibai biosphere reserves.

reserves. For annual mean temperature, projections under all SSPs remain relatively close during the first period (2021–2050) yet already show statistically significant increases compared to the baseline. As the century progresses, differences between emission scenarios become more pronounced. By 2071–2100, temperatures are projected to rise by approximately 4°C under the high-emission scenario (SSP5-8.5), while increases remain more moderate at around 1.4°C under the low-emission scenario (SSP1-2.6).

In contrast, total annual precipitation shows no significant deviations from baseline values, with little variation among scenarios or time horizons. Evapotranspiration patterns closely mirror those of temperature, although slightly greater increases are observed in Urdaibai than in Picos de Europa during the final period. Finally, the minimum temperature of the coldest month remains largely unchanged in the near future but begins to rise noticeably from mid-century onwards, reaching increases of up to 1.7°C under SSP5-8.5.

3.2 Current suitability patterns

Based on the suitability distribution patterns of the 58 selected species, we conducted a visual analysis of each distribution map. Combined with the evaluation of statistical values and other key attributes, this allowed us to classify the species into six principal groups, whose characteristics are summarised in **Table 1**. It is important to note that the visual analysis was conducted across the entire extent of the study areas, including certain details beyond the boundaries of the Biosphere Reserves themselves.

Group A—Widespread Cantabrian Species (11 species), includes those with the broadest representation across the Cantabrian Range, displaying continuous distributions along altitudinal gradients—from low elevations near sea level in Urdaibai to high mountain zones in Picos de Europa. Group B—Picos de Europa-dominant Species (12 species) is characterised by a strong presence and distribution in Picos de Europa, while exhibiting limited occurrence in Urdaibai. Conversely, Group C—Urdaibai-dominant Species (9 species) shows significant distribution in Urdaibai but much lower presence in Picos de Europa.

Group D—Picos de Europa-exclusive Species (11 species) comprises species almost exclusively associated with Picos de Europa, whereas Group E—Urdaibai-exclusive Species (2 species) is restricted to Urdaibai. Finally, Group F—Low Suitability Species (12 species) contains species with little or no predicted suitability in either reserve, despite achieving relatively high AUC values in the models. Notably, one species—*Limodorum abortivum*—shows no suitability across the entire extent of both Biosphere Reserves.

As a representative example of Group A, the suitability distribution pattern for *Fagus sylvatica* is shown in **Figure 6**. In Urdaibai, suitable areas range from approximately 150 m to the highest altitudes of the reserve (~250 m). A similar distribution is observed in Picos de Europa, where suitability spans mid-altitudes between 150 m and 1300 m.

Figure 7 presents the suitability distribution of four species, two species *Q. petraea* and *C. caudata* from Group B—Picos de Europa-dominant, and two species *Gentiana lutea* and *Potentilla nivalis* for Group D—Picos de Europa-exclusive. Species in Group B exhibit a broad altitudinal distribution. *Carex caudata* tends to occur at higher elevations, whereas *Quercus petraea* displays a wider range, extending from coastal areas to the southern slopes, but is absent from the highest altitudes. In contrast,

Classification group	Group description	Species	Calibration	P_URD	ROC_U	P_PE	ROC_PE	Environmental Variables
A (11 Spp)	Species in group A exhibit a high probability of suitability in both Biosphere Reserves, with statistical AUC values exceeding 0.93. The presence data used for model calibration include more than 20 records for all species, with many exceeding 100 occurrences. For Picos de Europa, the species generally show a higher number of presence records compared to Urdaibai.	<i>Ilex aquifolium</i>	6936	>20	0.935	>20	0.935	BIO12, BIO14, BIO05, BIO02, BIO43, BIO15, BIO06
		<i>Fagus sylvatica</i>	6322	>20	0.969	>20	0.965	BIO01, BIO15, BIO14, BIO41, BIO12, BIO04, BIO45
		<i>Ulex galli</i>	2270	>20	0.963	>20	0.963	BIO06, BIO09, BIO12, BIO14, BIO03, BIO02, Sand
		<i>Erica vagans</i>	1393	>20	0.963	>20	0.963	BIO15, BIO07, BIO01, BIO17, BIO19, BIO03, Sand
		<i>Erica tetralix</i>	352	2	0.906	>20	0.912	BIO12, BIO09, BIO11, BIO15, BIO07, Sand, BIO03
		<i>Narcissus pseudonarcissus</i>	171	2	0.946	>20	0.946	BIO12, BIO01, BIO04, BIO02, BIO14, BIO15, Sand
		<i>Erica ciliaris</i>	159	3	0.963	7	0.965	BIO04, BIO15, N, BIO06, BIO13, BIO02, BIO14
		<i>Vandenboschia speciosa</i>	77	9	0.983	4	0.983	N, BIO02, BIO14, BIO03, BIO04, Sand, BIO15
		<i>Hymenophyllum tunbrigense</i>	54	1	0.984	12	0.984	BIO04, BIO14, BIO13, BIO15, BIO02, BIO09
		<i>Cudita macrocarpa</i>	42	2	0.982	18	0.982	BIO15, BIO44, BIO02, N, BIO14, BIO13
		<i>Hornium pyrenaicum</i>	24	0	0.975	2	0.963	BIO14, BIO15, BIO13, BIO01, BIO02
		<i>Quercus petraea</i>	2462	6	0.953	>20	0.953	BIO14, BIO07, BIO41, BIO01, BIO12, BIO15, Sand
B (12 Spp)	Species in group B exhibit a high probability of suitability in the Picos de Europa Biosphere Reserve but medium to low suitability in the Urdaibai Biosphere Reserve. Statistical AUC values are consistently high, exceeding 0.90. The presence data used for model calibration include more than 20 records for all species, with many exceeding 40 occurrences. In Picos de Europa, species generally have a higher number of presence records, whereas in Urdaibai, records are sparse or absent for many species.	<i>Calluna vulgaris</i>	1798	4	0.908	>20	0.908	BIO01, SOC, BIO15, BIO14, BIO12, Sand, BIO41
		<i>Sideritis hysopifolia</i>	380	6	0.954	>20	0.954	BIO01, BIO15, BIO07, BIO17, BIO12, BIO43, Sand
		<i>Campanula trachelium</i>	229	0	0.92	14	0.92	BIO17, Ph, BIO07, BIO15, BIO03, SOC, Sand
		<i>Luzula sylvatica</i>	197	2	0.913	7	0.905	BIO12, BIO01, BIO07, BIO14, BIO45, BIO43, BIO03

Classification group	Group description	Species	Calibration	P_URD	ROC_U	P_PE	ROC_PE	Environmental Variables
C (9 Spp)	Species in group C exhibit a high probability of suitability in the Urdaibai Biosphere Reserve, while suitability in the Picos de Europa Biosphere Reserve is generally medium to low. Statistical AUC values remain acceptable, exceeding 0.75. Presence data for model calibration are substantial, with more than 30 records for half of the species and four species (>40%) with over 1000 occurrences. Nearly all species in this group have presence records in both reserves.	<i>Comallaria majalis</i>	73	0	0.931	1	0.944	Ph, BIO14, BIO43, SOC, BIO01, Sand, BIO03
		<i>Lilium pyrenaicum</i>	64	1	0.973	3	0.973	BIO14, BIO02, BIO04, Sand, BIO12, BIO01
		<i>Carex caudata</i>	57	0	0.977	20	0.982	BIO15, BIO04, BIO14, BIO43, BIO01, BIO02
		<i>Platanthera chlorantha</i>	46	0	0.89	2	0.905	Ph, BIO02, SOC, BIO15, BIO14, BIO03
		<i>Geum pyrenaicum</i>	45	0	0.978	12	0.979	BIO01, BIO13, BIO14, BIO45, BIO43, BIO15
		<i>Rorippa islandica</i>	36	0	0.937	10	0.918	BIO14, BIO15, BIO01, BIO07, BIO43, BIO45
		<i>Pseudorchis albida</i>	18	0	0.957	1	0.961	BIO01, BIO14, N, BIO04, BIO45
		<i>Quercus ilex</i>	42,059	>20	0.756	>20	0.748	Ph, N, BIO09, BIO12, BIO04, BIO42, BIO11
		<i>Quercus robur</i>	10,000	>20	0.961	>20	0.955	BIO12, BIO14, BIO03, BIO41, BIO02, BIO06, BIO15
		<i>Arbutus unedo</i>	7940	>20	0.896	>20	0.896	N, BIO01, BIO15, BIO03, BIO17, BIO12, BIO04
		<i>Phillyrea latifolia</i>	3081	>20	0.928	14	0.93	SOC, Sand, BIO09, BIO15, BIO06, BIO13, Ph
		<i>Dryopteris aemula</i>	112	19	0.977	9	0.981	BIO04, BIO14, Ph, BIO15, Sand, BIO13, BIO45
		<i>Woodwardia radicans</i>	81	17	0.989	4	0.989	N, Ph, BIO02, BIO14, Sand, BIO04, BIO03
		<i>Herniaria ciliolata</i>	41	3	0.852	1	0.879	BIO04, BIO14, BIO06, BIO41, BIO03, BIO45
		<i>Carpinus betulus</i>	39	1	0.887	0	0.884	BIO17, BIO06, BIO07, BIO16, N, BIO45
		<i>Cortaderia seloana</i>	30	0	0.774	0	0.762	BIO06, BIO45, BIO17, BIO07, BIO03

Classification group	Group description	Species	Calibration	P_URD	ROC_U	P_PE	ROC_PE	Environmental Variables
D (11 Spp)	Species in group D exhibit a high probability of suitability exclusively in the Picos de Europa Biosphere Reserve. Statistical AUC values are consistently high, exceeding 0.92. The presence data used for model calibration include more than 20 records for all species. Many species in this group have a large proportion of their presence records located within the reserve relative to the total number of calibration records.	<i>Gentiana lutea</i>	156	0	0.977	17	0.977	BIO01, NN, BIO03, BIO14, Sand, BIO13, BIO15
		<i>Arnica montana</i>	103	0	0.962	6	0.962	BIO01, BIO14, N, Ph, BIO13, BIO43, BIO04
		<i>Saxifraga praetermissa</i>	71	0	0.995	>20	0.995	BIO10, BIO13, BIO14, BIO11, Ph, BIO04, BIO03
		<i>Menyanthes trifoliata</i>	62	0	0.922	5	0.922	BIO01, BIO14, BIO43, BIO12, BIO45, BIO15
		<i>Carex parviflora</i>	54	0	0.986	17	0.99	BIO11, BIO10, BIO14, BIO15, BIO04, BIO09
		<i>Huperzia selago</i>	37	0	0.97	3	0.97	BIO01, BIO17, BIO45, BIO04, Sand, BIO15
		<i>Callitriche palustris</i>	33	0	0.969	10	0.971	BIO09, BIO10, BIO11, BIO02, N, BIO14
		<i>Carex capillaris</i>	30	0	0.965	2	0.937	BIO11, BIO09, BIO14, BIO45, BIO12
		<i>Potentilla nivalis</i>	23	0	0.964	>20	0.996	BIO09, BIO17, N, BIO03, Sand
		<i>Gymnadenia odoratissima</i>	22	0	0.936	9	0.936	Sand, BIO02, BIO04, BIO17, BIO43
E (2 Spp)	Group E comprises only two species, which exhibit a high probability of suitability exclusively in the Urdaibai Biosphere Reserve. Their statistical AUC values range between 0.72 and 0.90, indicating moderate to high model performance. Presence data for model calibration exceed 60 records, although only a small proportion of these records are located within the reserve.	<i>Campanula latifolia</i>	20	0	0.945	3	0.945	BIO01, BIO15, BIO14, BIO07, BIO13
		<i>Utricularia australis</i>	87	0	0.727	0	0.731	Ph, BIO05, N, BIO08, BIO15, BIO03, BIO19
		<i>Suaeda maritima</i>	62	8	0.877	0	0.868	BIO06, BIO02, BIO14, BIO04, BIO12, Sand
F (12 Spp)	Group F includes species with low or negligible probability of suitability in either of the Biosphere Reserves. Statistical AUC values are generally acceptable, exceeding 0.78 for all species, with some reaching values above 0.95. Approximately 50% of the species have more than 100 presence records for model calibration, although none exceed 500 occurrences.	<i>Ruscus aculeatus</i>	483	0	0.787	8	0.793	SOC, BIO06, Ph, BIO44, BIO19, BIO09, BIO14
		<i>Taxus baccata</i>	382	6	0.858	9	0.86	SOC, BIO02, BIO41, BIO01, BIO04, BIO03, BIO19
		<i>Equisetum hyemale</i>	233	3	0.915	4	0.923	BIO14, Ph, BIO19, BIO01, N, BIO03, BIO07

Classification group	Group description	Species	Calibration	P_URD	ROC_U	P_PE	ROC_PE	Environmental Variables
		<i>Leucanthemum maximum</i>	189	0	0.887	0	0.928	N, BIO17, BIO01, BIO04, Ph
		<i>Zostera noltii</i>	146	3	0.817	0	0.853	BIO02, BIO04, BIO15, Sand
		<i>Daboecia cantabrica</i>	44	5	0.939	>20	0.941	BIO04, BIO01, BIO14, BIO12, Sand, BIO02, BIO15
		<i>Geranium pratense</i>	37	0	0.96	4	0.958	Ph, BIO01, BIO14, BIO43, BIO15, BIO45
		<i>Phlegopteris cornectilis</i>	20	0	0.993	2	0.993	BIO05, BIO15, BIO13, BIO45, BIO43, BIO04
		<i>Salix breviserrata</i>	18	0	0.978	17	0.993	BIO10, BIO11, BIO03, BIO09, BIO17
		<i>Aquilegia pyrenaica</i>	18	0	0.935	18	0.98	BIO10, BIO09, BIO04, BIO11, Ph
		<i>Nothofarsia spricata</i>	12	0	0.957	10	0.942	BIO41, N, BIO15, BIO04
		<i>Sonchus maritimus</i>	9	1	0.811	0	0.811	Ph, BIO45, Sand, BIO19, BIO04, BIO05, BIO02

Table 1. Classification of the 58 selected species into six main groups based on visual analysis of their suitability distribution patterns, supported by statistical metrics and key ecological attributes.

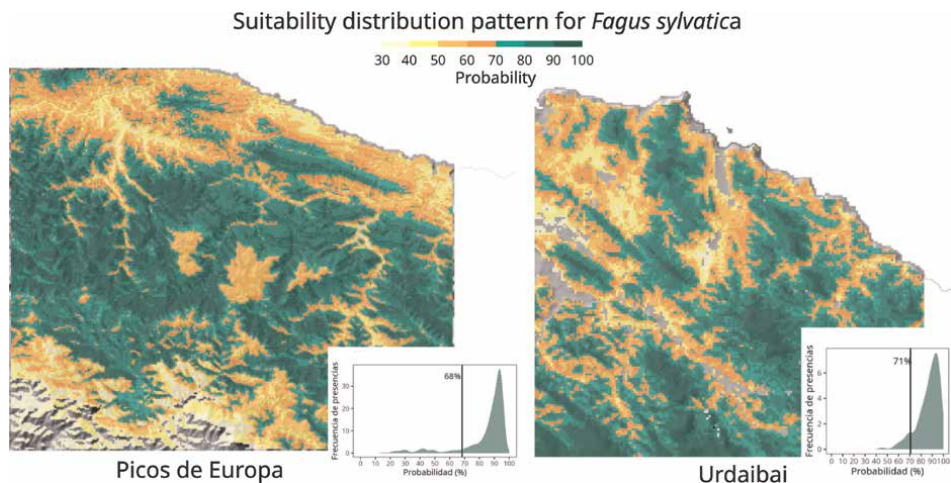


Figure 6.
Suitability distribution for *Fagus sylvatica* in the Picos de Europa and Urdaibai biosphere reserves. The lower panel shows the frequency distribution of probability values, with the threshold for statistical presence indicated.

species in Group D are primarily distributed on the southern slopes and at higher altitudes, a characteristic shared by nearly all species in this group.

Groups C and E are represented in **Figure 8** by three species. Within Group C, *Quercus robur* exhibits broad suitability across nearly the entire area, while *Phillyrea latifolia* is mainly associated with low to mid-altitudes within the Urdaibai Biosphere Reserve, forming a restricted fringe.

For Group E, which comprises only two species, *Suaeda maritima* displays a highly restricted distribution confined to lowland areas near the coast (rías). It is important to note that these two Group E species have no recorded presence within the study area; however, they were modelled using more than 60 occurrence records from other regions for calibration purposes.

3.3 Species suitability under future climate scenarios

Suitability under future climate scenarios was projected for all species and habitats, considering three future periods (2021–2050, 2041–2070, and 2071–2100) and four SSP carbon emission scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5). As described in the methods, the 120 resulting projections were summarised by calculating both the median and the Percentage of Climate Models Predicting Suitability (PCM-PS). **Figure 8** illustrates these projections for *Fagus sylvatica* in the Picos de Europa biosphere reserve, as an example representative of the 58 modelled species.

In the first horizon (2021–2050), we already see a noticeable reduction in the extent of suitable areas compared to the current distribution (**Figure 6**). This pattern remains broadly consistent across all SSP scenarios. Over the subsequent horizons, the contraction of suitability continues, and there is a subtle but clear shift of suitable areas towards higher elevations. These changes are particularly pronounced under the more severe SSP scenarios. Such trends are closely linked to key bioclimatic variables —BIO01, BIO41, BIO04, and BIO45—whose increasing values appear to drive the species' range upwards along the altitudinal gradient.

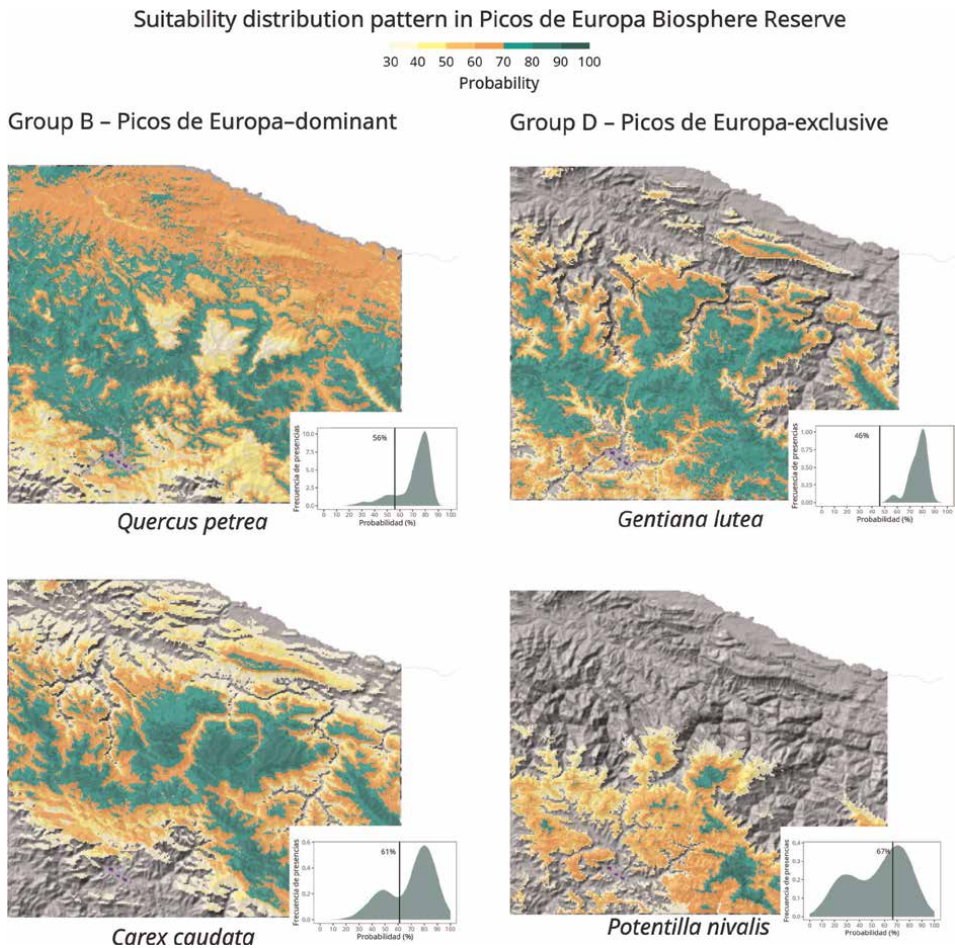


Figure 7. Suitability distribution for *Quercus petraea* and *Carex caudata* (Group B—Picos de Europa-dominant) and *Gentiana lutea* and *Potentilla nivalis* (Group D—Picos de Europa-exclusive). The lower panels show the frequency distribution of suitability probability values for each species, with thresholds for statistical presence indicated.

3.4 Biodiversity Refugia

3.4.1 Biodiversity refugia map type

To illustrate how refugium maps can be interpreted for each species, we present a representative example (**Figure 9**). The maps reflect their use during workshops with stakeholders from the Biosphere Reserves. The refugium categories shown correspond to the definitions described in the methodology section.

3.4.2 Biodiversity refugia classification

Through a detailed examination of the refugium distribution patterns for each species in the Picos de Europa and Urdaibai Biosphere Reserves, we were able to identify distinct types of refugia, each shaped by specific ecological and spatial characteristics within the reserves.

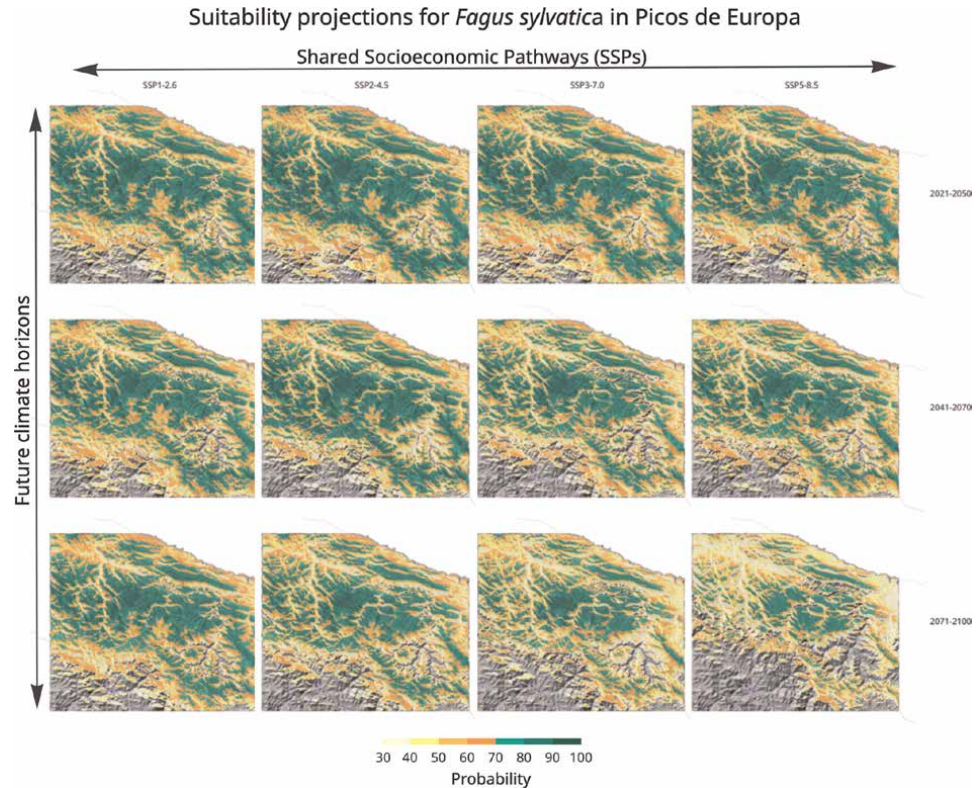


Figure 8.
Projected suitability for *Fagus sylvatica* in the Picos de Europa Biosphere Reserve, across three time horizons (2021–2050, 2041–2070, 2071–2100) and four SSP scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5).

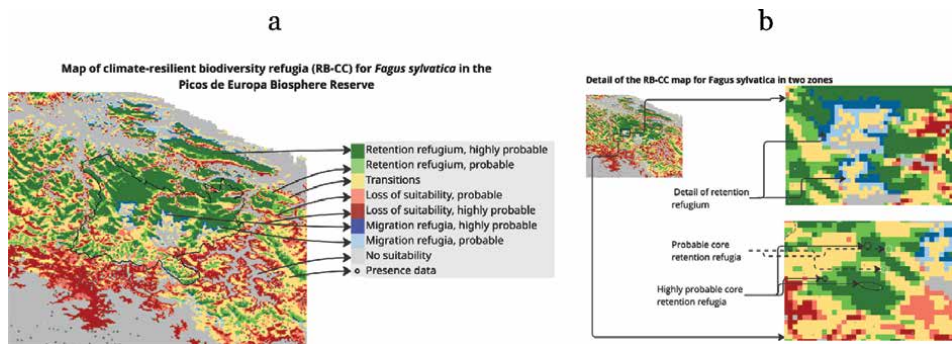


Figure 9.
Refugium maps showing (a) species refugium map and (b) detailed view of a species refugium map. Categories correspond to the definitions provided in the methodology section and were also used during stakeholder workshops.

This classification considered not only the type of refugium—whether retention, migration, or disappearance—but also the spatial dynamics within the landscape. These included upward or downward shifts along altitudinal gradients, zones where suitability either disappears or emerges, orientation with respect to cardinal directions, and other landscape factors influencing refugial persistence.

We also assessed the degree of impact by comparing future projections with the current reference period, categorising changes as low (minimal alteration or very limited loss of suitable area), medium (loss of around 50% of the reference area), or high (loss affecting more than 80% of the area). Together, these elements provide a nuanced picture of how species may persist or shift under changing climatic conditions.

Tables 2 and 3 summarise this classification, presenting the refugium types identified for all species in each Biosphere Reserve. In total, 49 species with appropriate data were considered for Picos de Europa, and 33 species for Urdaibai. For Picos de Europa, **Table 2** shows that 17 species (35%) exhibit no significant changes in their projected distributions, with their current ranges effectively persisting as retention refugia. Two species retain refugia but display a downward shift to lower elevations, accompanied by substantial area loss. A considerable proportion of species,

Species	Refugium class. Picos de Europa
<i>Amica montana</i>	Retention refugium, low impact
<i>Calluna vulgaris</i>	
<i>Carpinus betulus</i>	
<i>Convallaria majalis</i>	
<i>Culcita macrocarpa</i>	
<i>Daboecia cantabrica</i>	
<i>Equisetum hyemale</i>	
<i>Erica tetralix</i>	
<i>Gentiana lutea</i>	
<i>Gymnadenia odoratissima</i>	
<i>Herniaria ciliolata</i>	
<i>Ilex aquifolium</i>	
<i>Luzula sylvatica</i>	
<i>Menyanthes trifoliata</i>	
<i>Narcissus pseudonarcissus</i>	
<i>Platanthera chlorantha</i>	
<i>Taxus baccata</i>	
<i>Hymenophyllum tunbrigense</i>	Retention refugium at lower altitudes, high impact
<i>Vandenboschia speciosa</i>	
<i>Carex capillaris</i>	Retention refugium at higher altitudes, with loss at mid- and low altitudes, medium impact
<i>Erica ciliaris</i>	
<i>Erica vagans</i>	
<i>Horminum pyrenaicum</i>	
<i>Huperzia selago</i>	
<i>Pseudorchis albida</i>	
<i>Sideritis hyssopifolia</i>	

Species	Refugium class. Picos de Europa
<i>Callitriche palustris</i>	Retention refugium at higher altitudes, with loss at mid- and low altitudes, high impact
<i>Campanula trachelium</i>	
<i>Carex caudata</i>	
<i>Carex parviflora</i>	
<i>Geum pyrenaicum</i>	
<i>Lilium pyrenaicum</i>	
<i>Rorippa islandica</i>	
<i>Saxifraga praetermissa</i>	
<i>Ulex galli</i>	
<i>Zostera noltii</i>	
<i>Cortaderia selloana</i>	Retention and migration refugium at lower altitudes, low impact
<i>Quercus robur</i>	
<i>Phillyrea latifolia</i>	Retention and migration refugium at lower altitudes, high impact
<i>Fagus sylvatica</i>	
<i>Quercus petraea</i>	Retention and migration refugium at higher altitudes, low impact
<i>Ruscus aculeatus</i>	
<i>Geranium pratense</i>	Retention and migration refugium at higher altitudes, high impact
<i>Leucanthemum maximum</i>	
<i>Phegopteris connectilis</i>	
<i>Arbutus unedo</i>	Migration refugium at lower altitudes, associated with watercourses
<i>Aquilegia pyrenaica</i>	
<i>Campanula latifolia</i>	No refugium, high impact
<i>Potentilla nivalis</i>	

Table 2.
Classification of refugia for species in the Picos de Europa biosphere reserve.

Species	Refugium class. Urdaibai
<i>Carpinus betulus</i>	Retention refugium, low impact
<i>Horminum pyrenaicum</i>	
<i>Suaeda maritima</i>	
<i>Utricularia australis</i>	
<i>Quercus petraea</i>	Retention refugium in northern zones, with loss at mid-altitudes, medium impact
<i>Rorippa islandica</i>	Retention refugium in northern zones, with loss at mid-altitudes, high impact
<i>Quercus ilex</i>	Retention refugium at higher altitudes, with loss at mid- and low altitudes, low impact

Species	Refugium class. Urdaibai
<i>Erica ciliaris</i>	Retention refugium at higher altitudes, with loss at mid- and low altitudes, medium impact
<i>Lilium pyrenaicum</i>	
<i>Quercus robur</i>	
<i>Taxus baccata</i>	
<i>Vandenboschia speciosa</i>	
<i>Woodwardia radicans</i>	Retention refugium at higher altitudes, with loss at mid- and low altitudes, high impact
<i>Dryopteris aemula</i>	
<i>Erica tetralix</i>	
<i>Fagus sylvatica</i>	
<i>Ilex aquifolium</i>	
<i>Luzula sylvatica</i>	
<i>Narcissus pseudonarcissus</i>	
<i>Arbutus unedo</i>	Retention and migration refugium, low impact
<i>Cortaderia selloana</i>	
<i>Herniaria ciliolata</i>	
<i>Leucanthemum maximum</i>	
<i>Phillyrea latifolia</i>	
<i>Ruscus aculeatus</i>	
<i>Zostera noltii</i>	Retention and migration refugium, high impact
<i>Culcita macrocarpa</i>	No refugium, high impact
<i>Daboecia cantabrica</i>	
<i>Erica vagans</i>	
<i>Hymenophyllum tunbrigense</i>	
<i>Platanthera chlorantha</i>	
<i>Sideritis hyssopifolia</i>	
<i>Ulex galli</i>	

Table 3.
Classification of refugia for species in the Urdaibai biosphere reserve.

also 17 (35%), are projected to maintain retention refugia at higher altitudes, although with medium to high levels of area reduction.

In contrast, nine species (18%) display both retention and migration refugia, either at lower or higher altitudes, with varying degrees of area loss from low to high. Notably, *Arbutus unedo* is the only species showing exclusively migration refugia at lower elevations, likely expanding into the reserve from surrounding areas. Finally, three species are projected to lose their entire suitable area within the reserve.

Table 3 presents the refugium classification for species in Urdaibai. Four species (12%) show no significant changes in their projected distributions, with their current ranges largely persisting as retention refugia. Two species are projected to maintain

retention refugia at higher altitudes, with notable area loss in mid-elevation zones and medium to high levels of overall reduction. *Quercus ilex* retains refugia at higher elevations while losing suitable areas at low to mid-altitudes, although the reduction here is relatively minor compared to its reference distribution.

In addition, 12 species (36%) are expected to retain refugia at higher altitudes within the reserve, with losses occurring at mid- and low-elevation zones. This pattern

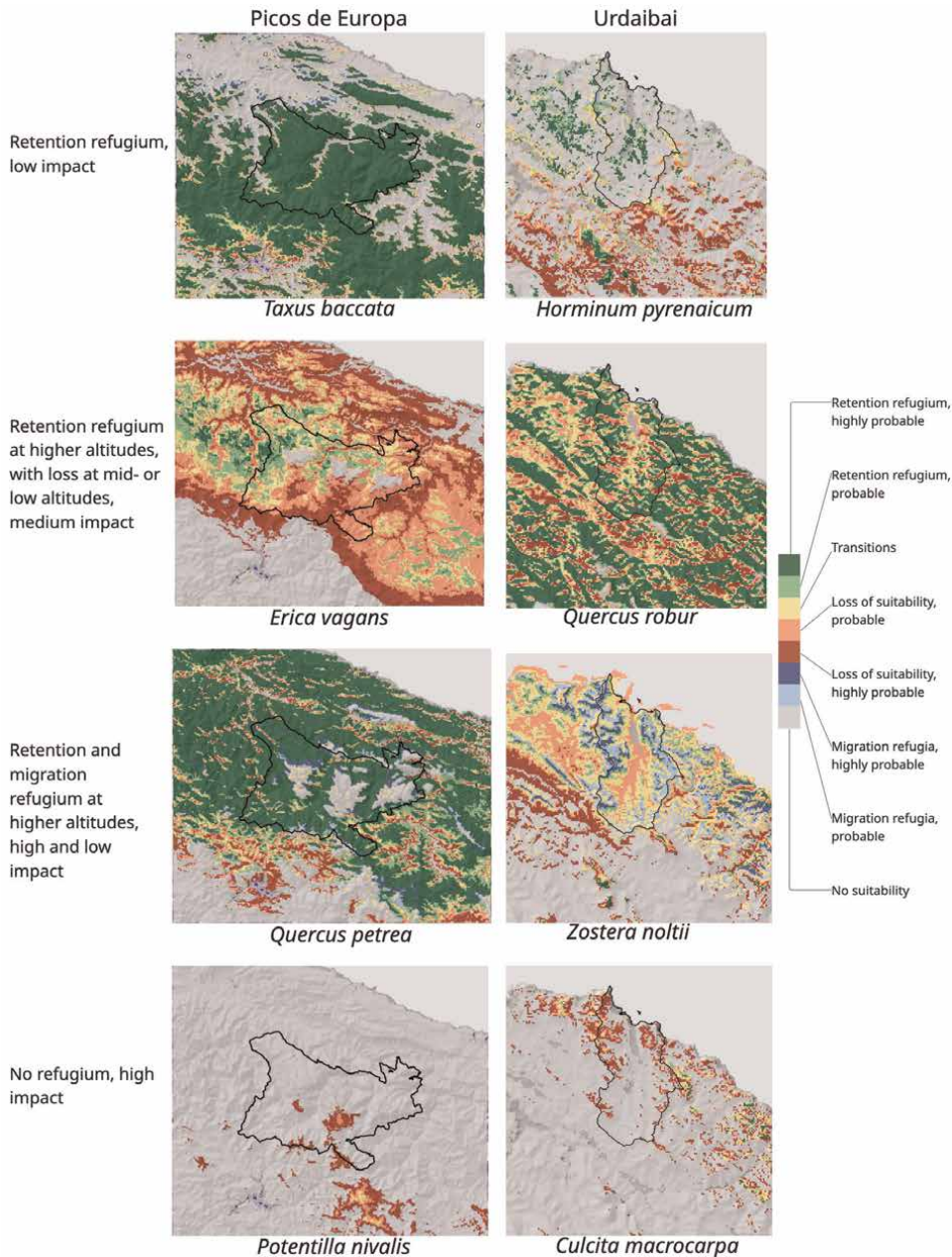


Figure 10.
Maps of climate-resilient biodiversity refugia for eight species with four refugia classes in the Picos de Europa and Urdaibai biosphere reserve.

indicates a transitional disappearance of suitable habitat, accompanied by medium to high impact levels.

Seven species (21%) exhibit a combination of retention and migration refugia, with varying degrees of area loss ranging from low to high. A further seven species (21%) are projected to lose all suitable habitat within the reserve under future climate scenarios.

3.4.3 Climate-resilient biodiversity refugia maps

As one of the main outputs presented to the stakeholders of the Picos de Europa and Urdaibai Biosphere Reserves, climate-resilient biodiversity refugia were summarised in a series of technical sheets for each species and habitat. These sheets compiled modelling results, the dynamics of suitability across future horizons and scenarios, and the corresponding refugia maps.

Figure 10 provides a synthesis for species, highlighting the main refugial patterns identified in the classification. We illustrate eight examples covering the range of observed responses. *Taxus baccata* and *Horminum pyrenaicum* show little or no change in projected suitability, with their entire current range acting as retention refugia. *Quercus robur* and *Erica vagans* represent a recurrent pattern characterised by retention refugia at higher altitudes, transitional areas, and zones of disappearance at mid- and low altitudes, often with medium to high levels of impact. Similarly, *Zostera noltii* and *Quercus petraea* display retention refugia at higher elevations but also include migration refugia, reflecting more dynamic range shifts. Finally, *Culcita macrocarpa* and *Potentilla nivalis* exemplify species facing the greatest impacts, with widespread loss of suitable areas under future climate scenarios.

4. Discussion

4.1 Incorporating future climate scenarios into biodiversity conservation planning

Integrating climate scenarios into biodiversity conservation has shifted from methodological innovation to necessity. Climate and land-use change remain key drivers of biodiversity loss, with recent projections suggesting that climate impacts may soon outweigh those of land use, especially under high-emission scenarios like SSP5-8.5 [40–43]. These scenarios forecast accelerated extinctions, habitat contraction, and ecosystem disruption [44–46], while low-emission pathways such as SSP1-2.6 are associated with more moderate losses, highlighting the importance of timely mitigation [47, 48]. Despite this, regional conservation planning rarely incorporates climate projections. This study addressed that gap by implementing 120 downscaled projections (10 GCMs $\times$ 4 SSPs $\times$ 3 periods) for two northern Spanish Biosphere Reserves—Picos de Europa and Urdaibai—using 29 environmental predictors at 250 m resolution to model suitability for 58 species.

Results confirm a robust warming trend, reaching up to +4°C (SSP5-8.5) and +1.4°C (SSP1-2.6) by 2100; while precipitation changes were minor, evapotranspiration increased notably, especially in Urdaibai. Scenario divergence became more marked after mid-century. These climatic shifts directly affect species such as *Fagus sylvatica*, which showed range contraction and elevational shifts, particularly in Urdaibai where topographic buffering is limited. Species with narrow niches, poor dispersal, or

endemic distribution are especially vulnerable under future conditions [49–51], and static protected areas may lose effectiveness without climate-adaptive strategies [52, 53]. Scenario-based ecological modelling enabled the identification of climate-resilient refugia, distinguishing between retention, migration, and loss areas. Picos de Europa retained more species in persistent areas, while Urdaibai had more projected losses or transitional refugia. Approximately 35% of species retained suitable conditions at higher altitudes, and 20% combined retention and migration potential, underscoring the buffering role of topographic heterogeneity.

4.2 Species distribution models: A strategic pillar for climate-informed conservation

Species distribution models (SDMs) have become indispensable tools for assessing the impacts of climate change and guiding spatially explicit conservation strategies [30, 54]. In this study, we adopted a methodological framework consistent with current best practices, applying nested species distribution models (N-SDMs). Peninsular-scale calibrations were refined to the reserve level through ensemble modelling with three algorithms (GLM, RF, and GBM), using climate projections from the IPCC's SSP framework and 29 high-resolution climatic, edaphic, and evapotranspiration predictors across three future timeframes. Model outputs were synthesised using the Percentage of Climate Models Predicting Suitability (PCM-PS), a consensus-based spatial metric that captures both model agreement and scenario uncertainty.

Our approach responds to international recommendations advocating methodological diversity to enhance forecasting robustness [40]. Findings from our study mirror global evidence: *Bergenia stracheyi* in the Himalayas displayed upslope range shifts and habitat loss [54], and similar contractions were observed for *Fagus sylvatica*, *Ilex aquifolium*, and *Betula pubescens* in Urdaibai. Predictors such as isothermality, nitrogen content, and soil texture—highlighted in models of *Illicium griffithii* [55]—also emerged as key drivers in our results. Zhao et al. [56] reported over 90% habitat loss for endemic Chinese conifers under IUCN criteria, underscoring the relevance of SDMs in extinction risk assessments. In Benin, future suitable areas for key tree species were found outside current protected zones [57], a pattern echoed in Urdaibai. At a continental scale, Archibald et al. [58] applied CMIP5-based models across thousands of Australian species, reinforcing the value of scenario-driven, multi-species approaches. Methodological pillars consistently cited in the literature include the use of edaphic and topographic variables to enhance ecological realism, ensemble modelling for greater robustness, and multiple climate scenarios to capture uncertainty [54, 56, 59–61], and our modelling framework directly addresses these challenges by integrating probabilistic consensus and spatial analysis to inform adaptive, evidence-based conservation planning.

4.3 Climate-resilient biodiversity refugia: A core component of adaptive conservation

Climate-resilient biodiversity refugia are increasingly central to conservation planning under global change, offering areas where species and ecosystems can persist despite climatic stress [7, 8]. In this study, we applied a spatially explicit framework to classify refugia for 58 species across two Cantabrian Biosphere Reserves using down-scaled projections from ten GCMs under four SSPs.

Retention refugia—areas consistently suitable under all scenarios—were most prevalent in Picos de Europa, with species such as *Taxus baccata* and *Horminum pyrenaicum* showing strong persistence. Migration refugia, currently unsuitable but expected to become favourable, were prominent in Urdaibai for species like *Quercus petraea* and *Zostera noltii*, highlighting needs for habitat restoration and assisted migration. Transitional refugia exhibited temporal variability and served as dispersal corridors for species like *Quercus robur* and *Erica vagans*. Additionally, consistently unsuitable areas were mapped, which, while not refugia, may still provide ecosystem services or host other ecological functions.

A distinctive element of our framework was the use of the Percentage of Climate Models Predicting Suitability (PCM-PS), allowing probabilistic interpretation of suitability and explicit mapping of uncertainty. This aligns with current standards for scenario-guided conservation that embrace uncertainty as a design feature [30, 40, 62]. Our findings have key implications for conservation planning: - Prioritisation of native and endemic species with limited adaptive capacity, many of which are confined to shrinking or fragmented refugia.- Spatial targeting of functionally diverse refugia (retention and migration types), supporting the design of connectivity corridors and focused restoration. - Re-evaluation of protected area boundaries, particularly in Urdaibai, where emergent refugia frequently fall outside current conservation designations.

Importantly, the results of this classification were translated into high-resolution GIS products and technical factsheets for use by reserve managers. These outputs have already been integrated into regional spatial planning and serve as operational tools for climate-adaptive conservation.

4.4 Enhancing landscape connectivity for climate adaptation

One of the key applications of climate-resilient refugia lies in their potential to inform connectivity planning across fragmented or vulnerable landscapes. The identification of climate-resilient biodiversity refugia provides a strategic basis for enhancing ecological connectivity under climate change. By pinpointing areas expected to retain or gain suitability, these results support the design of ecological corridors that facilitate species movement across fragmented landscapes, especially for taxa with limited dispersal capacity or those constrained by physical barriers such as mountain ranges [63, 64]. Connectivity planning becomes particularly critical when combined with complementary strategies such as assisted migration, which may be necessary for cold-adapted or range-restricted species that are unlikely to track shifting climates unaided [65, 66]. These measures should prioritise areas of low anthropogenic disturbance and high ecological value, ensuring that dynamic responses to climate change are supported by a resilient and well-connected landscape matrix.

4.5 Study limitations and future directions

This study provides valuable insights into climate-resilient refugia, but key limitations remain. Habitat suitability models, while robust, rely on static assumptions and may not fully account for species' dispersal, adaptation, or biotic interactions. Uncertainty also stems from model inputs and the selection of environmental predictors.

Moreover, despite the integration of local input and actionable outputs, the spatial resolution may overlook microrefugia, and socio-political factors influencing conservation feasibility were not addressed. Future work should incorporate land-use dynamics, adaptive capacity, and finer-scale ecological processes.

5. Conclusions

Climate change poses a profound and accelerating challenge to biodiversity conservation, especially in ecologically rich and topographically complex regions such as the Cantabrian Biosphere Reserves. In this context, the incorporation of climate projections into conservation planning is not only feasible but indispensable for maintaining ecological function in a rapidly changing world. This study demonstrates that integrating high-resolution climate projections and ecological modelling into biodiversity strategies is essential for anticipating and mitigating species and habitat loss under future scenarios. Failing to adopt this forward-looking approach risks misaligning conservation objectives with emerging ecological realities, thereby compromising both the resilience of natural systems and the long-term effectiveness of conservation efforts.

The use of a high working resolution (250 m) and the integration of non-traditional variables—such as evapotranspiration, slope, and aspect—have been crucial for identifying climate refugia at the local scale. These fine-scale patterns would likely be overlooked in coarser-resolution models (e.g., 1 km), particularly in topographically complex mountain landscapes.

By combining ensemble species and habitat distribution modelling with multiple Shared Socioeconomic Pathways (SSPs) and General Circulation Models (GCMs), this study demonstrates a robust and integrative framework for climate-informed conservation planning. Central to this approach is the use of the Percentage of Climate Models Predicting Suitability (PCM-PS), a transparent metric that captures model consensus and enables spatially explicit representation of uncertainty. This integration of diverse modelling tools and climate projections strengthens the scientific basis for decision-making and facilitates the prioritisation of adaptive strategies. Such an approach underscores the critical role of habitat suitability modelling in guiding the design of biodiversity refugia, ecological connectivity, and restoration actions under future climate conditions.

Importantly, the refugia maps and classifications were not conceived as static outputs, but as operational tools co-produced with local actors and adaptable to decision-making contexts. They have already informed spatial planning and restoration prioritisation processes in the reserves, demonstrating the real-world utility of climate-informed modelling.

Beyond their spatial definition, climate-resilient biodiversity refugia should be understood as foundational components of an adaptive conservation paradigm—integrating ecological function, social engagement, and long-term resilience under uncertainty. This work underscores the importance of aligning conservation targets with future ecological realities, and provides a replicable framework for guiding proactive and equitable biodiversity strategies in other Mediterranean mountain systems and beyond.

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A. Appendix

See **Table A1**.

Cod	Description
BIO01	Annual mean temperature
BIO02	Diurnal temperature range (monthly mean (max temp-min temp))
BIO03	Isothermality: Relationship between the temperature range between day and night and between summer and winter
BIO04	Seasonality in temperature (standard deviation $\times$ 100)
BIO05	Maximum temperature of the warmest month
BIO06	Minimum temperature of the coldest month
BIO07	Annual temperature range (BIO05-BIO06)
BIO08	Average temperature of the wet quarter
BIO09	Average temperature of the dry quarter
BIO10	Average temperature of the warmest quarter
BIO11	Average temperature of the coldest quarter
BIO12	Annual precipitation
BIO13	Precipitation of the wettest month
BIO14	Precipitation of the driest month
BIO15	Seasonality in precipitation (Coefficient of variation)
BIO16	Precipitation of the wettest quarter
BIO17	Precipitation of the driest quarter
BIO18	Precipitation of the hot quarter
BIO19	Precipitation of the coldest quarter
BIO41	Annual evapotranspiration
BIO42	Evapotranspiration of the driest month
BIO43	Evapotranspiration of the wettest or rainiest month
BIO44	Evapotranspiration of the warmest month
BIO45	Evapotranspiration of the coldest month
BIO46	Seasonality of evapotranspiration. Highest ETo-minimum ETo

Table A1.
Describing the bioclimatic variables used in this study.

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Corridors of Coexistence: Integrating Ecological Connectivity with Local Benefits in Protected Area Management in Central Annamite, Vietnam

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Abstract

This chapter examines how biodiversity corridors can be effectively managed to enhance ecological connectivity while delivering tangible benefits to local communities. Focusing on Vietnam's Central Annamite Landscape, it explores how corridors serve as critical linkages between protected areas, supporting species movement and resilience in the face of habitat fragmentation and climate change. Drawing on spatial modeling and field research, the chapter highlights the importance of community engagement, equitable benefit-sharing mechanisms, and supportive policy frameworks. It discusses the role of non-timber forest products (NTFPs), Payment for Forest Environmental Services (PFES), and conservation incentives in improving local livelihoods. The chapter offers practical insights into integrating ecological and socioeconomic objectives, proposing governance models that align conservation priorities with the community development goals.

Keywords: biodiversity corridors, ecological connectivity, protected area management, community engagement, sustainable livelihoods, payment for forest environmental services, conservation governance, central Annamite

1. Introduction

The concept of biodiversity corridors for improving connectivity between protected areas (PAs) has been around since the early twentieth century [1, 2]. In many countries, initiatives have been taken to improve connectivity between PAs and natural ecosystems. These initiatives make use of a wide variety of terms to represent the spatial concept that they have established or aspire to establish [2, 3]. Biodiversity corridors were initially promoted as habitat corridors to enable the movement of species [4, 5];

they can, therefore, be characterized as the interlinking between patches of appropriate habitat for an individual organism (i.e., wildlife corridors) [6].

In Southeast Asia, and particularly in Viet Nam's Central Annamite Landscape (CAL), the need for functional connectivity is urgent. While the CAL is characterized by high biodiversity values, home to numerous endemic species, and is one of the Global 200 Ecoregions, it also faces chronic threats from habitat degradation, poaching, and illegal logging [7, 8]. This situation is exacerbated by infrastructure expansion such as the Ho Chi Minh highway [9]. This landscape is also under increasing anthropogenic pressure, which has reduced the distribution and abundance of some of the region's most important species. Habitat loss and fragmentation are recognized as leading threats along with poaching for the lucrative Southeast Asian wildlife trade [9]. The pressures of road expansion, agricultural conversion, and hydropower development have fragmented forest habitats, increasing risks to biodiversity and local livelihoods. PAs such as Bach Ma National Park (NP), Phong Dien Nature Reserve (NR), Song Thanh NP, Elephant habitat and species conservation area (HSCA) and Saola NRs in Quang Nam (QN), and Thua Thien Hue (TTH) form critical biodiversity strongholds. However, without functional ecological corridors connecting them, the effectiveness of these PAs is compromised.

This chapter explores how biodiversity corridors in the Central Annamite can be designed and governed not only for ecological integrity but also for equitable socioeconomic outcomes. It builds on spatial and participatory research conducted in QN and TTH provinces, where community perceptions, conservation incentives, and institutional frameworks were analyzed to assess the viability of corridor-based conservation. A central theme of the chapter is the need to move beyond conservation that isolates people from nature. While PAs remain crucial, their long-term success depends on adjacent landscapes being managed in ways that promote both species movement and human well-being. This means addressing challenges such as insecure land tenure, inequitable benefit-sharing, and limited participation in decision-making by forest-dependent communities. For example, while Viet Nam's Payment for Forest Environmental Services (PFES) policy has provided financial incentives for forest protection and community-based models for aligning conservation and livelihood goals, they do require robust institutional support and capacity building.

The chapter also addresses the governance dimensions of corridor management, highlighting the importance of coordination between state actors, local communities, and non-governmental organizations. Viet Nam currently lacks a legal framework for biodiversity corridors, which complicates the allocation of responsibilities and resources for their implementation. Drawing from international experiences and regional examples, the chapter advocates for a multi-level governance approach that recognizes community roles, supports cross-sectoral collaboration, and aligns with national commitments under the Convention on Biological Diversity (CBD) and the Sustainable Development Goals (SDGs).

In doing so, the chapter positions biodiversity corridors not simply as technical solutions to fragmentation but as socio-ecological systems that require inclusive design, participatory governance, and long-term financial and institutional commitment. By integrating ecological science with local knowledge, and by connecting conservation outcomes with the development priorities, corridors can become platforms for both biodiversity recovery and rural resilience in Viet Nam.

The following sections outline the ecological rationale for connectivity in the Central Annamite, describe case studies from participatory mapping and benefit-sharing initiatives, assess the institutional context for corridor governance, and offer

the strategic recommendations for aligning biodiversity conservation with community development. Ultimately, this chapter seeks to contribute to the growing body of knowledge on how to build conservation landscapes that work for both people and nature in a rapidly changing world.

2. The Central Annamite Landscape and the need for connectivity

The Central Annamite Landscape is a globally significant biodiversity hotspot, home to numerous endemic species, including the saola (*Pseudoryx nghetinhensis*), large antlered muntjac (*Muntiacus vuquangensis*), Truong Son muntjac (*Muntiacus truongsongensis*), Owston's Civet (*Chrotogale owstoni*), crested argus (*Rheinardia ocellata*), and Annamite striped rabbit (*Nesolagus timminsi*) [10]; as well as other species of high conservation value including gibbons (*Nomascus spp.*) and douc langurs (*Pygathrix spp.*) [11].

The CAL is characterized by rugged mountain ranges of the Annamite chain, dissected valleys, and steep slopes that create a mosaic of habitats. Elevations range from lowland plains (<200 m) to high mountain ridges (>2000 m), producing a variety of microclimates and vegetation zones. The climate is tropical monsoonal, with distinct wet and dry seasons, annual rainfall exceeding 2500 mm in many areas, and frequent typhoons that shape the geomorphology [12, 13]. Vegetation is diverse and stratified by altitude: lowland evergreen and semi-evergreen forests, mid-elevation broadleaf forests, and montane cloud forests dominated by conifers and mosses [14, 15]. This complex topography and climate underpin the region's exceptional biodiversity and high levels of endemism [16].

Coexisting with the biodiverse wildlife community in CAL is one of the fastest growing human economies in the world [17]. Economic growth can increase the vulnerability of nearby wildlife populations due to increased demand for wild meat, clearing of forests for agricultural and residential land use, infrastructure (e.g., roads), and exploitation of wildlife for commercial gain (e.g., pet trade, traditional medicine). In particular, the loss of forested land outside of protected areas (PAs) and intense logging and hunting pressure has resulted in fragmented species distributions in the CAL [18–20]. If habitat outside of PAs is not preserved, they can become isolated from one another and are effectively rendered “islands” of habitat in a sea of anthropogenic land use. Facilitating connectivity (i.e., the ability of animals to move between PAs) makes wildlife populations more resilient to extinction due to “demographic rescue”—the ability of nearby populations to recolonize areas that have been temporarily extirpated.

Habitat fragmentation in CAL isolates wildlife populations, reducing genetic diversity and resilience. Biodiversity corridors play a critical role in maintaining connectivity between the protected areas, enabling species movement and long-term conservation success [18, 19]. Strengthening corridor effectiveness is essential for preserving CAL's biodiversity amidst growing human activity. In order to achieve this, it is important to assess the direct and indirect threats impacting biodiversity corridors. Indirect threats include weak institutional coordination, unclear legal frameworks, and inadequate incentives for conservation. Despite the Vietnam Forestry Law (2004, amended 2007), challenges persist in enforcing protection, securing funding, and engaging local stakeholders [21, 22]. Economic growth places further pressures on biodiversity through increased deforestation, infrastructure expansion, and wildlife exploitation [23].

The CAL is inhabited by 11 ethnic minority groups (87% of the population) who rely heavily on forest resources for livelihoods [24]. The remaining 13% are Kinh people, who practice permanent cultivation with less forest dependence. Economic hardship and limited livelihood alternatives drive forest encroachment, further intensifying deforestation and biodiversity loss [25–29].

In 2018, three biodiversity corridors were established in Quang Tri, Thua Thien Hue, and Quang Nam provinces. In Quang Tri, a corridor connects Bac Huong Hoa NR to Dak Rong NR (**Figure 1**). In Thua Thien Hue, a corridor connects Phong Dien NR to Hue Saola NR. In Quang Nam, a two-part corridor connects Quang Nam Saola NR to Song Thanh NP and Song Thanh NP to Elephant HSCA. The part of this corridor that connects Quang Nam Saola NR to Song Thanh NP is also transboundary, connecting with Xe Sap National Biodiversity Conservation Area in Lao PDR. These corridors are managed at the provincial level under the Ministry of Agriculture and Environment (MOAE) Pilot Guidelines for the Establishment and Management of Provincial Biodiversity Corridors.

Several challenges must be met to ensure successful implementation of biodiversity corridors. Success will rely on coordination among multiple agencies, engagement with key stakeholders, attractive incentives for forest landowners in biodiversity corridors, funding to implement conservation efforts, the establishment of clear guidelines for monitoring and evaluation, and long-term funding streams to support continued monitoring.

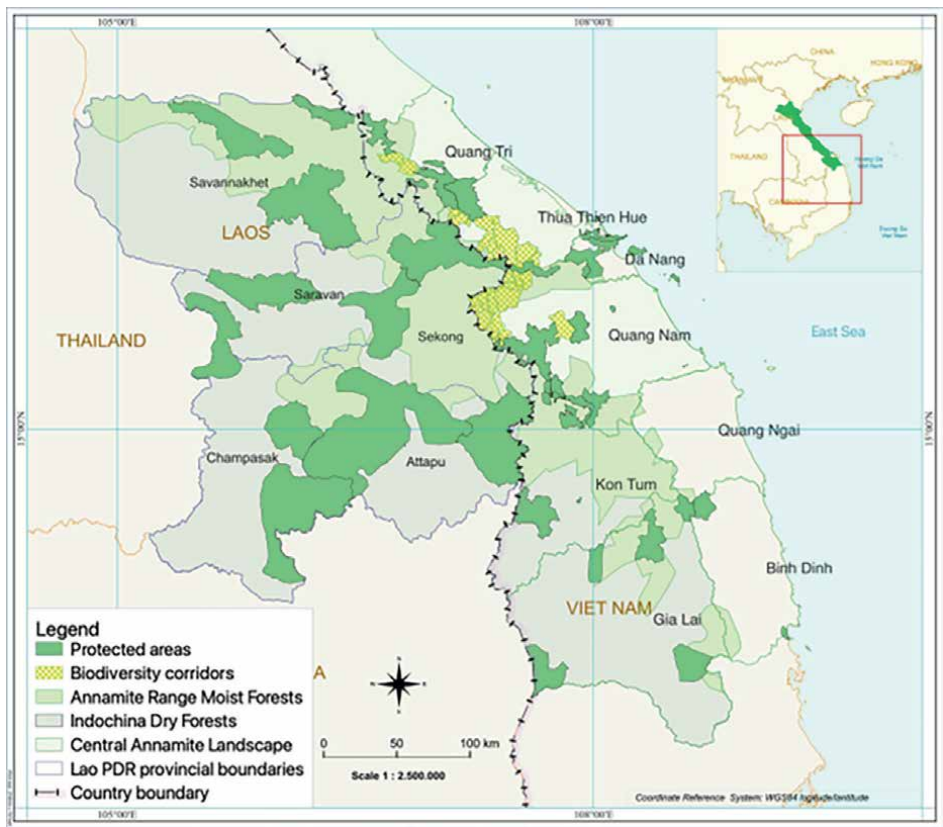


Figure 1. Location of biodiversity corridors between the protected areas in the Central Annamite Landscape Vietnam [19].

In short, the Central Annamite Landscape is a conservation priority not only because of its rich biodiversity but also because of the socioecological challenges it encapsulates. Addressing the threats to connectivity in this region will require a coordinated, multi-sectoral approach that includes ecological restoration, spatial planning, community engagement, and policy reform. The next sections of this chapter will delve into specific strategies and examples of how connectivity can be enhanced in the CAL, drawing on both field evidence and stakeholder perspectives.

3. Ecological connectivity and corridor design

In the fragmented forest landscapes of Viet Nam's Central Annamite Landscape, maintaining and restoring ecological connectivity is fundamental for ensuring the long-term viability of threatened species and sustaining ecosystem functions across the region. This section draws on spatial modeling, ecological theory, and field validation to describe how connectivity can be operationalized through the design of functional biodiversity corridors.

3.1 Modeling connectivity

To assess the forest habitat connectivity patterns of the biodiversity corridors in the CAL, the Linkage Mapper version 2.0 toolbox (Washington Wildlife Habitat Connectivity Working Group) for ESRI ArcGIS (version 10.8) was employed; Linkage Mapper is a GIS tool developed to support regional wildlife connectivity analyses. It accomplishes this by offering several tools to identify likely corridors and key barriers to movement on the landscape [30]. The biodiversity corridor maps were compiled using four GIS base layers representing natural landscape characteristics (land use and slope) and human impacts (roads and household density) that are expected to impact the potential for forest animals to move through this landscape. Contiguous protected areas were grouped into “constellations” to limit corridor analyses to non-adjacent PAs—for example, since QN Saola NR and TTH Saola NR are contiguous, they are considered as a single constellation. The cost-weighted and Euclidean network adjacency techniques were utilized to prune the network to a single connected nearest neighbor and corridors were estimated among the closest pairs of core area “constellations.” The creation of cost-weighted distance (CWD) and least-cost corridor maps was performed using ArcGIS (version 10.8).

3.2 Developing a resistance surface

The resistance surface served as the principal input data for conducting connectivity analyses [31] and was based on land use types, population density, distance to barriers such as major roads, and slope of the terrain surface. Each of the four variables were assigned resistance values on a scale of 1–100 based on expert consensus (Table A1). The resistance value represents the difficulty of moving from one pixel to another in a rasterized map of the landscape. Experts considered multi-species landscape permeability based on previous experience developing similar models in Nghe An province, Viet Nam. A separate resistance surface was created for each of the four landscape variables. Then, the four resistance surfaces were summed to create the final composite resistance surface.

3.3 Criteria and data

The design of the biodiversity conservation corridor network was implemented in the context that empirical information on the dynamics of the specific wildlife species is not available; therefore, the criteria taken into consideration are understood as generalized criteria for the CAL forest community. From an expert knowledge perspective, the following criteria were considered:

- i. the land use type: High-quality natural forest is assumed to be more suitable for wildlife movement than degraded natural forest, while plantation and croplands are not as suitable as natural forest.
- ii. proximity to transportation network: Areas further away from transportation networks are more suitable than those nearer to transport.
- iii. slope: Wildlife species (especially large mammals) are assumed to prefer flat terrain to steep terrain.
- iv. household density: Wildlife movement is more likely at places of lower density of residential settlements.

GIS data was used to compile the criteria map layers. **Table 1** shows the data source of the four criteria used as inputs to the final composite resistance surface model for landscape connectivity modeling.

The four GIS base layers were mapped across QN and TTH provinces (**Figure 2**). The resistance value in these maps represents the relative difficulty moving across each pixel, where a value of 1 represents ideal movement conditions and a value of 100 represents a complete barrier to movement. For instance, for the slope criterion, for pixels of slope more than 40 degrees, their resistance values were set to 30. This

Data layer	Source	Note
Land use types	Forest protection departments (FPD) of TTH and QN provinces	Map layers of land use types in TTH and QN of scale 1/100,000. The map layers are updated annually and reviewed every 5 years. The version of these map layers is for 2017.
Transportation network	Natural Resource and Environment Departments of TTH and QN	Transportation network of the scale 1/100,000
DEM	Natural Resource and Environment Departments of TTH and QN	Digital elevation model (DEM) raster layers of TTH and QN in UTM 48 N projection. The layers have pixel size of 30 meters.
Household locations	Natural Resource and Environment Departments of TTH and QN	Household location layer in UTM 48 N projection
Protected areas	Forest protection departments (FPD) of TTH and QN	Map layers of protected areas in TTH and QN. These layers are derived from land use type layers; therefore, they inherited the scale 1/100,000 and projection UTM 48 N from the source layers.

Table 1.
Spatial data layers used in the analysis (all layers projected in UTM Zone 48N).

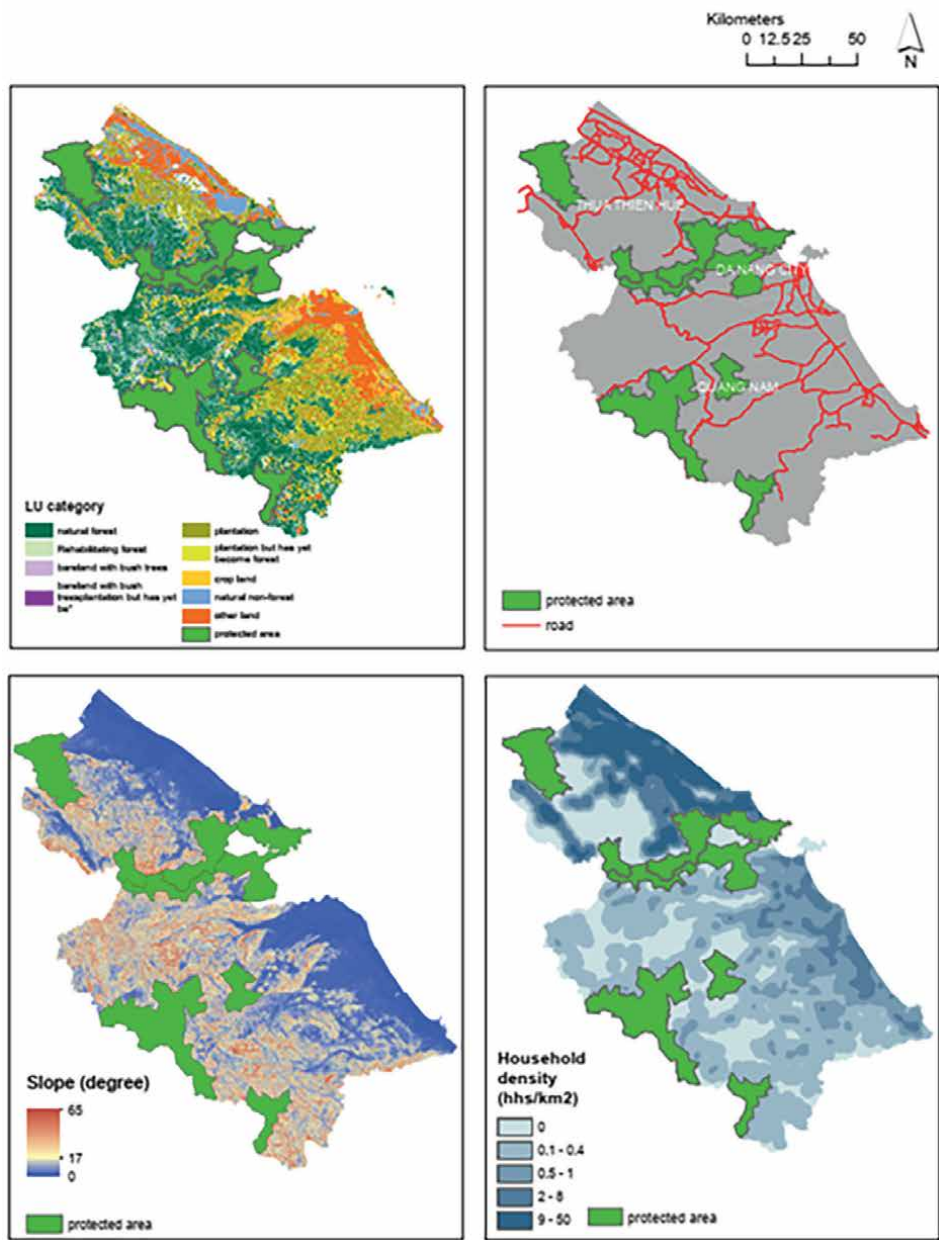


Figure 2.
Base GIS layers for forest habitat connectivity assessment included land cover, roads, village household density, and slope.

means that moving through such a pixel is 30 times more difficult than moving through an ideal flat area. The concept was applied to all four criteria: land use, distance to the transportation network, slope, and household density. The resistance values for different types of criteria were based on the opinions of the biological conservation experts from World Wildlife Fund and research institutes in Vietnam and the United States (Table A2).

3.4 Derivation of resistance layers

- *Land use resistance layer:* Land use layers were dissolved by the land use types. Depending on the resistance values proposed through the expert consultation, each land use type was assigned to a corresponding resistance value (**Table A1**). The vector layer was then rasterized at a resolution of 30 meters.
- *Transportation resistance layer:* From the transportation network, we multi-buffered the areas of 0–299 meters, 300–499 meters, 500–999 meters, and 1000–2000 meters distance from roads. Correspondingly, resistance values of 75, 50, 30, and 10 were assigned to the areas (**Table 2**). For areas of more than 2000 meters, a resistance of two was assigned (**Table 2**). From this, the transportation resistance layer was derived by rasterizing the map of buffer areas.
- *Slope resistance layer:* From the digital elevation model (DEM), a slope layer in degrees was generated using the slope tool in ArcGIS. This slope layer was then reclassified into two classes, namely <40 and > 40 degrees. A resistance value of 30 was assigned to the latter value, while a resistance of zero was assigned to the former (**Table 3**).
- *Household density resistance layer:* To generate the household density layer, the household location layers of the two provinces were used. The density tool in ArcGIS was run with a radius size of 20 pixels. This gave a household density layer of household per square kilometer. This household density layer was then classified into five classes: zero household per square kilometer, <5 households per square kilometer, 5–15 households per square kilometer, 15–30 households per square kilometer, and > 30 households per square kilometer. Resistance values of 0, 2, 5, 20, and 100 were then correspondingly assigned to the classes to derive the household density resistance layer (**Table 4**).

To represent the total resistance effect of all the criteria of concern, all the resistance layers were combined into a single layer, the composite resistance surface, which

	Distance from road	Resistance
Road	0–299 m	75
	300–499 m	50
	500–999 m	30
	1000–2000 m	10

Table 2.
Resistance values assigned to distance buffers from roads.

Slope (Degrees)	Resistance	Comments
0 to 40	0	Preference is for movement through gentle ground
Over 40	30	Penalty for movement through very steep areas

Table 3.
Resistance values assigned based on slope classes.

Household density	Resistance	Comments
0	0	Areas without human/household are low resistant to movement
0 to 5	2	Areas with low household density (< 10 household/km ²) are highly permeable
5 to 15	5	Areas with medium household density (11–20 household/km ²) are average resistant to movement
15 to 30	20	Areas with medium high household density (21–30 household/km ²) are medium high resistant to movement
Over 30	100	Areas with high household density (> 30 households/km ²) are highly resistant to movement

Table 4.
Resistance values associated with five levels of village household density.

was used as the input for the corridor modeling process. To combine the layers, the equal weight scheme was used, meaning that none of the resistance criteria are more important than the other ones. Land use resistance, transportation resistance, slope resistance, and household density resistance layers were summed using the map algebra tool in ArcGIS. The composite resistance surface represents the hypothesized resistance to CAL forest wildlife movement and is the basis for subsequent cost-weighted distance analysis (**Figures 3 and 4**).

First, least-cost paths were identified between all reserves or constellations of reserves. While the least-cost path location itself is an overly optimistic representation of animal movement [32], the least-cost path distance provides an informative metric for comparing relative permeability between different corridors and identifying how changes to the landscape, such as restoration or barrier removal, change the effectiveness of corridors. Barrier areas are places where high resistance values contribute to rapid accumulation of cost-weighted distance and thus can highlight locations where conservation or restoration activities may provide the greatest benefit for broader-scale habitat connectivity. In addition to least-cost path mapping, a cost-weighted distance map was created showing the cumulative cost-weighted distance of each pixel from the nearest reserve. Next, the least-cost corridor width was estimated by identifying all paths between reserves. Lastly, the Linkage Mapper's Barrier Mapper tool [33] was used to identify the potential areas for habitat connectivity conservation or restoration based on barrier effects.

A critical step in translating model output into practical conservation interventions was ground-truthing and participatory validation with local communities and protected area staff. Field visits, transect surveys, and participatory mapping exercises were conducted in priority sites to confirm the ecological value and feasibility of corridor implementation. These activities helped identify critical bottlenecks and barriers to connectivity, such as areas of high snaring pressure, newly constructed roads, or contested land use. Community members often highlighted the traditional wildlife movement paths or forested ridgelines used by animals that correspond to modeled corridors, reinforcing the importance of local knowledge in conservation planning. One example of such alignment occurred in the landscape between Elephant HSCA and Song Thanh NP, where community members in Phuoc Ninh commune described the seasonal elephant movements and gibbon calls along ridgelines that matched corridor models. This site was also identified as a hotspot for snaring, suggesting that both connectivity enhancement and threat reduction measures should be prioritized here.

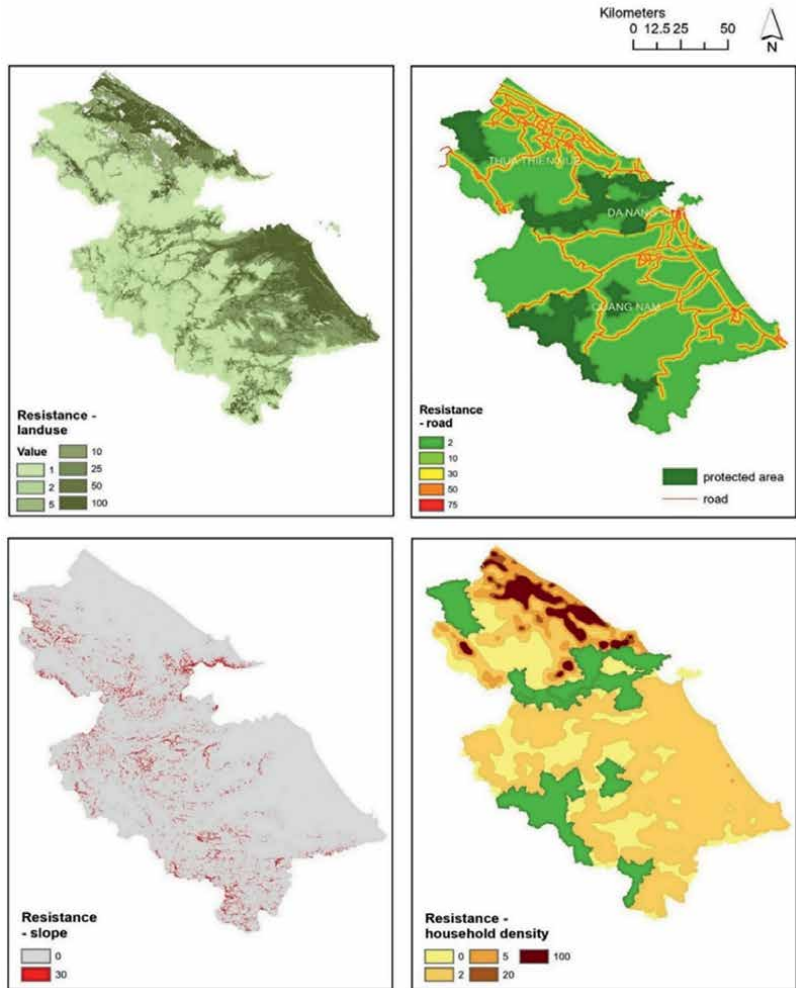


Figure 3.
Component resistance to wildlife species movement for each of the base layers: land cover, roads, household density, and slope in biodiversity corridors.

Designing corridors in Viet Nam also requires addressing the complex land tenure and management regimes that intersect the landscape. Many proposed corridor paths run through a mosaic of forest types ranging from Special-use Forest (SUF) to Protection Forest and Production Forest each governed by different regulatory frameworks and land-use constraints. Moreover, community forest lands, though legally recognized, are often under-resourced and under-supported. Therefore, the implementation of corridors must be supported by cross-sectoral coordination and flexible mechanisms that allow for adaptive co-management, including the establishment of conservation agreements or zoning changes within existing forest categories.

Overall, the corridor design process in the CAL demonstrates that effective connectivity planning must combine science-based modeling with local realities. It must be adaptable to changing sociopolitical and ecological conditions and must be grounded in a vision that balances conservation priorities with human development needs. The next section of the chapter will examine how community engagement

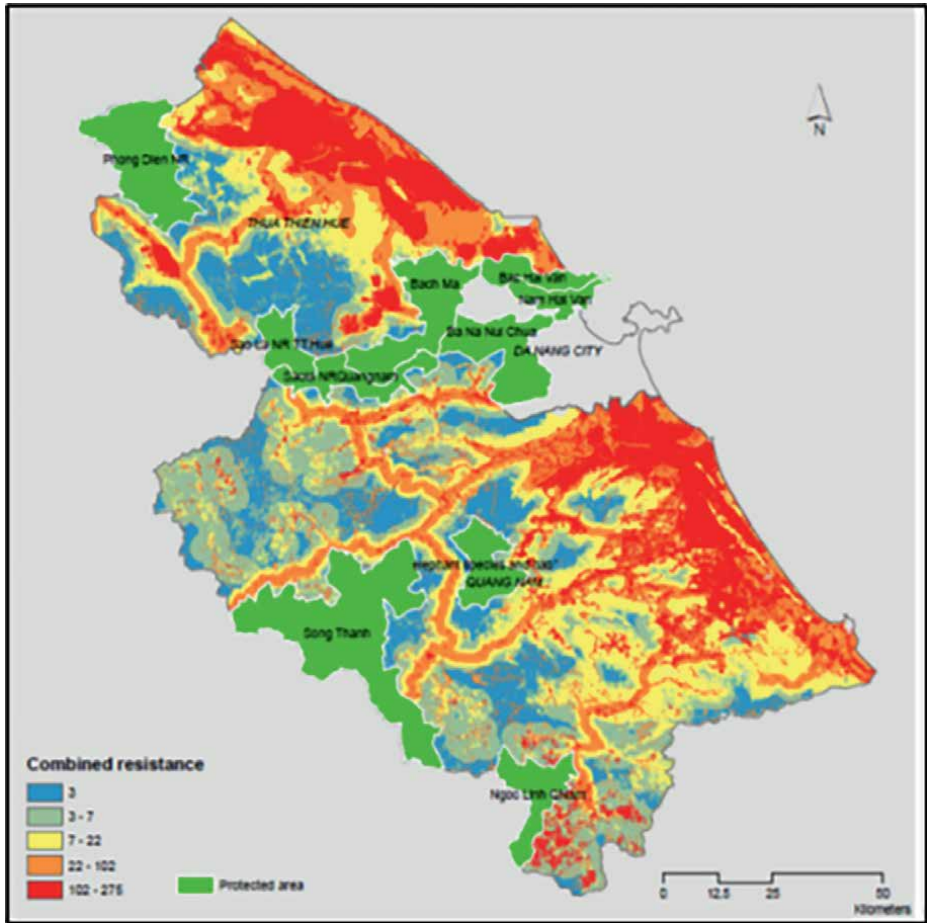


Figure 4.
 Total resistance to wildlife species movement based on land cover, proximity to roads, village household density, and slope.

and benefit-sharing mechanisms—particularly through the lens of non-timber forest products (NTFPs) and Payment for Forest Environmental Services (PFES)—can help make these corridors socially and economically viable.

4. Community engagement and benefit-sharing in corridor areas

The establishment of biodiversity corridors, together with relevant regulations, policies and frameworks for management and governance, can also have negative impacts on local communities. Regulations and policies can limit or restrict access to land and natural resources or change the status of land tenure and use, thereby negatively impacting the livelihoods of landowners [34, 35]. Efforts to integrate conservation-oriented livelihoods are ongoing but there has been limited community engagement and stakeholder consultation in the development and implementation of biodiversity corridor programs. Understanding the socioeconomic impacts is crucial for improving both ecological and livelihood outcomes. Recognizing this,

conservation strategies must align biodiversity goals with local development needs, ensuring that connectivity does not come at the expense of human well-being. This section highlights the mechanisms—particularly the use of non-timber forest products (NTFPs), Payment for Forest Environmental Services (PFES), and co-management models—that integrate community engagement into corridor management and governance.

4.1 The socioeconomic context of corridor communities

The CAL is home to 11 ethnic minority groups that comprise approximately 87% of the total population. They have resided here for many generations and are the indigenous inhabitants of the region. Kinh people who immigrated from the plain area to this region account for 13% of the population [24]. The dependence and impact on forest resources vary across ethnic groups. The ethnicity of local communities is a strong indicator of the type of impact on forest resources [26]. Ethnic minority groups, frequently situated in remote mountainous areas, commonly grapple with economic hardships and rely heavily on forest resources for sustenance, including food production, construction materials, materials for crafts, and cultural traditions [24]. Many ethnic minority people still practice shifting cultivation. On the other hand, the Kinh majority culture has a lesser dependence on forests, despite engaging in hunting and gathering practices within these areas [27, 36]. Notably, the Kinh community primarily practices permanent cultivation. As settlements and agricultural expansions continue, substantial portions of lowland forests are cleared, resulting in diminished lowland forest habitats and reduced biodiversity, along with the fragmented forest cover [29].

Poor ethnic minorities have limited alternative income sources due to their rural isolation, market access, and limited education and, therefore, continue to encroach upon forested areas and use forest resources illegally, further contributing to forest degradation, fragmentation, and biodiversity loss [24]. Anthropogenic threats to the ecological integrity of the CAL include hunting, logging, overharvesting of non-timber forest products, infrastructure development, and forest encroachment by acacia plantations [25].

There are many socioeconomic development activities under the district-level administrative units, including activities such as cultivation, livestock raising, aquaculture, forestry, agriculture extension, and fishery. The source of income of these households is mainly from forestry, crops, animal husbandry, and non-farm activities. Crops, such as cassava, paddy rice on the hill, and maize, have low productivity compared to other lowland areas due to poor soil characteristics and weather conditions. Many households have livestock such as cows, goats, and buffaloes, which are mainly raised for self-consumption rather than for income generation [37, 38]. Non-farm activities including trading, business, skilled jobs, and services, significantly contribute to household income through remittances at a higher rate compared to income generated from farming activities [39, 40].

There are efforts underway in the biodiversity corridors to improve the outcomes for biodiversity and landowners and local communities through the development of conservation-oriented livelihoods. Forest restoration and provision of NTFPs for adjacent communities now occur in certain parts of the biodiversity corridors. However, there has been limited consultation with these groups, including landowners within biodiversity corridors, which could help to better understand how to improve these programs with respect to improved livelihoods.

4.2 Non-timber Forest products as livelihood strategies

The non-timber forest products (NTFPs) constitute a significant income source for landowners situated in the buffer zones and corridors [41–44]. This resource category encompasses food supplies, medicinal herbs, and cultural products, and serves as a primary income source for communities reliant upon it [42, 45–48].

Local people gathered various types of NTFPs from natural forests located both within and outside of the biodiversity corridors. They indicated utilizing these forest resources for four primary purposes: sustenance as food supplies, medicinal treatments, ceremonial rituals, and commercial selling. Bamboo shoots, fruits, leaves, and rattan sprouts were commonly procured for daily sustenance as they were readily collectible. Moreover, these items were easily accessible and sold in local markets. Additionally, these NTFPs held cultural significance, being employed in rituals, festivals, and religious ceremonies. Local people also used NTFPs to treat their diseases because they cannot afford access to the modern healthcare system.

In the context of corridor conservation, sustainable NTFPs management presents a dual opportunity: (i) to maintain forest cover and ecological integrity, and (ii) to generate livelihood benefits that incentivize community participation. Successful pilot programs in Quang Nam have introduced NTFPs certification, collective marketing strategies, and microenterprise development to improve the returns to local harvesters. For example, a honey cooperative in Thuong Lo commune increased household income by 40% over 2 years while adhering to the sustainable harvesting guidelines.

4.3 PFES and incentive-based conservation

The Payment for Forest Environmental Service (PFES) in Vietnam is regarded as a program designed to provide incentives to communities engaged in the sustainable management and protection of forests. This initiative compensates these communities for their efforts in safeguarding forests. PFES is considered a successful model for mobilizing funding from organizations and individuals benefiting from the forest environmental services [49]. It serves to support activities related to forest protection, rural development, and poverty reduction. PFES is now a national policy regulated by Decree No.99/ND/CP/2010 and followed by Revised Decree No 147 ND/CP/2016 to increase the economic benefits that can be derived from protecting forests with an annual average revenue of USD 60 million covering protection of 5.3 million ha of forests [50, 51].

The correlation between land size and monetary income is expected because the PFES payment rate is proportional to the forest land size [52]. Therefore, the more forest area owned by households within the biodiversity corridor, the higher the payment they receive. In addition, family size and labor also contributed to non-monetary benefits for landholders in biodiversity corridors. Landholders with large families and associated labor generate more income from different activities, including upland cultivation such as paddy rice, maize, and casava farming and ecotourism services such as homestays, guides, and food services [24].

To better support corridor objectives, PFES mechanisms could be tailored to reward conservation behaviors specifically linked to connectivity, such as protecting movement corridors, reporting illegal snaring, or restoring degraded patches. Additionally, leveraging PFES revenues to co-finance livelihood diversification or ecotourism initiatives could enhance the impact.

4.4 Toward equitable benefit-sharing in corridor design

Benefit-sharing mechanisms must go beyond one-time payments or symbolic participation. The sustainability of corridor initiatives depends on embedding equity, voice, and transparency into their design and implementation. This includes:

- Participatory planning processes that meaningfully involve marginalized groups;
- Transparent allocation of conservation benefits (e.g., PFES, ecotourism, or donor funding);
- Monitoring systems that include social as well as ecological indicators;
- Feedback mechanisms that enable adaptive management and learning.

Equity-based conservation is not merely a social goal—it is an ecological necessity. When communities perceive conservation as aligned with their own interests and values, they become long-term stewards of the landscape.

5. Policy and governance for connectivity corridors

Biodiversity corridors often comprise large and complex landscapes with many land tenures and activities [52]. The establishment of a large-scale biodiversity corridor often takes place against a background of conservation and land allocation actions and projects that preceded it. This creates challenges for the ongoing management of the biodiversity corridor. To be effective, a biodiversity corridor also needs to be actively managed at the site- and landscape-levels. Active management of biodiversity corridors or connectivity areas relates to four important elements of management functions, including leadership, planning, implementation, and evaluation [53]. Because the biodiversity corridor and the protected areas it connects are dynamic, management must be adaptive to ensure that ecological processes and functions are maintained and protected, habitats are restored, and wildlife species are conserved [6, 54].

Biodiversity corridor management and governance requires all stakeholders with tenure and use rights to have a say in the social and economic benefits of the biodiversity corridor. As a result, biodiversity corridor management needs to be regulated by authorities [55]. The long-term success of biodiversity corridors hinges not only on ecological and community-based approaches but also on robust, inclusive, and coordinated governance. In Vietnam, policy frameworks related to biodiversity, protected areas, and land use planning are evolving but remain fragmented when it comes to explicitly supporting ecological connectivity. This section examines the legal and institutional context for corridor implementation, identifies governance challenges and gaps, and proposes directions for improving coordination, legitimacy, and effectiveness in corridor management in the Central Annamite Landscape (CAL).

5.1 Absence of a legal framework for biodiversity corridors

Government policy regarding connectivity in Viet Nam is primarily conducted at the provincial level. No national guidance or governance structure exists for the

establishment, monitoring, or management of biodiversity corridors. Pilot Guidelines for the Establishment and Management of Provincial Biodiversity Corridors have been developed using the three established biodiversity corridors in Quang Nam, Thua Thien Hue, and Quang Tri provinces as a model. Many of the steps for identifying the locations of corridors or proposed corridors have been undertaken. Imminent needs include the establishment of robust monitoring and management strategies.

In the absence of legal recognition, corridors risk being deprioritized in land-use planning processes. Local authorities may favor short-term economic gains (e.g., hydropower projects, acacia plantations) over maintaining landscape connectivity, especially when conservation mandates are weak or poorly resourced.

5.2 Overlapping mandates and coordination gaps

One of the challenges to establishing a management plan for biodiversity corridors in Vietnam is coordinating governance across large areas with multiple ownerships and established land use rights. There is no established management plan for the corridors, and thus, their on-the-ground management is similar to unprotected lands with socioeconomic priorities outweighing biodiversity conservation priorities. The corridors also span several different land uses and land ownerships: protection forests, production forests, community forests, private lands. To ensure connectivity-friendly practices can be enforced across these different land types, we need to clearly define the roles and responsibilities of the governing bodies involved.

Another challenge is the overlapping mandates of various agencies involved in forest management, biodiversity conservation, and rural development. The Ministry of Agriculture and Environment (MOAE), and provincial People's Committees all have roles, but lack a unified coordination mechanism for managing cross-boundary corridors. At the provincial level, inconsistencies in interpretation and prioritization of conservation goals further hinder alignment. For instance, while Thua Thien Hue has taken proactive steps to integrate ecological concerns into its spatial plans, neighboring provinces have prioritized economic development targets, leading to fragmented and inconsistent corridor planning.

Cross-sectoral coordination is particularly weak at the landscape scale. Protected area management boards, commune authorities, forestry enterprises, and NGOs often work in silos. Mechanisms such as interagency task forces or joint land-use planning platforms are rare, and where they exist, they lack decision-making authority and long-term funding.

5.3 Toward a multi-level, inclusive governance model

In the case of a biodiversity corridor in a large multiple-use landscape, such as the CAL, governance cannot rely on one type only. Because of the various land use and landowner types in different localities, and in the absence of national legislation on corridors and corridor governance, different sections are under different governance arrangements. The biodiversity corridors in Quang Nam and Thua Thien Hue incorporate many of governance and prominent stakeholders are government departments and agencies (e.g., the Department of Agriculture and Environment, Protection Forest Management Boards, the Forest Protection Department, district people's committees), adjacent communities, plantation owners, State Forest Enterprises, beekeepers and beekeeper associations, nursery operators, water companies, hydro-electric dam management authorities, and mass organizations like the Farmer's Union [55].

Given the complexity of biodiversity corridors, an important connection between current government policies is the call for an adaptive management framework that uses science-based, empirical evidence to evaluate the success of biodiversity corridor interventions. The adaptive management strategy works as a cycle: It begins with a quantitative, science-based assessment of baseline conditions, followed by conservation interventions, then repeating the science-based assessment to determine the intervention's impacts and the establishment of new baseline conditions. Critical to this framework is the establishment of a quantitative baseline of connectivity in the CAL, and determination of the science-based metrics needed to perpetuate the adaptive management cycle.

As research in the CAL demonstrated, inclusive governance where communities are not merely consulted but actively participate in rulemaking and benefit-sharing—leads to stronger legitimacy, better compliance, and more sustainable conservation outcomes.

6. Integrating science and technology for monitoring connectivity

Effective monitoring of biodiversity corridors is essential to evaluate ecological outcomes, guide adaptive management, and ensure the accountability for conservation investments. In the CAL, a growing array of scientific and technological tools have been introduced to support the assessment of both structural and functional connectivity. These include spatial modeling, camera trapping, genetic sampling, and participatory monitoring systems. This section reviews how these tools have been applied, their benefits and limitations, and recommendations for building a robust, locally owned monitoring framework.

6.1 From structural to functional connectivity: A conceptual shift

Historically, conservation planning in Vietnam has focused on static measures of protection—such as forest cover or the size of protected areas. However, ecological connectivity requires understanding not just where habitats are located (structural connectivity), but also how species move and interact with the landscape (functional connectivity).

- *Structural connectivity*: Structural connectivity is an effective method for establishing basic connectivity information. Structural connectivity analysis requires only land cover (i.e., forest cover) or land status (i.e., Protected Areas) geospatial data, and can be quantified simply based on the size, shape, and distance between forest blocks/PAs [56]. Therefore, structural connectivity analysis can be conducted with the limited field data, assuming appropriate GIS data are available. However, a considerable trade-off is that structural connectivity does not consider specific habitat preferences nor movement habits of individual species, such as climate and remoteness from human impacts [57]. For example, a structural connectivity analysis that treats all forest types as suitable habitat and assumes a generic long-distance dispersal threshold (e.g., 10 km) would misrepresent connectivity for the Annamite striped rabbit, which depends on moist evergreen forest, in particular, and is very unlikely to disperse 10 km.
- *Functional connectivity*: Functional connectivity is a more comprehensive assessment of animal movement across the landscape. Measuring functional

connectivity offers a complete and more realistic picture of connectivity by incorporating additional biological and species-specific information [58]. However, measuring functional connectivity requires substantially more field data and more complex data analysis [59].

Functional connectivity should, ideally, be estimated with the empirical movement data or from individual-based genetic data (described below). In the absence of these data types, presence-based methods or expert elicitation techniques can serve as proxies for functional connectivity [60, 61].

6.2 Gold standard methods: GPS collaring and non-invasive genetic sampling

GPS collars are the gold standard for understanding movement and functional connectivity. However, few landscapes have the resources to deploy a collaring effort on the scale needed to understand the frequency of movement between the protected areas with statistical confidence. One example is the Kavango-Zambezi Transfrontier Conservation Area in southern Africa, where more than a dozen organizations have collaborated to produce a dataset of hundreds of collared elephants, creating a unique scientific opportunity to use movement data to explicitly measure connectivity between the protected areas [62].

Given the difficulty of obtaining such a dataset, non-invasive genetic sampling is a promising alternative that can provide direct or indirect empirical evidence of movement between protected areas [63–66]. Direct evidence of connectivity can be obtained by detecting identical genotypes in non-invasive samples (hair, feces) from different locations in the landscape. For example, *Sawaya et al.* [67] genotyped hair samples collected from forests on either side of major highways in Banff National Park to assess the effectiveness of artificial road crossings in enhancing trans-highway connectivity. Indirect evidence of connectivity leverages the genetic relatedness of samples collected in different locations, under the assumption that populations that are more closely related to one another exchange more individuals and, thus, are more connected [63]. Modeling approaches can build on this assumption to answer specific questions about corridor locations [67] or leverage density estimation methods to better inform connectivity inference [66].

Although non-invasive DNA may be more cost-effective or more practical to collect at large sample sizes than GPS collar data, it does not come without challenges. The logistics of collecting fecal DNA in densely vegetated, remote, rugged areas, such as the Central Annamite, can be prohibitive. In such cases, fecal DNA detection dogs have proven to be an effective means of obtaining fecal DNA samples in challenging conditions [68–70]. Of particular interest to the case of the Central Annamite, Orkin et al. [71] found that detection dogs were significantly more effective than humans at finding feces of gibbons and langurs taxa that are of significant conservation importance in the CAL. Although GPS collaring and fecal DNA sampling have not been conducted yet in the CAL, there is promise that these approaches can soon be employed effectively, even for the rarest and most challenging CAL species.

6.3 Presence-based methods: Camera trapping and acoustic monitoring

Camera trapping has emerged as a cost-effective and scalable method for monitoring biodiversity. In the CAL, extensive camera-trap networks deployed under the WWF Vietnam's projects have documented movement patterns of key species across

proposed corridors. These include sightings of large-antlered muntjac, Owston's civet, and other cryptic or nocturnal species that are difficult to observe through the traditional means.

Although camera traps typically do not directly detect movement and connectivity between the protected areas, they can inform basic inferences about connectivity and support model-based estimates of connectivity. For example, detection of species along the predicted corridors may imply movement between core PAs, validating corridor assumptions and reinforcing the importance of maintaining these linkages. For example, camera traps placed within the hypothesized corridors connecting protected areas in the Terai Arc Landscape of India and Nepal revealed that tigers were indeed using the hypothesized corridors [72]. Furthermore, spatial and temporal analysis of camera trap data can reveal habitat preferences, corridor use, and the influence of human presence (e.g., snaring, road proximity). This information can be used to create a habitat suitability or occupancy model, which can then form the basis for functional connectivity analysis using common approaches such as Linkage Mapper [73] and Circuit-scape [71].

Yet, camera trapping is not without challenges. Equipment can be damaged or stolen, especially in areas with high human activity. Additionally, maintenance and data processing require significant human resources and technical capacity—both of which are currently limited in some Vietnamese institutions.

Whereas camera trapping has been well established at large scale in the CAL, some of the most culturally important CAL species live in the tree canopies (i.e., gibbons, douc langurs) and are not reliably detected. For these species, alternative methods of determining presence can be used to replicate the camera trap-based methods described above. For example, Vu et al. [74] and Thapa et al. [75] demonstrated the ability of acoustic monitors for standardized monitoring of gibbon populations in Phong Dien Nature Reserve in the CAL. Scaling these methods to complement the camera trapping surveys could produce a more holistic, standardized connectivity monitoring protocol for the CAL.

6.4 Community-based monitoring and SMART tools

To ensure monitoring systems are sustainable and grounded in local ownership, community-based approaches are essential. In the CAL, Spatial Monitoring and Reporting Tool (SMART) has been used to systematize patrol data and improve the enforcement efficiency. Local rangers and community forest groups record the patrol routes, wildlife sightings, and signs of illegal activity using handheld devices, feeding into a central database.

This data helps identify the threat hotspots, evaluate ranger performance, and adapt the management plans. In areas where connectivity corridors are vulnerable to snaring, encroachment, or infrastructure development, SMART offers a responsive mechanism for early detection and mitigation. Community-based data and SMART patrols may also support connectivity monitoring for species that are too rare to yield sufficient sample sizes with other methods. In these instances, an expert elicitation technique can be used for connectivity modeling (i.e., *Aylward et al.* [63]) using community observation and SMART patrol data.

Importantly, involving communities in data collection through citizen science, co-patrolling, or participatory mapping also strengthens local commitment to corridor conservation. Residents who are trained and trusted as ecological monitors often become strong advocates for forest protection.

6.5 Toward a national monitoring framework

Despite these efforts, Vietnam lacks a coordinated national framework for monitoring the connectivity. Monitoring protocols vary by project and geography, data are often siloed, and results are not always integrated into policy or planning. To address this, the following recommendations were developed:

- *Standardized protocols*: Develop national guidelines for monitoring ecological connectivity using camera traps, genetic sampling, and acoustic methods.
- *Data sharing platforms*: Establish centralized databases where monitoring data can be stored, accessed, and analyzed by multiple stakeholders.
- *Training and capacity building*: Partner with universities and NGOs to offer training in field methods, data analysis, and adaptive management.
- *Monitoring indicators*: Define a set of core indicators (e.g., species movement, forest cover change, threat incidence) that can be used across landscapes and projects.
- *Integration with policy*: Ensure that monitoring results inform decision-making at the national and provincial levels, particularly in land-use planning, PFES allocation, and protected area zoning.

6.6 Adaptive and inclusive monitoring

Finally, monitoring systems must be designed not just for ecological validity, but for adaptive use (i.e., Ringold *et al.* [76]) [77]. Data should feed back into the management cycles, informing where additional protection is needed, where corridors are functioning, and where interventions should be adjusted. This requires institutional buy-in, budget allocation, and a culture of evidence-based planning.

Inclusivity is also key. Monitoring should engage ethnic minority groups, women, and youth, offering not just information but incentives and recognition. Programs such as the Forest Guardians or village conservation teams can serve both conservation and development goals.

7. Challenges and lessons learned

Despite the growing momentum behind ecological connectivity and biodiversity corridors in Vietnam, particularly in the CAL, the implementation of integrated corridor management faces multiple challenges. These obstacles span ecological, institutional, social, and economic dimensions, often intersecting in ways that complicate conservation outcomes. Drawing from field research, interviews, and policy reviews, this section outlines key barriers encountered and the critical lessons learned for the future connectivity efforts.

7.1 Fragmentation, infrastructure, and the pace of development

One of the most pressing challenges is the rapid expansion of infrastructure within and around protected areas. Road networks, hydropower projects, and transmission

lines continue to encroach upon previously contiguous forest blocks, fragmenting habitats and disrupting wildlife movement corridors. In some districts like A Luoi and Nam Giang, planned road upgrades intersect directly with the proposed ecological corridors, creating urgent trade-offs between the development and conservation.

The limited coordination between conservation authorities and infrastructure planners exacerbates this issue. Although Vietnam's environmental impact assessment (EIA) framework theoretically includes biodiversity considerations, enforcement remains weak, and biodiversity corridor maps are rarely incorporated into early-stage planning processes. As a result, conservation interests are often reactive rather than proactive.

Lesson learned: Connectivity planning must be embedded in national and provincial infrastructure planning, including transport, energy, and land-use sectors. Tools such as the Asian Elephant Infrastructure Handbook (Asian Elephant Transport Working Group [78]) [79] and Green Listing criteria could support biodiversity-friendly development if mainstreamed earlier in project cycles.

7.2 Balancing conservation goals with community livelihoods

An essential condition for successful corridor conservation in the CAL is benefiting local communities that rely on the current land use plans in the corridors. Interventions to improve connectivity will most likely involve changes to the landscape *via* restoration, alternative agricultural practices, or environmental safeguards for infrastructure development. These changes must also improve the livelihoods of communities in biodiversity corridors. In recent interviews with the provincial government officials and reserve managers in Quang Nam and Thua Thien Hue Provinces, the three most-referenced community benefits were PFES, patrol income, and forest restoration (C. Aylward unpublished report). Many reserves stated that the support from PFES (\$2000 USD/village/year) was helpful, but not enough [50, 51]. Some alternative income streams included snare patrol jobs were viewed as community benefits by nearly all PAs. By expanding patrol jobs from PAs to biodiversity corridors, local communities may benefit economically while simultaneously promoting wildlife connectivity.

Interviews with local officials and reserve managers also revealed that forest restoration was widely viewed as a mutual benefit for communities and wildlife [80, 81]. Several PAs, such as Song Thanh National Park, support restoration in the buffer zones to provide ecosystem services to communities, such as erosion control, medicinal plant enrichment, and sources of food. By targeting key sites within biodiversity corridors, a restoration campaign could simultaneously promote wildlife connectivity while providing important ecosystem services to benefit local communities.

A significant amount of land in the corridors is comprised of Acacia plantations, which support the livelihoods for local communities. These plantations are persistently encroaching upon the natural forest, often illegally, because of their economic benefits. While it is widely believed that these plantations negatively impact wildlife populations, it is also suspected that wildlife may use plantations temporarily for movement [80, 81]; therefore, smaller plantations may not negatively impact connectivity. There may be a compromise between wildlife connectivity and Acacia plantations that can be supported by guidelines on plantation size, shape, or age. However, empirical data is required to understand the appropriate guidelines based on wildlife use of plantations. Programs such as beekeeping, medicinal plant harvesting, and rattan cultivation can have positive outcomes, but their scale and economic returns varied widely.

Lesson learned: Conservation interventions must be co-designed with communities, respecting customary rights and aligning with local development aspirations. Clear communication, equitable benefit-sharing mechanisms, and participatory mapping are essential to ensuring that corridors do not become new sources of conflict or exclusion.

7.3 Institution and governance complexity

Vietnam's governance structure creates another layer of challenge. Responsibilities for biodiversity, forestry, infrastructure, and land use are divided among multiple ministries and further fragmented at the provincial level. This leads to inconsistent policy implementation and competition over mandates, especially when corridor areas overlap with state forest enterprises, commune forests, or infrastructure zones.

There is no established management plan for the corridors, and thus, their on-the-ground management is similar to unprotected lands—with socioeconomic priorities outweighing biodiversity conservation priorities (*C. Aylward* unpublished report). The corridors also span several different land uses and land ownerships: protection forests, production forests, community forests, private lands. While there have been successful joint activities (e.g., enforcement patrols, saola monitoring), there is no formal mechanism or platform for collaborative corridor governance across administrative borders. To ensure connectivity-friendly practices can be enforced across these different land types, clearly defined the roles and responsibilities of the governing bodies involved are required.

Lesson learned: Multi-level and cross-sectoral governance platforms must be strengthened to support corridor implementation. This could involve formal agreements between provinces, joint management boards, or the use of Other Effective Area-based Conservation Measures (OECMs) to capture diverse governance types.

7.4 Monitoring and measuring success

As outlined in Section 6, monitoring connectivity is inherently complex. Structural connectivity is easier to visualize (e.g., through forest cover maps), but functional connectivity—actual movement of species—requires time, technology, and resources to assess. In many cases, baseline data are lacking, making it difficult to set the realistic targets or measure changes.

Furthermore, different stakeholders define success differently. For scientists, success might mean increased genetic flow; for communities, it might mean reduced human-wildlife conflict; for policymakers, it might mean alignment with biodiversity targets. Without a shared monitoring framework and common indicators, it is challenging to build consensus or demonstrate impact.

Lesson learned: A shared, multi-dimensional monitoring framework combining ecological, social, and governance indicators is necessary to track the effectiveness of corridors over time.

The CAL offers a valuable laboratory for testing models of integrated corridor conservation. While challenges remain, experience to date reveals that with strong governance, meaningful community participation, adequate financing, and science-based monitoring, ecological connectivity and local development can be mutually reinforced. By institutionalizing these approaches and aligning them with global goals, Vietnam can lead in demonstrating how corridors of coexistence can build ecological resilience, climate adaptation, and sustainable development in one of Southeast Asia's most vital conservation landscapes.

8. Conclusion

The CAL of Vietnam stands at a critical juncture rich in biodiversity and cultural heritage, yet increasingly vulnerable to fragmentation, climate impacts, and development pressures. As this chapter has argued, biodiversity corridors are not just conservation tools for maintaining ecological connectivity; they are also powerful frameworks for aligning conservation with human development in ways that respect the ecological thresholds and community aspirations.

Drawing on evidence from spatial modeling, ecological surveys, and fieldwork with local communities in Quang Nam and Thua Thien Hue provinces, the chapter has shown how well-designed and participatory corridor initiatives can simultaneously enhance wildlife movement, support forest-dependent livelihoods, and foster inclusive governance. Mechanisms such as PFES, sustainable NTFP harvesting, and participatory monitoring (e.g., SMART, camera trapping, C2C) demonstrate that when local people are empowered and fairly compensated, conservation outcomes are significantly improved.

However, institutional, legal, and financial challenges persist. Biodiversity corridors remain under-recognized in national legal frameworks, and implementation is often hindered by fragmented governance, short project cycles, and land-use conflicts. Addressing these barriers will require legal reform, mainstreaming of connectivity into planning processes, long-term funding commitments, and the creation of multi-level governance platforms that are inclusive and adaptive.

Looking ahead, future research should expand to assess the impacts of climate change on corridor functionality, particularly shifts in species ranges and ecosystem services under different climate scenarios [82]. Advancements in remote sensing, environmental DNA (eDNA), and AI-assisted monitoring can further improve understanding of wildlife movement and habitat dynamics [83, 84]. There is also scope for piloting innovative financing mechanisms, such as biodiversity credits and blended finance, to sustain the corridor management beyond project cycles [85]. Comparative studies across Southeast Asia would provide valuable insights for scaling connectivity models in other transboundary landscapes [86].

Nevertheless, limitations remain. Data gaps on lesser-known species and ecosystem processes constrain the ability to design fully representative corridors [87]. Long-term monitoring is costly and often donor-dependent, raising concerns about sustainability once projects end [88]. Social dimensions—such as power asymmetries, benefit-sharing mechanisms, and cultural differences among ethnic groups—pose additional challenges that may slow or complicate implementation [89]. Furthermore, political and economic shifts can reshape land-use priorities, creating risks for continuity of conservation programs [90].

The success of Vietnam's biodiversity corridors, particularly in the CAL, will depend not only on ecological science or funding, but on the ability to build trust, share power, and align interests across sectors and scales. This means treating communities not as beneficiaries, but as co-managers of shared landscapes. It means seeing biodiversity not as separate from development, but integral to its sustainability.

By advancing corridors of coexistence—where both wildlife and people thrive—Vietnam has the opportunity to lead in demonstrating how ambitious global biodiversity targets (e.g., CBD 30x30, SDGs, NDCs) can be grounded in local action, cultural values, and long-term stewardship. The lessons from the CAL offer both inspiration and practical direction for scaling such approaches across Southeast Asia and beyond.

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Conflict of interest

The authors have no potential conflicts of interest to declare.

Appendices and nomenclature

Category/Type	Description	Resistance
Plantation but has not yet become forest	Sandy land	10
Bare land with bush trees plantation but has not yet become forest	Sandy land with scattered trees	10
Natural forest	Natural Aceraceae on freshwater wetland	1
Other land	Other land	100
Other land	Other forestry land	100
Bare land with bush trees	Bare land on soil mountain	5
Bare land with bush trees	Non-forest rocky mountain	5
Rehabilitating forest	Land with rehabilitation trees on soil mountain	2
Rehabilitating forest	Land with rehabilitation trees on rocky mountain	2
Plantation forest	Planted land on soil mountain	10
Plantation forest	Planted sandy land	10
Plantation forest	Planted mangrove land	10
Natural forest	Bamboo mix with wood tree	1
Natural forest	Bamboo	1
Natural non-forest	Water surface	25
Crop land	Agricultural land	50
Natural forest	Bamboo	1
Natural forest	Natural rich forest	1
Plantation forest	Planted woody forest on sandy land	10
Plantation	Planted Aceraceae on wetland	10
Plantation	Planted woody forest on soil mountain	10

Category/Type	Description	Resistance
Plantation	Other planted forest on soil mountain	10
Plantation	Planted woody forest on mangrove wetland	10
Plantation	Planted bamboo forest on soil mountain	10
Natural forest	Other natural bamboo forest on soil mountain	1
Natural forest	Medium natural woody evergreen forest on soil mountain	1
Natural forest	Medium natural woody evergreen forest on rocky mountain	1
Natural forest	Rich natural woody evergreen forest on soil mountain	1
Natural forest	Very poor natural woody evergreen forest on soil mountain	1
Natural forest	Poor natural woody evergreen forest on soil mountain	1
Natural forest	Rehabilitating woody evergreen forest on soil mountain	1
Plantation but has yet become forest	Bare land in alum wetland	10
Plantation but has not yet become forest	Land with rehabilitating trees on alum wetland	10
Plantation forest	Planted land on rocky mountain	10
Natural forest	Mixed woody forest on soil mountain	1
Natural forest	Medium natural forest on soil mountain	1
Natural forest	Very poor natural forest on soil mountain	1
Natural forest	Poor natural forest on soil mountain	1
Crop land	Land with crop tree on wetland	50
Natural forest	Natural rehabilitating woody forest on wetland	1
Plantation	Woody plantation forest on rocky mountain	10

Table A1.

Land cover categories and their assigned resistance values used in connectivity modelling.

No	Name	Organization
1	Dr. Peter Singleton - Research Wildlife Biologist	US Forest Service Pacific Northwest Research Station
2	Dr. Nguyen Truong Son - Mammal specialist	Department Vertebrate of Zoology, Institute of Ecology and Biological Resources.
3	Dr. Le Manh Hung – Bird specialist	Department Vertebrate of Zoology, Institute of Ecology and Biological Resources.
4	Dr. Cao Tien Trung – Reptile and amphibian specialist	Faculty of Biology, Vinh University

No	Name	Organization
5	Dr. Van Ngoc Thinh – Primate specialist	WWF Vietnam
6	Mr. Nguyen Quang Hoa Anh - Biodiversity Monitoring specialist	WWF Vietnam
7	Mr. Luong Viet Hung - Protected Areas Management specialist	WWF Vietnam

Table A2.
List of experts participating in the development of consensus estimates for resistance surface and connectivity modeling.

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Improving Fruition and Protecting Nature through Landscape Design and Nature-Based Solutions: The Case of West Iceland

Daniele Stefano

Abstract

Iceland is situated on the fault line that separates the European continent from the North American continent, making it a virtually unique location in the subarctic belt of the planet. Lava flows caused by the collision and movement of the two platforms have created a unique land. To protect this uniqueness, there are several protected natural areas and three national parks in Iceland. In the western part, the Snæfellsnes peninsula is recognisable by the profile of the Snæfellsjökull volcano and its glacier, home to one of the national parks. One of the current challenges is managing the flow of tourists and protecting nature. Recent landscape architecture projects by renowned design studios, such as Landslag and Arkís, have redefined access points and routes to iconic sites, including the Saxholl crater. Walkability has proven crucial in both protecting nature and enabling the public to reconnect with it. Another successful example was the riverbank restoration in the Andakilsá nature reserve in Borgarnes, which demonstrates the relevance of nature-based solutions in areas of ecological importance. The use of nature-based solutions is also becoming relevant in responding to societal and environmental challenges. The text aims to demonstrate the benefits of carefully designing public spaces in relation to natural elements within and adjacent to protected areas, balancing functionality and aesthetics to create a destination that attracts visitors from around the world due to its unique natural and cultural characteristics.

Keywords: landscape project, walkability, nature protection, National Park, Iceland, volcanic land, glacier, nature-based solutions

1. Introduction

Iceland is an island nation with many extraordinary features, both in terms of nature and culture. It is situated on a fault line in the subarctic zone that divides the European and North American continents. Lava flows caused by the collisions and movements of the two platforms have created a unique land. Iceland's severe subarctic climate is a result of its geographic location. In terms of phytogeography, the

island is a part of the Arctic province of the Circumboreal region and lies within the Holarctic floristic domain. The tundra zone encompasses the majority of the nation. Throughout most of Iceland's surface, plant cover is sparse, with only 25% of its land area covered by stable vegetation. Only 0.1% of Iceland is arable, with 76.0% consisting of uncultivated and arid land (sand fields, lava flows, and glaciers), followed by pastures and meadows (22.7%) and woods (1.2%) [1].

In recent decades, Icelandic society has faced significant changes, partly due to tourists' growing interest in visiting the island for its natural and cultural attractions. The country offers three national parks: Thingvellir, Vatnajökull, and Snæfellsjökull. Thus, Iceland's tourism industry is evolving, and these changes are accelerated by easier access to formerly inaccessible natural sites. Increased accessibility heightens the need for further infrastructure development to mitigate the environmental strain that tourism is placing on Iceland's environment. This underscores the importance of preserving specific natural areas in their natural state while still allowing locals and foreign visitors to enjoy a range of recreational options (**Figure 1**) [2, 3].

Nature-based and engineering-based solutions have also been expanding throughout Iceland. As national and regional authorities are beginning to adopt these solutions, it could raise the demand for funding for actual NBS projects. Flood dangers, habitat regeneration to boost biodiversity and plant life, wetland restoration, and coastal and marine protection are just a few of the societal issues that these projects are attempting to address. Much research has been conducted through the Nordic Co-operation, an extensive form of regional collaboration involving Denmark, Finland, Iceland, Norway, Sweden, and the Faroe Islands [4].



Figure 1.

*The Snæfellsness peninsula in western Iceland is home to the Snæfellsjökull volcano and the glacier above it. The unspoiled nature is home to a unique array of flora and fauna in a subarctic environment. Small remote towns are scattered throughout the area, with a sparse population. The volcanic landscape, unique in the world, which inspired Jules Verne's novel *Journey to the Centre of the Earth*, is now visited by numerous tourists. Today, the park's management also involves the creation of trails that blend seamlessly into the natural and cultural context, allowing visitors to enjoy the area while protecting the surrounding nature. Photo by D. Stefãno, 2024.*



Figure 2.
 A map of the case study and the respective protected areas in West Iceland. In brown, the National Park of Snæfellsjökull is visible as well as Andakill Protected Habitat Area. In yellow, the singular cases are shown. The representation is synthetic for communication purposes and only the place mentioned in the chapter are displayed. Graphic developed by D. Stefano, 2025.

This phenomenon highlights the importance of tourism management and its sustainability in relation to nature conservation. The purpose of sustainability is to meet current demands without compromising the needs of future generations [5]. Nowadays, integrating social, environmental, and economic factors is the primary goal of Iceland's active sustainability policy. Long-term objectives and initiatives that facilitate this integration are given priority [6]. For this reason, the concepts of landscape and landscape design play a crucial role in the management of these areas, whether through large- or small-scale designs.

Taking cultural and natural elements into consideration, the discipline of landscape architecture has been making a significant contribution to preserving the well-being and quality of life. The profession encourages sustainable development that is founded on a harmonious and balanced interaction between the environment, economic activity, cultural factors, and social demands. New opportunities for both practical and educational research are emerging in these domains. Thanks to this awareness, landscape design culture has developed significantly in recent years, and several projects have focused on the management of protected natural areas [7].

The selection of certain cases is not intended to be exhaustive. In fact, many others could have been used as examples (and therefore reference should be made to the various publications mentioned). Instead, the intention is to use a few clear-cut cases to show that intervention in protected areas can be simple and effective. The aim is to initiate a debate that can be extended to various other disciplines and geographical areas, thereby raising awareness of the available means (**Figure 2**).

2. Realised projects in Snæfellsness Peninsula

Several natural landmarks may be found in West Iceland. Reykjavík is the nation's capital. Then the area includes the strongest hot spring in Europe, glaciers, waterfalls,

and significant historical sites. Skardsheidi and the mountain Hafnarfjall are part of a 4-million-year-old extinct core volcano near Borgarnes. In western Iceland, the Snæfellsnes Peninsula is recognisable by the profile of the Snæfellsjökull volcano and its glacier, which forms one of the island's three national parks. Crossing the peninsula on the northern side, visitors will find Stykkishólmur, a small town with a small port, as well as Sugandisey, which used to be an island but is now connected to the mainland. Many visitors enjoy walking to this former island to observe the birds and appreciate the stunning scenery of Breidafjord Bay and its surrounding area, where a lighthouse overlooks the West Fjords.

In recent years, various municipalities in Iceland have launched design competitions to restore accessibility to various natural sites. In this way, the authorities have sought to promote conscious and careful design that takes landscape issues into account while also regulating tourist flows, given that the peninsula is a place of great interest to both residents and tourists alike. Below are four projects in particular that have improved the usability of the landscape, with aesthetic and functional qualities also taken into consideration. These four areas are Stykkishólmur, Svöðufoss, Saxhóll, and Hellissandi.

In Stykkishólmur, in a little marina that overlooks the West Fjords, we found one project that has reinterpreted pedestrian accessibility in natural areas on the peninsula [8]. A competition was recently organised in collaboration with the Icelandic Association of Landscape Architects (FÍLA). According to the jury, the main objectives of the competition were enhancing safety at a popular viewpoint, encouraging experiences in nature, and further increasing the attractiveness of Stykkishólmur as a desirable tourist destination in Snæfellsnes [8]. Glámu-Kím and Landslag created the winning design in collaboration with Ólöf Nordal and Gunnar Karlsson. The report states that the project intended to strike a balance between the natural and the artificial, with caution, respect, and humility towards the site serving as the guiding principles for both the conceptual work and the project solution (**Figure 3**).

Another example of recently designed and constructed walking trails can be found in Svöðufoss. This waterfall is 10 metres high and cascades down from a majestic basalt column that surrounds it. The public authorities developed a trail composed of simple materials which enabled tourists to see the incredible magnificence of the place, with the Snæfellsjökull glacier in the background. Many visitors, including photographers, often gather around the waterfall on sunny days to capture the picturesque views (**Figure 4**) [9].

Inside the National Park, Saxhóll is a 45-metre-high oval-shaped volcanic crater that rises from the moss-covered lava fields in Snæfellsnes Peninsula in western Iceland. The hill is a popular destination offering stunning views of the endless lava, the Atlantic Ocean and the Snæfellsjökull glacier. The walk follows a path that has been formed over time by visitors climbing the easiest ramp to reach the summit. With the rapid increase in visitors in recent years, the loose material on the hill was beginning to deteriorate, and the ascent route was already split into parallel, deformed paths. In 2014, authorities decided to take action to prevent further damage to this vulnerable landscape.

In 2016, landscape architects at Landslag redesigned the crater of the Saxhóll volcano with a curvilinear path. The extinct volcano became a mountain of lava covered with moss and Arctic vegetation, overlooking the picturesque Snæfells glacier. A stairway follows an old, crumbling path, now obscured by the growing crowds of tourists, and marks the boundary of the crater. The trail was completed in 2016, and the black steel surface quickly rusted, blending in well with the red hues of the



Figure 3.
The Stykkishólmur project, designed by Landslag, fits in with great simplicity and consistency, respecting the morphology. The colours and materials chosen also reflect the surrounding nature. Considering that landscape is the combination of natural and anthropogenic phenomena, the design of the trails allows visitors to appreciate the beauty of nature without compromising its biodiversity. This means that many tourists can visit the area every day. Photo by D. Stefano, 2024.



Figure 4.
The path designed to make the Svodusfoss waterfall accessible follows a minimalist aesthetic, aiming to have the least possible ecological and visual impact. However, the architectural details are carefully crafted, and the materials have been chosen with care. Even natural patterns are evoked in some way by the path, which mirrors the course of the river and the landscape's morphology. The colours blend into the landscape, remaining visible yet harmonious. The landscape design shows all its consistency and effectiveness here. Along the route to visit Svodusfoss, dry stone walls have been built according to Icelandic building traditions, using stones from the local area. These elements evoke aspects of the local landscape and are integral to the local culture. Seats have been installed on top of them to offer visitors the opportunity to stop and rest, sheltered from the wind, and to enjoy the best and most significant views of the natural monument. Photo by D. Stefano, 2024.



Figure 5. *“It’s not what is upon this island, but what is underneath that interests me.” (Verne, Journey to the Center of the Earth). The climb up the crater is a design that makes a utopian design realistic. It is a way to allow people to visit a place that is generally inaccessible and difficult to see. The landscape project successfully opens up the landscape and its spectacular views to the public. The attention to morphology, materials, and colours has made this project iconic, and it has won awards in several competitions. Photo by D. Stefano, 2024.*

volcanic crater and the vegetation. As a result, nearly all visitors are now using this trail (**Figure 5**) [10].

The curve consists of two staircases that meet halfway up, emphasising a pause in the ascent. The steps, made of perforated steel, rest dry on the ground and are placed on the red hues of volcanic activity and spontaneous vegetation, forming an extension of the orography. The geometry is barely perceptible, yet it clearly defines a slow and evocative ascent, offering a meditative arrival. The summit provides a panoramic view of the deep crater, the surrounding lava fields, the Atlantic Ocean, and Snæfellsjökull (**Figure 6**).

The environmental impact is also minimal. The units are joined together and require no foundations other than the rigid steel plates fixed in the slag. Therefore, the structure can be removed without leaving any permanent traces. To prevent damage from tourist traffic at the summit, a panoramic platform is being constructed on top of the crater. In 2017, the Saxhóll Crater Stairway was nominated for the Nordic Architecture Fair Award in Gothenburg, the Icelandic Design Awards, and the DV Cultural Awards in Reykjavík, Iceland. Hence, an award-winning metal stairway now protects the fragile landscape and guides visitors quickly up the volcanic crater (**Figure 7**).

In Hellið, the public authority has realised yet another project. The Snæfellsjökull National Park Centre is a building designed by architects at Arkís, which won a competition in 2006. Construction of the building was completed in 2022, and the centre officially opened in 2023. The uniqueness of this structure implies the possibility of walking on the roof, making it open to visitors as a terrace.



Figure 6.
The oxidised stainless steel staircase blends in quietly, but leaves the design visible. Walkability in national parks ensures that tourists can explore protected areas while respecting nature by controlling tourist flows. In a world like today's, where people flows can be very large, this is a solution that is both functional and aesthetic. The volcanic rocks are displayed in all their splendour, celebrating the beauty of this natural monument. Photo by D. Stefãno, 2024.



Figure 7.
The view of the Snæfellsokull glacier is enhanced by the panoramic railing at the end of the walk. All structures have a minimal environmental impact, while also being designed to withstand heavy use and ensure visitor safety. Slow walking is also synonymous with quality tourism, and this feature is encouraged by the design. The 360-degree view is a favourite spot for visitors, which does credit to the national park. Photo by D. Stefãno, 2024.



Figure 8.

The new structure, designed as the entrance and bookshop for the national park, is a piece of architecture that uses the roof as an open, walkable space. A public space overlooking the volcano, offering an impressive view. This relationship between new architecture and landscape, landmarks, and patterns of the territory demonstrates the quality of the park's service facilities. The beauty of nature is also celebrated by human interventions that intelligently respect it. Photo by D. Stefano, 2024.



Figure 9.

The beautiful Snæfellsjokull glacier, featured in Jules Verne's Journey to the Center of the Earth, is inexorably melting, but it remains an imposing natural monument visible from far away on clear days. Today, the national park is visited by numerous tourists and locals who come to admire the glacier above the volcano, which is melting day by day. The summit is recognisable even from many kilometres away thanks to its iconic peaks. It is undoubtedly one of the main landmarks of the entire peninsula. The view is from the terrace of the aforementioned building. Photo by D. Stefano, 2024.

The entire construction and management process has been carried out using environmentally friendly methods, and the choice of materials is based on low-maintenance principles, as no exterior paint (**Figures 8 and 9**) [11]. This fascinating building cleverly plays with volumes, creating interesting geometric shapes with high-quality details. The services it offers are integrated into a beautiful and functional structure that has an important relationship with the surrounding landscape. Events and exhibitions can be hosted inside, where there is a small library with informative materials about the park [11].

The case studies on the Snæfellsness peninsula, although distant from each other, form an important network that defines a quality across the entire territory. Created in the most iconic and therefore most visited sites, they consistently maintain an excellent standard, ensuring the quality of both the public space and the project remains constant, both inside and outside the park perimeter. This illustrates how individual projects can consider their connections with other sites on a broader scale. These are, therefore, model cases that can also inspire areas with different situations.

3. Nature-based solutions in Andakill protected area

The Andakill Protected Habitat Area is a protected nature reserve and habitat, situated near the estuary of the fjord Borgarfjörður. It includes the lake Vatnshamravatn and two rivers (Hvítá and Andakilsá), as well as marshes, controlled hayfields, and alluvial floodplains. Among the many waterbird species found in the area's freshwater lakes are the White-Tailed Sea Eagle (*Haliaeetus albicilla*) and shelducks (*Tadorna tadorna*). Regular floods along the Hvítá River have produced alluvial plains with large sediment loads, which are a crucial place for wetland birds such as Greenland white-fronted geese (*Anser albifrons flavirostris*) [12].

Promoting the preservation and upkeep of the natural state of various wetlands and the habitats of different bird species is the goal of protection. Additionally, the protection ensures public access to the region for educational and recreational purposes, including nature viewing. Additionally, the protection aims to provide study opportunities and monitor the local ecosystem, with a particular emphasis on wetlands and bird habitats.

The Andakilsá River, located on the opposite side of the peninsula, features extensive wetlands and marshes. Flood control, sediment and nutrient retention, carbon storage, and coastal stability are the wetland's primary hydrological needs. In recent years, the riverbank has suffered from intense erosion, and the public authority has encouraged projects utilising nature-based solutions for its restoration. By applying sustainable bank protection and utilising materials from the nearby area, riverbank erosion was mitigated, thereby enhancing biodiversity [12].

Nature-based solutions are defined by the IUCN as "actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" [13]. Replicating natural physical processes is a strategy to increase sustainability and provide resilience against climate change. Increased biodiversity has resulted from sustainable methods of controlling landslides and erosion. Also, fish in the rivers have more formidable reproductive habitats. To mitigate sociocultural barriers, local stakeholder involvement was crucial.

The technique used in Andakilsá is less intrusive. It preserves the river's aesthetic and natural integrity because it relies on the use of wooden buildings rather than



Figure 10.

The erosion of the Andakilsá riverbank has been controlled thanks to an intervention that is now barely visible and therefore successful. The renaturalisation of the bank was the final phase, which followed the insertion of large logs across the section of the river to allow the watercourse to recover its bank. This type of intervention avoids more invasive ones and is ideal in protected areas. Photo. D. Stefano, 2025.

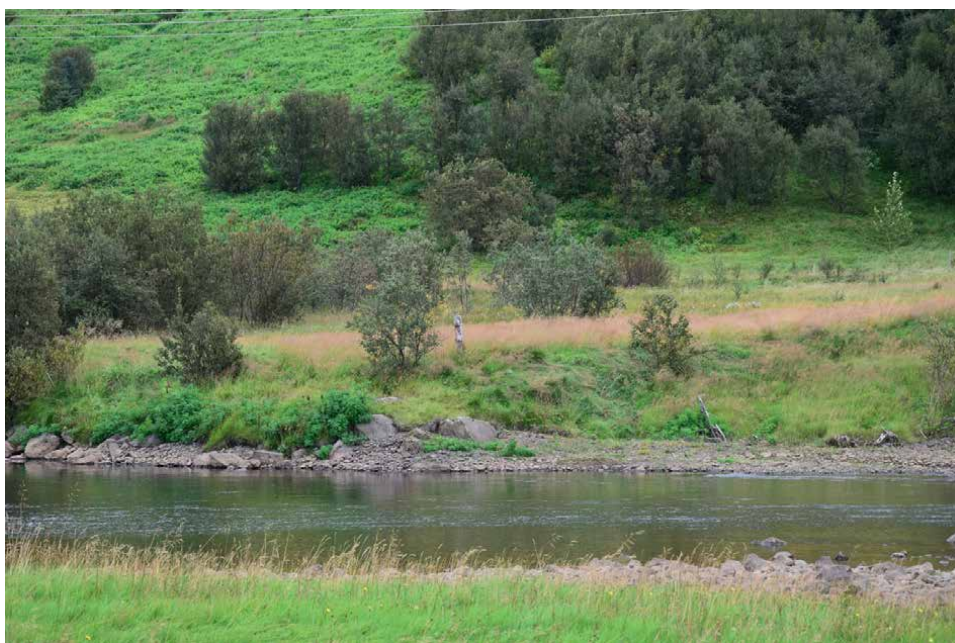


Figure 11.

With this nature-based solution technique, the natural system is able to heal itself, and it is possible to reintroduce local vegetation that gradually recovers the surface area in harmony with the vegetation of the protected natural area. This project has been a success story, demonstrating how NBS can be useful in areas of this type. Today, the area is also very popular with fishermen, who have formed a local association. This makes the place very interesting, as it has preserved traditions in the anthropic uses of the river. Photo. D. Stefano, 2025.

structures made mostly of stone to stabilise the riverbank. Because rivers serve as breeding grounds for salmonid pairs, which eventually migrate to the ocean, this method of riverbank restoration can enhance coastal and marine ecosystems. The bank, where a tree's root plate shuts off the flow, is stabilised by large wood structures. The entire tree, or a trunk measuring five to six metres, is now utilised. Vegetation can develop to better stabilise the soil (**Figure 10**) [14].

This method is based on the idea of reproducing a natural process, and as a result, continuous operations to stabilise the riverbank should not be required. Since there is no usage of grey infrastructure or synthetic materials, monitoring and maintenance is low. Following this intervention, progress can be tracked by periodically monitoring the biodiversity, vegetation, and soil stability of the riverbank [14]. Research on riverbank restoration techniques and strategies is expanding globally. There may be limitations related to the availability of nearby natural resources or whether the necessary machinery can access a region. Employing local resources it is less expensive than relying solely on rocks to defend a riverbank, a technique that was frequently used in the past (**Figure 11**).

4. Genius loci and aesthetic in the project: Defining a methodology

These are just some of the recent realisations occurred in Iceland, but iconic for the new trend in landscape design, especially in relation with protected areas. When we discuss protected areas or national parks, we often think of minimal-impact interventions. In any case, projects that are attentive to the landscape and the environment are necessary, especially in this era of abundant tourist flows in places like Iceland. Through good design, it is possible to ensure that trails are well integrated into the context, both from a functional and aesthetic point of view. In this way, it is possible to better protect the surrounding nature by avoiding confusion within the natural environment.

The relevance of this chapter lies in highlighting the importance of landscape design and its methodology in promoting sustainable tourism. This methodology starts on a large scale and, in a coordinated manner, finds a system that extends throughout the territory, including protected areas. This enables targeted interventions with customised solutions, tailored to each specific situation, while respecting the unique characteristics of the location. This is precisely why Iceland represents a large field of experimentation where it is possible to interact with an imposing and unique natural environment. Here, landscape sensitivity can be applied not only functionally but also aesthetically, leaving a visible and significant mark. Even more naturalistic operations, such as Nature-Based Solutions, when implemented systematically, have positive effects on environmental protection and the preservation of the natural and cultural characteristics of the place.

Considering the importance of walkability, understanding landscape design must encompass both functional and aesthetic aspects. First, emphasis should be placed on *Genius loci*, taking into account the characteristics of the place. Cultural and natural heritage are the prerequisites for conscious design in public spaces. The concept of *Genius loci* in relation to landscapes enables an understanding of a specific context, providing valuable tools for enhancing landscape, urban, and architectural design within protected areas. Landscape design can be understood by reading the plan as well as by reading the surrounding context. This concept is becoming important in managing various crises proposing solutions that are connected with reality [15].

As said in the introduction, the landscape consists of numerous elements which, taken together, determine the specificity and originality of a site. Also, for its evaluation, each constituent element of the landscape must therefore be considered in terms of its relationship with the others that compose and characterise it. An integrated reading of the functioning of the various components of the landscape allows us to consider the relationships between the identifying characteristics of the landscape. The value of a landscape must be identified in:

- ecological value as a set of ecosystem functions capable of defining the degree of vulnerability and intrinsic value of ecosystem structures;
- cultural value as a source of inputs that interact with human creativity. It is the expression and history of each community.
- social value as a territory where a group, through its own organisational system, asserts its sovereignty, where a system of values deriving from its own “experience” is clearly present and perceptible;
- economic value in that the demand for beauty increases the price of homes, spaces, and proximity located in an environmental and visual setting shared as a “beautiful landscape.”

Perception and social identity are also fundamental. Landscape identity can be defined as the perceived uniqueness of a place. Learning to perceive and experience a particular landscape cannot be separated from understanding its multifaceted identities, which are linked to its social uses. The concept of landscape identity helps us to explore the interaction between people and their surrounding environment. Thus, the links between physical landscapes and communities are indissoluble [16].

These concepts can be taken into consideration more often, since design interventions are necessary. Some of them must be visible and also create a perceptible aesthetic that fits in harmoniously with the context (as we have seen in the cases of the Snæfellsness peninsula). In contrast, others may be less visible and only consider the use of natural elements from the site (as in the case of Nature-Based Solutions in the Andakill protected area). We saw how protected areas need to control walking routes for visitors, offer services, protect nature, and minimise both visual and ecological impacts. Finally, landscape design can also add meaning by interpreting the natural and cultural forms of the place, creating poetic interventions that reflect the identity of the place. All this is done in the service of visitors and nature.

5. Conclusions

That research emphasised the importance of recognising that each place is unique and has its own distinct soul or spirit, which sets it apart from other places. At the same time, the need for each place to offer something unique, something that cannot be found elsewhere, is increasing. That need is equally shared by those who visit the places as tourists, by residents who want to attract new job opportunities, and by those who are looking for the threads that connect society.

Local awareness is a fundamental concept, and its importance is expected to increase in Iceland in the coming years, as the country follows the wave that has

already passed through its neighbouring countries. A good sense of place consists in being able to identify many elements on which the spirit of the place is based, understand the interaction between them, evaluate the factors that reduce peculiarities and the factors that strengthen them.

In conclusion, the examples shown suggest a methodology that can be applied in protected natural areas and national parks. These cases demonstrate that designers, public authorities, and the population can collaborate effectively to create virtuous situations, both from a functional and aesthetic perspective. These cases also serve as examples for other areas at different latitudes and with different characteristics. These concepts can then be adapted to each specific situation in a manner suitable for various areas and cultural and natural contexts.

It is hoped that much more can be done in terms of planning, design, research, education, and dissemination to care for the territory and protect the nature and culture that have shaped it, with the collaboration of the population. In this way, conscious and sustainable tourism can also grow in relation to protected natural areas and national parks.

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Perspective Chapter: Reshaping Governance at Tram Chim National Park – From Conservation Conflict to Ecological Consensus

Nguyen Kim Dung

Abstract

This chapter analyzes the governance transformation at Tram Chim National Park, detailing its shift from a failed “Fortress Conservation” model to an integrated, ecosystem-based approach. The primary objective is to demonstrate how this new model, which treats the park and its buffer zone as a single social-ecological system, can reconcile biodiversity conservation with sustainable livelihoods. The initial fortress model, characterized by a closed dyke system, severely disrupted the wetland’s natural hydrological pulse, leading to habitat degradation and the disappearance of the iconic Sarus Crane. Faced with this failure, the Dong Thap provincial government initiated a change guided by scientific evidence. The analysis reveals that the new governance model is built on key pillars: ecological zoning of the buffer zone, transitioning to sustainable agriculture (e.g., “Crane-calling Rice”), building community partnerships, and establishing a formal co-management regulation to harmonize stakeholder actions. A key result is the initial recovery of the ecosystem, symbolized by the successful return of the Sarus Crane. This positions Tram Chim as a vital “living laboratory” for a resilient Mekong Delta facing climate change.

Keywords: ecosystem-based governance, Fortress Conservation, Sarus Crane restoration, sustainable livelihoods, social-ecological system, Vietnam

1. Introduction

The governance of protected areas is a critical global issue, often caught between the imperative of biodiversity conservation and the socio-economic needs of local communities [1, 2]. For decades, the dominant paradigm was “Fortress Conservation,” which sought to protect nature by creating isolated reserves, strictly separated from human activities [3, 4]. However, this model has been increasingly criticized for its social costs and ecological ineffectiveness, particularly in complex landscapes where human and natural systems are deeply intertwined [4, 5]. In response, there has been a global shift toward more integrated and participatory models, such as

the “Ecosystem-based Approach” promoted by the Convention on Biological Diversity and the “Wise Use” philosophy of the Ramsar Convention [6]. These approaches recognize that sustainable conservation must address the entire social-ecological system, integrating livelihood development and stakeholder collaboration into governance frameworks [7]. This chapter examines such a governance transformation through the case study of Tram Chim National Park in the Vietnamese Mekong Delta, a critical wetland ecosystem that has moved from a failing fortress model to a pioneering, integrated approach.

Tram Chim National Park, a remaining natural heritage of the vast Plain of Reeds, is one of the most ecologically and biologically significant special-use forests in the Mekong Delta [8–10]. Established in 1998, the park covers a core area of 7313 hectares. Its international status was affirmed in 2012 when Tram Chim was recognized as the world’s 2000th Ramsar site, a testament to its indispensable role in conserving habitats for water birds. With outstanding biodiversity, including 231 bird species, 238 plant species, 129 fish species, and as a home to iconic species like the Sarus Crane (*Antigone antigone*), Tram Chim is considered a cornerstone for conservation, sustainable livelihood development, and climate change adaptation within Vietnam’s entire special-use forest system [11].

Situated in a tropical monsoon climate, the region experiences two distinct seasons: a rainy season from May to November and a dry season from December to April, with an average annual rainfall of 1499 mm. The park’s hydrology is directly influenced by the Mekong River’s flood regime, and its topography is characterized by low-lying wetlands typical of the Plain of Reeds. This natural “pulse”—a seasonal wet-dry cycle—is the lifeblood of its ecosystems, which include melaleuca forests, seasonal marshes, and permanent wetlands (**Figure 1**) [10].

However, this precious gem does not exist in isolation. It is situated within a complex socio-economic and environmental context, where conservation efforts face fierce internal challenges and external pressures [12–14]. Once part of a vast

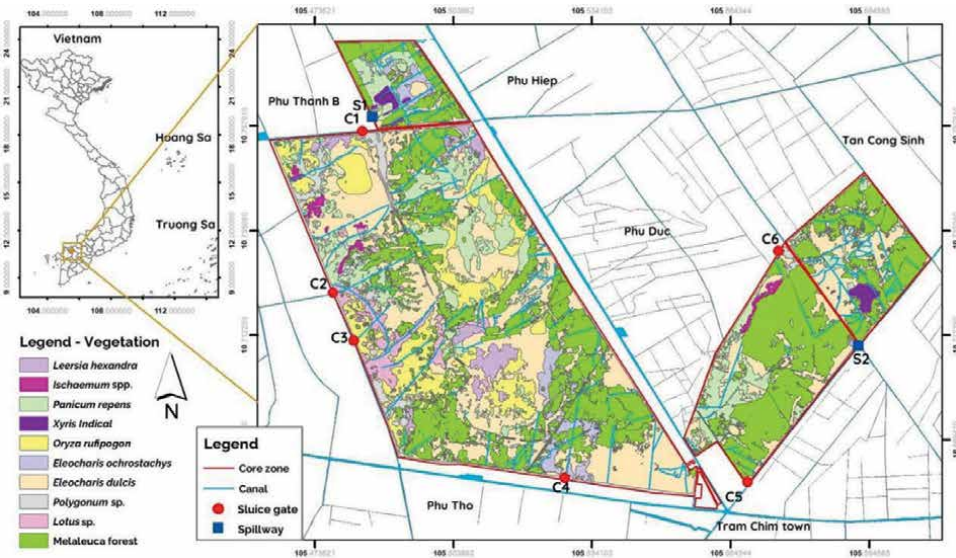


Figure 1.
The Tràm Chim National Park and its vegetation.

inundated wetland, after the country's reunification, the entire landscape surrounding Tram Chim underwent a dramatic transformation toward intensive agriculture, with a new culture tied to a system of solid dykes for flood control. This development model, despite its achievements in food security, has gradually pushed the region into an economic rut and created profound consequences [15, 16]. Communities in the buffer zone—the land surrounding and directly impacting the Park—face a high poverty rate [17]. A survey from the Buffer Zone Development Project showed that in 2022, this rate was 3.4%, higher than the district's average of 2.8%. Their livelihoods are primarily based on low-efficiency rice monoculture and a poorly diversified job market. This livelihood pressure inevitably leads to the exploitation of resources from the Park as a last resort [18].

Paradoxically, the greatest threats to Tram Chim stem from the very efforts to protect it. Inside the core zone, to mitigate the risk of forest fires, a closed dyke system was built to maintain high water levels year-round. This intervention, while solving an immediate problem, inadvertently disrupted the natural hydrological “pulse”—the seasonal flood-dry cycle—which is a core characteristic of the ecosystem [14, 19, 20]. Consequently, many important habitats were altered, vegetation degraded, and ironically, the food source for the Sarus Crane was severely affected, contributing to their declining numbers in recent years, culminating in 2020 when not a single crane was recorded returning—a “tipping point” marking the undeniable failure of the old model.

Compounding these management-induced pressures is the overarching threat of climate change. The Mekong Delta is one of the world's most vulnerable regions to experience its impacts. The region is facing an intensifying trend of climate change, with mean annual temperatures having already risen by +0.76°C (1981–2018) and projected to climb another 1.3°C to 1.8°C by mid-century, alongside an increase in extreme rainfall events [21]. For Tram Chim National Park, these changes pose direct threats: shifting rainfall patterns will disrupt the critical hydrological “pulse” essential for its vegetation and wildlife, while more severe heatwaves create a dramatic risk of large-scale forest fires from accumulated dry fuel. In response, as noted by the report from Espagne et al. [20], “hard” adaptation measures like dykes often cause secondary problems, such as blocking sediment and altering ecosystems. Therefore, Tram Chim requires a comprehensive strategy centered on nature-based solutions to restore its natural functions, integrated with the control of wider anthropogenic pressures like groundwater and sand mining [21].

Meanwhile, from the outside, activities in the buffer zone are creating increasing cross-boundary pressures. Survey results from the “*Development of Tram Chim National Park Buffer Zone, 2021–2030*” project recorded the overuse of fertilizers and pesticides at alarming levels, with 11 banned active ingredients still in use. Spontaneous shrimp farming by exploiting brackish groundwater or spreading salt poses a risk of salinization, threatening to permanently alter the native freshwater ecosystem. Along with this are long-standing conflicts between humans and wildlife, such as illegal cattle grazing in the park [18].

This dilemma—between a global natural heritage in need of protection and the pressure of human livelihoods coupled with the consequences of an inappropriate management model—has posed an urgent demand. Clearly, the “Fortress Conservation” approach, which views humans and nature as two separate and opposing entities, has revealed its systemic failures. Focusing solely on strict protection within boundaries while ignoring the organic hydrological, ecological, and socio-economic linkages with the surrounding landscape is an unsustainable strategy [9, 10, 13, 14].

This chapter analyzes the profound shift in the governance model at Tràm Chim, from the failures of isolated conservation to the development of a new, integrated approach. The primary objective is to demonstrate how a transition to an ecosystem-based governance model, which treats the park and its buffer zone as a single social-ecological system, can reconcile conservation with sustainable development. This analysis is based on the comprehensive findings of the “*Development of Tràm Chim National Park Buffer Zone, 2021-2030*” project, which involved interdisciplinary scientific research, including biodiversity surveys, environmental quality assessments (soil, water), and detailed socio-economic investigations through household interviews and stakeholder focus groups [18]. By analyzing the pillars of spatial, institutional, economic, and social reforms, this chapter will demonstrate that Tràm Chim is not just a protected area being saved, but also a pioneering “living laboratory,” providing invaluable lessons for a sustainable and climate-resilient future for the entire Mekong Delta region and elsewhere.

2. A note on methodology

The analysis in this chapter is grounded in extensive data from the “*Development of Tràm Chim National Park Buffer Zone, 2021-2030*” project, where the author served as both a project manager and a social researcher. This multidisciplinary project employed a mixed-methods approach to build a holistic understanding of the Tràm Chim social-ecological system.

1. Data collection: This involved both the collation of secondary data (socio-economic statistics, environmental reports, policy documents) and the collection of new primary data. Field surveys were conducted across two seasons (wet and dry) to assess biodiversity (flora and fauna), land use, and water quality. Socio-economic data were gathered through structured interviews with 130 households representing diverse livelihoods and focus group discussions with local managers and community leaders.
2. Data analysis: Quantitative methods were used to analyze the economic efficiency of different livelihoods, the usage rates of agrochemicals, and water quality parameters against national standards. Qualitative data from interviews and discussions were analyzed to understand community perspectives, institutional challenges, and strategic opportunities. Geographic Information Systems (GIS) and remote sensing data were utilized to map land use, ecological zones, and hydrological flows.
3. Framework: The overall analytical framework is built on the principles of the Ecosystem-based Approach (EbA) [22, 23] and Social-Ecological Systems (SES) thinking [24, 25], which guided the diagnosis of the old model’s failures and the formulation of the new, integrated governance structure.

This evidence-based methodology provides the robust foundation for the analysis that follows, detailing the transition from a failed conservation model to a more holistic and resilient governance system.

3. Breaking down the “Fortress Conservation”: Analyzing the failures of the isolated conservation model

In the history of nature conservation, the approach applied at Tram Chim for decades was not an isolated case but a reflection of a global conservation philosophy known as “Fortress Conservation.” This philosophy is built on a romanticized notion of a pure “wilderness,” needing absolute protection from all human interventions [3, 26]. This model operates on a rigid dichotomy between humans and nature, viewing them as separate and opposing entities, inevitably leading to the establishment of strict administrative boundaries and prohibitive regulations, turning protected areas into isolated “fortresses.”

3.1 The management paradox in the core zone: Hydrological intervention and ecological consequences

At the Tram Chim National Park, the “Fortress Conservation” philosophy was realized through a management solution that seemed logical but caused severe ecological consequences. To reduce the risk of forest fires and protect the Melaleuca Forest vegetation, the Park built and operated a closed dyke system with water control gates to maintain high water levels year-round [12, 27].

This intervention, while solving the immediate problem of forest fires, inadvertently disrupted the core natural operating principle of the Plain of Reeds ecosystem. In essence, this is an ecosystem shaped by a distinct seasonal “wet-dry” rhythm. Maintaining year-round inundation severely disrupted this natural hydrological flow, causing a series of paradoxical negative consequences:

1. Disrupting the ecosystem’s natural “Pulse”: Maintaining a continuously flooded state completely eliminated the natural dry cycle. This cycle plays an essential role in decomposing organic material, regenerating soil, and maintaining the diversity of plant communities adapted to alternating wet-dry conditions [12, 27].
2. Habitat degradation and loss of food sources: Prolonged inundation profoundly changed the species composition of the vegetation. Shrubs and Melaleuca trees tended to dominate, while the *Eleocharis* grass fields—a seasonally flooded grassland habitat and the most important tuber food source for the Sarus Crane—were severely degraded. Ironically, the very efforts to protect the cranes by retaining water were destroying their essential food sources and habitats, contributing to the decline in the number of cranes returning to Tram Chim in recent years [27].
3. Increased risk of catastrophic fires (The paradox): Preventing the dry cycle hindered the natural decomposition of dead vegetation. This dry litter accumulated thicker and thicker, year after year, creating a massive fuel load. This created a paradox: when a fire does occur (from lightning or human causes), it will be much more intense, harder to control, and cause more severe damage to the ecosystem than natural fires in a normally functioning ecosystem [27, 28].

3.2 The buffer zone as a source of pressure: Cross-boundary threats

While misguided management measures harmed the core zone from within, the “Fortress Conservation” model also revealed a fatal weakness in its complete inability

to address the growing threats from the buffer zone. Focusing solely on administrative boundaries created a strategic blind spot, ignoring the organic and inseparable ecological linkages between the core zone and the surrounding landscape [12]. Socio-economic activities in the buffer zone have been creating serious pressures that cross the invisible “walls” of the National Park.

1. Chemical and organic pollution: Survey results from the buffer zone project show that intensive agriculture is overusing fertilizers and pesticides at an alarming rate. The average fertilizer use is 1166.7 kg/ha/year, much higher than the national average. More alarmingly, 11 banned pesticide-active ingredients were recorded in use, indicating a serious failure of management. In addition, wastewater from aquaculture ponds and untreated domestic wastewater are discharged directly into the canal system, causing polluted wastewater that flows into the core zone [18].
2. Risk of salinization and groundwater depletion: Field surveys from the buffer zone project also identified a new but extremely dangerous threat: the risk of salinization of the freshwater ecosystem. Some shrimp farmers have arbitrarily drilled wells to extract brackish groundwater or salt spread directly into their ponds. This activity not only increases the salinity of the surface water but also poses a risk of permanently altering the native freshwater ecosystem. Scientific evidence shows this threat is real: monitoring data show that the Electrical Conductivity (EC) index, an indicator of salinity, in subdivision A1 of the core zone showed a clear increasing trend in the 2017–2022 period [18].
3. Human-wildlife conflict: Surveys from the buffer zone project also pointed out the growing conflict over resource use. Illegal grazing of livestock (buffalo, cattle) in the core zone not only disturbs the ecosystem but also creates intense social conflicts between the local community and the Park’s management force [18].

The failure of the “Fortress Conservation” model at Tram Chim is a dual failure. From within, it has caused a serious ecological damage due to unnatural management measures. From the outside, it has been completely powerless against pressures from the buffer zone. This reality has exposed an undeniable truth: a wetland ecosystem cannot be protected by isolating it. The life of Tram Chim depends on managing the entire landscape, including both the core and buffer zones, as a unified whole [12, 16].

4. The foundation for change: The role of science and open policy

The clear failures of the old model created a “window of opportunity” for change. The starting point for the revolution in governance thinking at Tram Chim did not come from external pressures or international projects, but from the proactive role and strategic vision of the Dong Thap provincial government. This landmark change originated from the vision of dedicated provincial leaders who bravely acknowledged the weaknesses of the old model and persistently sought a new direction based on scientific evidence and social consensus.

Instead of continuing down the path of a management model that had proven ineffective, the provincial government took a pioneering step: opening up a new policy space by initiating the project “*Development of Tram Chim National Park*

Buffer Zone, 2021-2030.” This initiative was crucial because it was not just a typical investment project. In essence, it was an official acknowledgment of the failure of the isolated approach and a strong commitment to finding a new, science-based, and participatory model. Furthermore, this decision was made in the context where previous co-management efforts, though supported by international organizations, had revealed their lack of sustainability [13].

The analysis by Mai and Kim [13] provides a critical insight: pilot programs like the Resource User Groups (RUGs), supported by the Cooperative for Assistance and Relief Everywhere (CARE) and World Wildlife Fund, Inc. (WWF)-Coca Cola, while bringing temporary economic benefits to the poor, collapsed as soon as the international funding ended. This failure highlighted a lack of sustainable commitment from local authorities and proved that co-management models could not survive if they relied solely on external factors. Similarly, the development of tourism under the “Wise Use” philosophy only benefited a small group with capital, while the poorest community members were excluded. The lessons learned from these failures became a significant catalyst, prompting the provincial government to realize that genuine change must come from within, with a more comprehensive approach and a stronger political commitment [13].

By assigning consulting tasks to interdisciplinary scientists from the University of Science (Vietnam National University, Ho Chi Minh City (VNU-HCMC)) and collaborating with international organizations like the International Crane Foundation (ICF), the government facilitated a process of deep and objective scientific consultation. For the first time, a “comprehensive health check” for the entire Tram Chim landscape was systematically conducted, covering everything from biodiversity and environmental quality to complex socio-economic aspects. It was this evidence-based scientific research process that provided the solid and irrefutable arguments for abandoning the old model and building a new approach.

This shift was guided by progressive international theoretical foundations and frameworks that have proven effective globally. In addition, the domestic legal context had also seen important changes. Government Decree 66/2019/ND-CP on the conservation and sustainable use of wetlands created a solid legal corridor, encouraging management methods with community participation and benefit-sharing, officially legalizing the abandonment of the closed conservation model.

The two main theoretical pillars from international conventions are the “Wise Use” of the Ramsar Convention and the “Ecosystem-based Approach” (EbA) of the Convention on Biological Diversity.

1. “Wise Use” is the core philosophy of the Ramsar Convention, defined as the maintenance of their ecological character, achieved through the implementation of ecosystem approaches, within the context of sustainable development [29, 30]. This philosophy breaks the confrontation between humans and nature, affirming that the sustainable use of resources by humans is fully compatible with conservation goals. It recognizes humans as an integral part of the system, and their well-being as a legitimate objective to be integrated into conservation strategies [31].
2. The “Ecosystem-based Approach” provides a concrete action framework to realize this philosophy. Systematized into 12 principles, EbA is an integrated strategy for the equitable management of land, water, and living resources. It requires the participation of stakeholders, management at appropriate scales (e.g., landscape scale, instead of administrative boundaries), and a balance between conservation and use [32]. This approach particularly emphasizes the need to understand

and manage ecosystems as complex Social-Ecological Systems (SES), where natural and social factors interact and are interdependent [33].

The combination of an open, visionary policy from the government, a favorable national legal corridor, and a solid theoretical-scientific foundation created a powerful, irreversible momentum for completely reshaping the governance model at Tram Chim. It was a shift from confrontation to dialog, from isolation to integration, and from command-based management to cooperation-based governance.

5. Building a new governance model: Pillars for sustainable development

Based on the new theoretical foundation and scientific evidence collected from the “*Development of Tram Chim National Park Buffer Zone, 2021-2030*” project, a comprehensive, multi-pillar governance model is being built for Tram Chim. This model is not a collection of separate projects but an integrated system where reforms in space, livelihoods, and community empowerment resonate together to create a positive feedback loop, aiming for consensus between conservation and development, while building resilience for both the ecosystem and the community.

5.1 Reshaping space: Ecological functional zoning for the buffer zone

The first pillar of the new model is a revolution in the perception of space. Instead of viewing the buffer zone as a passive “belt” merely for blocking impacts, the new approach recognizes it as an inseparable “supportive ecological space,” with significant biodiversity roles and serving as an essential ecological corridor. Scientific survey results from the buffer zone project have confirmed that the buffer zone is not just a “support” area but also holds high biodiversity value, complementing and completing the core zone’s ecosystem. Many species, such as the Small-scale Mud Carp, Silver Barb, and Bighead Catfish, are even found only in the buffer zone and not in the core zone. The survey also discovered the presence of rare species like the Giant Asian Pond Turtle (*Heosemys grandis*), listed as “CR - Critically Endangered” in the International Union for Conservation of Nature (IUCN) Red List, within the buffer zone [18].

Based on this understanding of ecological linkages and mutual relationships, the new model proposes dividing the buffer zone into two ecological functional zones with clear management objectives:

1. Environmental impact mitigation zone: This is a 1-km wide area directly adjacent to the core zone boundary (**Figure 2**). The main objective of this zone is to strictly control sources of direct pollution and disturbance, such as wastewater from aquaculture, agricultural chemicals, noise from traffic, and illegal entry. This is the first line of defense for the integrity of the core zone. This approach is supported by Government Decree 66/2019/ND-CP on the conservation and sustainable use of wetlands [34].
2. Biodiversity support zone: This area includes the rest of the buffer zone. The main role of this zone is to maintain ecological linkages and protect agricultural habitats (mainly rice fields) to serve as living, feeding, and movement corridors for organisms, especially indicator species like the Sarus Crane and migratory fish from the Mekong River.



Figure 2.
Land use and ecological zoning for the Tràm Chim National Park buffer zone.

This functional zoning provides a clear spatial framework to guide socio-economic development activities, allowing for the application of management regulations appropriate to each specific ecological role, instead of applying a uniform policy to the entire buffer zone.

5.2 Livelihood transformation and resilience building

To realize the ecosystem-based governance model, transitioning from intensive, harmful economic activities to sustainable livelihood models is a key factor. This approach not only aims to minimize negative impacts but also proactively builds community resilience to climate change. The proposed solutions focus on applying Nature-based Solutions (NbS), leveraging the principles of the wetland ecosystem to create economic benefits while restoring natural values [35].

1. Ecological and nature-based agriculture: Transitioning from 3-crop rice to 2-crop rice combined with flood-season livelihoods (natural fish catching), developing organic rice and rice-fish models. These models not only increase income for people through high-value products but also directly contribute to conservation goals by creating safe habitats and food sources for wild species, especially the Sarus Crane. In terms of resilience, this model helps to reduce dependence on a single crop, diversifies income sources, and restores the natural silt cycle, increasing soil fertility and reducing the need for chemical fertilizers.
2. Community-based ecotourism and local product development: Expanding tourism programs into the buffer zone, creating satellite points for visitors to

experience ecological agriculture models and traditional craft villages. At the same time, the buffer zone project proposes supporting brand building and value chains for local specialty products such as Phu Tho dried fish, Huong Tram honey, and Phu Hiep scallions under the “One Commune One Product” (OCOP) program. This helps to create short value chains, strengthen the local economy, and reduce dependence on unstable external markets.

5.3 Building responsibility and partnership with the community

The foundation of the new governance model is not about granting land “ownership,” as the land in the buffer zone already belongs to the people. The key pillar here is the transformation of roles and responsibilities: from individual farmers focusing only on short-term economic benefits to responsible stakeholders, proactive and indispensable partners in protecting the entire Tram Chim landscape.

The biggest challenge is not changing ownership, but building a shared ideology of environmental responsibility and promoting effective multi-stakeholder cooperation. This requires recognizing the fact that the farming activities of each household directly affect the health of the National Park’s ecosystem. Therefore, protecting soil and water is not just a duty but a prerequisite for ensuring sustainable livelihoods and enhancing the value of their own agricultural products.

Activities in this pillar focus on creating genuine partnerships:

1. Capacity building and community organization: Supporting the establishment and strengthening of new-style cooperative groups and cooperatives. These organizations not only play a role in linking production and consumption but are also the nucleus for spreading responsible farming practices, environmental monitoring, and representing the community’s voice in dialog mechanisms with the Park’s Management Board and local authorities.
2. Building substantive cooperation mechanisms: The relationship between the Park and the people has improved significantly, shifting from confrontation and control to partnership and companionship. This marks a fundamental shift from previous models. Whereas the RUGs program, as analyzed by Mai and Kim [13], was successful temporarily but still operated as an “external project” that collapsed without funding, the current model is built on the investment and commitment of the local government [13]. To facilitate this cooperation, the National Park has coordinated with the government to invest in essential infrastructure such as rural roads, irrigation systems, and smart monitoring stations, while also training farmers in sustainable farming processes.
3. Linking conservation responsibility with economic benefits: The new model demonstrates that environmental protection brings direct economic benefits. By participating in ecological rice models, people not only contribute to creating a “safety belt” for the Park but also produce higher-value products with stable outlets, thanks to contracts with reputable enterprises. As farmer Nguyen Van Man (Tam Nong district) shared: *“My family switched to the ecological rice model to create a green-clean-beautiful environment with the hope of... welcoming the cranes back. In addition, we farmers can participate in tourism to promote the local image”* [36].

This statement shows a fundamental shift in mindset. When the community sees that their responsible farming actions not only protect the common heritage but also directly improve their income and quality of life, they will become the most effective and proactive protectors of the ecosystem. The success of the model is not only measured by the area of ecological rice (expected to reach over 312 ha by 2025), but more importantly, by the formation of a responsible, organized community that is a true partner in the conservation and sustainable development of Tram Chim.

5.4 Identifying challenges, risks, and trade-offs

However, implementing a new, multi-pillar, and complex governance model is not without significant challenges and risks. A critical perspective requires us to clearly identify potential trade-offs:

1. Challenges in livelihood transition: Persuading and supporting people to switch from the 3-crop intensive model to ecological agriculture requires significant investment resources and patience. In the initial phase, farmers may face risks of reduced productivity, new technical farming requirements, and especially the instability of the market for organic products, which has not yet been sustainably established.
2. Institutional and enforcement risks: The success of the “Coordination Regulation” depends heavily on the capacity and political commitment of the stakeholders. Potential risks include conflicts of interest between departments and agencies (e.g., between agricultural development and conservation goals); lack of financial and human resources to monitor and enforce the regulation effectively; or changes in the local government’s policy priorities that could disrupt the process.
3. Management trade-offs: Allowing sustainable resource extraction in the buffer zone (e.g., fishing during the flood season) is a trade-off. If not managed and monitored closely, this activity could exceed sustainable thresholds, creating new pressures on the ecosystem instead of mitigating them. Balancing the immediate economic benefits for the community with long-term conservation goals is always a challenging governance problem.
4. Risk of social inequality: As the lesson from the previous tourism model has been shown in the work of Van Mai and Kim [13], there is a potential risk that the benefits from new economic models may not be distributed equitably. Without targeted support policies, the poorest households, lacking capital and skills, could continue to be left behind, while benefits concentrate among wealthier households. This requires a fair and transparent mechanism for monitoring and benefit-sharing to ensure the inclusiveness of the new model.

6. The key pillar: Building a co-management regulation

For the pillars of space, livelihoods, and community to operate synchronously and effectively, reforming the governance institution is an urgent requirement and the biggest challenge. The problems at Tram Chim are not merely failures of

“management”—technical activities on the ground—but more profoundly, weaknesses in the “governance” system, including power structures, decision-making processes, and coordination mechanisms among stakeholders [37, 38]. An effective governance system is the backbone of all conservation and sustainable development efforts.

Instead of proposing the establishment of a new body like a “Landscape Council,” which could add administrative complexity and functional overlap, the new model focuses on a more substantive and fundamental solution: building a legal and operational framework for cooperation. The focus of this pillar is the development and issuance of a “*Regulation on Coordinated Management of Tram Chim National Park’s Buffer Zone*.” The detailed content of this regulation was developed from the research results of the project “*Development of Tram Chim National Park Buffer Zone, 2021-2030*.”

This is not just an ordinary administrative document, but the legal foundation to realize a polycentric and adaptive governance model [33]. A polycentric governance system acknowledges that no single center of power has enough information and capacity to manage a complex system like Tram Chim. Instead, it creates a network of decision-making centers at different levels, from the provincial to the commune and community levels, allowing for flexibility and mutual learning. This regulation will:

1. Legalize functional zones: Clearly define the objectives, management principles, and permitted/prohibited activities in each ecological functional zone of the proposed buffer zone. This creates clarity and transparency for managers, investors, and residents.
2. Clearly define roles and responsibilities: Clearly delineate the responsibilities of each stakeholder, from the National Park Management Board, provincial departments (Agriculture and Environment, Culture-Sports-Tourism, Industry and Trade...), local authorities (district, commune) to community organizations. This clarity is a prerequisite to avoid shifting the responsibility and management shortcomings.
3. Establish coordination mechanisms: Specify the forms and content of coordination, from regular information exchange, joint annual planning, to organizing interagency inspections and monitoring. This aims to break down administrative “silos,” ensuring that decisions on irrigation, agriculture, tourism, and conservation are made synchronously and harmoniously across the entire landscape.
4. Create a foundation for co-management: Most importantly, the Regulation will be the legal basis for co-management models of resources (e.g., fisheries, non-timber forest products) between the National Park Management Board and the community to be officially recognized and operated. It will specify the rights and obligations of the community, and especially a fair and reasonable benefit-sharing mechanism from the sustainable exploitation of resources and ecotourism activities.

The effective development and implementation of this Regulation is the prerequisite for transitioning from a fragmented, conflicting management system to a cooperative, flexible, and effective governance system, where all stakeholders share the responsibility and benefits in protecting and sustainably developing the Tram Chim

landscape. It turns the principles of the “Ecosystem-based Approach” from theory into enforceable regulations, creating a stable framework for consensus and collective action.

7. The return of the Sarus Crane: A symbol of consensus and resilience

In the overall picture of the governance transformation at Tram Chim, the story of the Sarus Crane emerges as the most vivid and convincing evidence. This rare bird is not just an object of conservation; it has become an ecological indicator, a cultural symbol, and an economic driver, crystallizing the efforts and achievements of the new governance model. The return of the crane flock is the most tangible measure of success, showing that the ecosystem is gradually recovering its resilience.

The severe decline in the number of cranes returning to Tram Chim over the past decades, culminating in years when not a single individual returned, was the most damning indictment of the previously flawed hydrological management model. Maintaining year-round water levels destroyed the *Eleocharis* grasslands, their essential tuber food source, turning the land that was once their “home” into an unsuitable habitat.

Deeply aware of this, the project “*Conservation and Development of Sarus Cranes at Tram Chim National Park for the period 2022-2032*” was approved by the Dong Thap Provincial People’s Committee, identifying it as a central task for the province’s biodiversity conservation. This strong political commitment was expressed by the Vice Chairman of the Dong Thap Provincial People’s Committee, Huynh Minh Tuan: “*The support and active participation from the community are important prerequisites for the project’s smooth and sustainable implementation. The province has created all favorable conditions in terms of mechanisms and resources to turn commitment into action*” [36].

The crane recovery strategy is built comprehensively, based on the close integration of the new governance pillars:

1. Core ecological restoration: Instead of maintaining fixed water levels, the Park Management Board has implemented flexible hydrological management solutions that simulate the natural wet-dry cycle. Proactive interventions such as “controlled burns” and soil tilling were carried out to regenerate *Eleocharis dulcis* and *Xyris indica* grasslands—the cranes’ favorite feeding habitats. These efforts have yielded astonishing results. After just one year of water regulation, scientists recorded the return of many bird species. Most encouragingly, in 2024, four wild Sarus Cranes returned to Tram Chim, showing that the habitat is being restored in the right direction [39].
2. Building a “Crane-Friendly” buffer zone: The recovery strategy does not stop at the core zone but recognizes the buffer zone’s rice fields as an indispensable part of the cranes’ living space. “Ecological rice” models are encouraged and supported, not only to increase income for the people but also to create a safe, chemical-free food source for the cranes. This has turned farmers from a potential threat into active partners. As the farmer Nguyen Van Man shared, he switched to ecological rice “*to create a green-clean-beautiful environment with the hope of... welcoming the cranes back*” and to participate in tourism, promoting the local image [36].

3. Reintroduction and international cooperation: When the ecosystem was ready, the next decisive step was taken. The culmination of these efforts was the historic event in April 2025, when six Sarus Cranes (three males, three females) were successfully transferred from Thailand to Tram Chim, under a cooperation framework with the International Crane Foundation (ICF). The project sets an ambitious goal: to breed and release 100 cranes in 10 years, with the hope of establishing a stable population at Tram Chim [40].

Through this holistic approach, the crane has transcended its role as a mere ecological indicator to become a powerful “brand.” Agricultural models like “Crane-calling Rice” are leveraging the crane’s image to create added value for sustainable agricultural products [41]. The crane is now a bridge, turning ecosystem governance principles into tangible economic benefits and a source of shared pride for the entire community.

8. Conclusion: Tram Chim - A “living laboratory” for a resilient Mekong Delta

The significance of the innovation at Tram Chim National Park extends far beyond the scope of a single protected area. In the current context, the entire Mekong Delta is facing unprecedented existential challenges from declining water and sediment resources, land subsidence, environmental pollution, and the increasingly severe impacts of climate change. The challenges Tram Chim faces—such as profound changes in hydrological regimes, pressure from local livelihoods on resources, and conflicts in land and water use—are, in fact, a microcosm of the challenges the entire Mekong Delta is facing on a larger scale [16, 20]. Therefore, Tram Chim is not merely an object to be protected; it has the potential to become a “living laboratory,” an important learning model for restructuring the development model of the entire delta.

The transformation journey at Tram Chim is a shift from the rigid “Fortress Conservation” model, based on separating humans from nature, to a new philosophy guided by the Ramsar Convention: “Wise Use” and the “Ecosystem-based Approach.” This revolution takes place on three main axes: philosophically, it shifts from confrontation to integration; spatially, it breaks down the boundary mindset to manage the entire landscape; and institutionally, it moves from command-and-control, single-center governance to cooperative, multi-stakeholder governance. This is operationalized through a clear co-management regulation that specifies the responsibilities of all stakeholders. For instance, the provincial Department of Agriculture and Environment is assigned the lead role in coordinating and monitoring the implementation of buffer zone development programs, while local commune-level People’s Committees are responsible for managing land use in line with ecological zoning [18]. This framework ensures that actions are not generic but are assigned, implemented, and monitored by specific entities.

Similar to the restoration of wetlands in the Chilika Lake basin in India [42] or the Camargue region in France [43], the experience at Tram Chim once again confirms that integrating community livelihoods into hydrological and ecological restoration efforts is key to saving wetland ecosystems globally. This is a pioneering, strategic effort to find a new, nature-based, and more sustainable development path for the entire Mekong Delta. The lesson from Tram Chim, at a deeper level, is a challenge to the “dyke mentality” and “intensive farming mentality” that have dominated the

Mekong Delta for decades [43, 44]. It is not just a story about managing a protected area, but about transitioning to a “delta thinking”—a nature-based mindset that accepts and lives with natural laws, viewing the pulse of the water not as a threat to be controlled but as a priceless asset to be respected and nurtured.

The success of this model will not just be measured by saving an ecosystem, but by the tangible outcomes of its specific, coordinated actions: the successful branding of

Pillar	Main objective	Specific activities	Key performance indicators (KPIs)
1. Reshaping space	Manage the buffer zone space according to its ecological role.	• Delineate “Impact Mitigation Zone” and “Biodiversity Support Zone.”	• 100% of the Impact Mitigation Zone area complies with environmental regulations. • Percentage of Biodiversity Support Zone areas converted to ecological agriculture.
2. Sustainable livelihood transformation	Harmonize economic activities with conservation goals, reduce pressure on resources, and build resilience.	• Promote ecological agriculture (2-crop rice + flood-season livelihoods, organic rice). • Develop community tourism, OCOP products.	• Percentage increase in average income of participating households. • Number of OCOP products certified and with successfully developed value chains.
3. Community empowerment	Transform the community from managed subjects to proactive partners.	• Establish resource co-management groups/teams. • Shift from formal “participation” to substantive “ownership.”	• Number of effectively operating co-management groups. • Percentage of households participating in decision-making related to resource management.
4. Building a co-management regulation	Create a legal and operational basis for integrated, multi-stakeholder management.	• Develop and issue the “Buffer Zone Coordinated Management Regulation.” • Clearly define roles, responsibilities, and coordination mechanisms among parties.	• Regulation signed and implemented by 100% of relevant stakeholders. • Number of interagency meetings/monitoring activities held annually according to the regulation.
5. Ecological and iconic species restoration	Reestablish core natural processes and restore indicator species, enhancing ecosystem resilience.	• Flexible hydrological management simulating the wet-dry cycle. • Restore <i>Eleocharis</i> grassland habitat. • Reintroduce and develop the Sarus Crane population.	• Number of Sarus Cranes returning/successfully breeding annually. • Percentage of <i>Eleocharis</i> grassland areas restored. • Improvement in water quality indicators (pH, dissolved oxygen (DO), EC) in the core zone.

Table 1.
The five pillars of the ecosystem-based governance model at Tram Chim.

local eco-friendly agricultural products led by the Department of Industry and Trade; the development of community-based ecotourism managed by the Department of Culture, Sports and Tourism in partnership with local communities; and the long-term ecological health of the park monitored by scientists and the Park's own Management Board [18]. More importantly, it will ignite a source of hope and provide valuable knowledge, contributing to shaping a safe, prosperous, and climate-resilient future for the millions of people living in Vietnam's largest rice bowl.

The return of the cranes in the skies of Tram Chim is not just good news for conservationists. It is a symbol of hope. It proves that, even when facing immense challenges, when people choose dialog over confrontation, and cooperation over isolation, nature can be revived. The journey of reshaping governance at Tram Chim, therefore, is not just a story about saving a wetland, but also a story about mending the broken relationship between humans and nature in the heart of the Mekong Delta. To continuously monitor and assess the implementation effectiveness, the performance evaluation indicators of the new governance model are summarized in the **Table 1**.

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Perspective Chapter: A Judicial Perspective on the Legal Structure of Protected Areas in Turkey

Ilknur Cesur

Abstract

Protected areas in Turkey are defined under various laws within the Turkish legal system. The definition and registration of the characteristics of these designated areas are carried out under specific laws. In the Turkish legal system, judicial decisions, which are among the written rules of law, play a significant role in filling legislative gaps. This study examines the fundamental legal data on protected areas, followed by disputes reflected in the judiciary. The most common dispute topics in the court decisions reviewed in the scope of the research are: inadequate environmental impact assessments of plans, failure to perform carrying capacity calculations, construction carried out without relying on higher-level protection plans (e.g., UDGP), and approval processes conducted without consultation with institutions. As a result of the study, it is recommended that environmental impact and climate sensitivity assessments be made mandatory for all plans prepared in protected areas.

Keywords: protected areas, Turkish legal system, environmental impact assessment, judicial decisions, climate sensitivity

1. Introduction

Protected areas are classified under different legal statuses based on their biological, ecological, cultural, and recreational values [1]. In Turkey, this classification includes various regulations aimed at both protecting natural heritage and ensuring sustainable use [2]. Protected areas in Turkey are established in accordance with several laws, including the National Parks Law No. 2873 [3], the Land Hunting Law No. 4915 [4], the Forestry Law No. 6831 [5], the Environmental Law No. 2872 [6], and Law No. 2863 on the Protection of Cultural and Natural Assets [7]. These laws, along with their implementing regulations, provide guidelines for the identification, registration, and management of protected areas.

National parks, nature parks, natural monuments, and nature conservation areas are protected under the National Parks Law No. 2873; special environmental protection areas are protected under the Environmental Law No. 2872; natural site areas are protected under the Law on the Protection of Cultural and Natural Assets

No. 2863; and wetlands are protected under international obligations such as the Ramsar Convention.

Each protection status corresponds to a different value group. For example, the natural beauty and values they possess, the diversity of living organisms within them, or the fact that they are home to rare species are factors considered in the designation of an area as a national park (e.g., Yozgat Pine Forest National Park, Turkey's first national park) [8]. Nature parks are more designated for daily use and recreational activities. In addition, some nature parks offer educational ecological tours (Boraboy Nature Park, Davulbaztepe Nature Park, Oluközü Nature Park), painting activities (Abant Lake Nature Park, Ayıkayası Nature Park, Vezirsuyu Nature Park), nature education (Cemal Tural Nature Park, Altıparmak Nature Park), nature-themed festivals (Balamba Nature Park, Göztepe Nature Park), and other recreational activities [9]. Natural monuments are used to describe natural areas that have formed as a result of natural events (geological, geomorphological, hydrogeological, climate change, etc.) [10] (e.g., Zeytin taşı Cave Natural Monument). Nature conservation areas are zones where only educational and scientific uses are permitted, as they are areas containing rare and fragile ecosystems, in line with the goal of absolute protection [10] (e.g., Sırtlandağı Aleppo Pine). Special environmental protection areas are places of ecological importance both nationally and globally, but which are at risk of degradation or destruction due to pressures such as industry, tourism, and construction (e.g., Kaş-Kekova Special Environmental Protection Area) [11]. Göreme and Cappadocia are also examples of natural heritage sites.

Figure 1 shows the number of protected areas in Turkey as of 2024.

Figure 2 shows the sizes of protected areas in Turkey as of 2024.

Table 1 below shows examples of the values held by protected areas, illustrating the values possessed by places designated as national parks in Turkey.

Table 1 shows the cultural, natural, geological, recreational, and other values of national parks in Turkey. This table highlights the fundamental characteristics underlying the protection status of each national park.

The national parks application [13] provided by the Turkish Ministry of Agriculture and Forestry, Directorate General of Nature Conservation and National Parks, displays protected areas marked on a map of Turkey, each represented by a

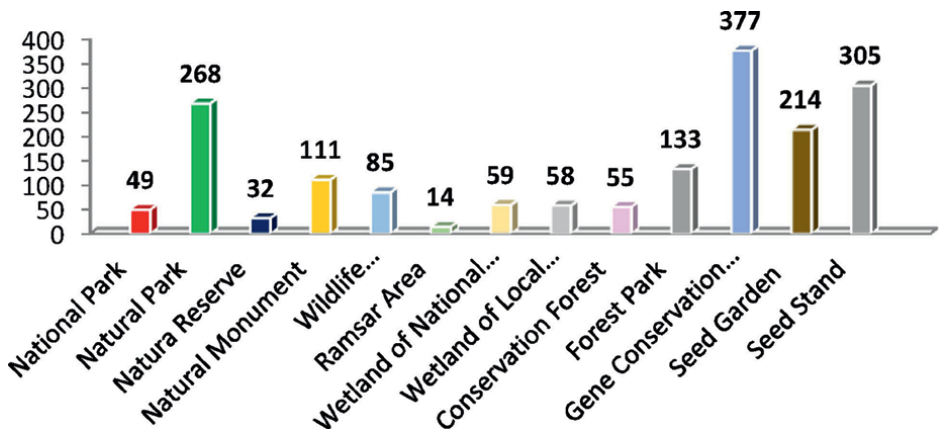


Figure 1.
Number of protected areas [12].

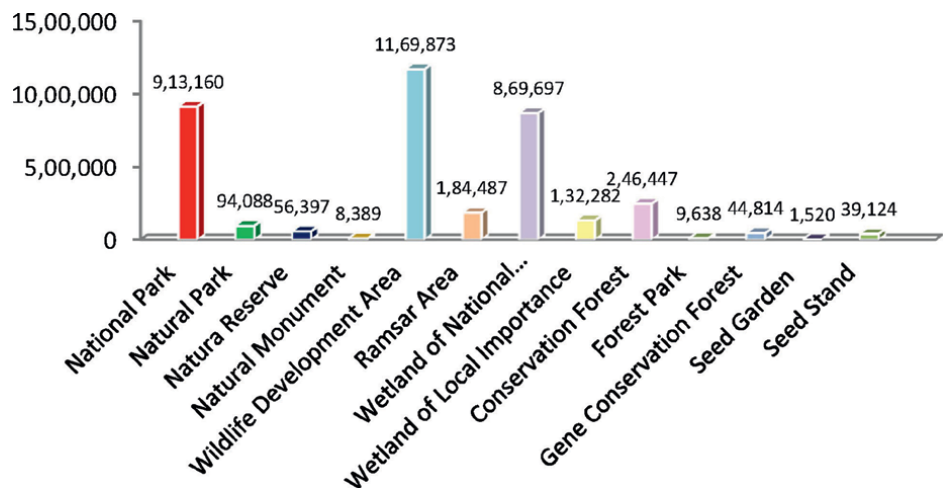


Figure 2.
Size of protected areas [12].

Site name	Values					
	Cultural	Natural	Wetlands	Geological	Landscape	Recreational
Gala Lake NP		✓	✓		✓	✓
Iğneada Longoz Forests NP		✓	✓		✓	✓
Kuş Cenneti National Park		✓	✓		✓	✓
Kazdağı NP		✓			✓	✓
Gallipoli Peninsula Historical						
Troya Historical NP	✓					
Dilek Peninsula-Büyük Menderes Delta National Park		✓	✓		✓	✓
Honaz Mountain NP		✓			✓	✓
Marmaris NP		✓	✓		✓	✓
Spil Mountain NP		✓			✓	✓
Uludağ NP		✓		✓	✓	✓
Abant Lake NP		✓	✓		✓	✓
Yedigöller NP		✓	✓	✓	✓	✓
Sarıçalı NP		✓				✓
Soğuksu NP		✓		✓	✓	✓

Site name	Values					
	Cultural	Natural	Wetlands	Geological	Landscape	Recreational
Sakarya Meydan Muharebesi NP	✓					
Derebucak Pine Forest Caves NP		✓		✓	✓	
Beyşehir Lake NP		✓	✓		✓	✓
Güllük Mountain-Termessos NP	✓	✓				✓
Beydağları Coastal NP	✓	✓			✓	✓
Köprülü Canyon NP	✓	✓		✓	✓	✓
Altınbeşik Cave NP			✓	✓	✓	
Kızıldağ NP		✓	✓		✓	✓
Kovada Lake NP		✓	✓		✓	✓
Yumurtalık Lagoon NP (3)		✓	✓		✓	✓
Karatepe-Aslantaş NP	✓				✓	✓
Göreme Historical NP	✓			✓	✓	✓
Sultan Marshes NP		✓	✓		✓	✓
Divriği NP (2)	✓	✓			✓	✓
Yozgat Pine NP		✓				✓
Boğazköy-Alacahöyük NP	✓					
Altındere Valley NP		✓	✓		✓	✓
Hatila Valley NP		✓		✓	✓	✓
Karagöl-Sahara NP		✓	✓		✓	✓
Nene Hatun Historical NP	✓					
Munzur Valley NP		✓	✓			✓
Malazgirt Meydan Muharebesi NP	✓					

Site name	Values					
	Cultural	Natural	Wetlands	Geological	Landscape	Recreational
Cilo ve Sat Mountains NP			✓		✓	
Tek Tek Mountains NP	✓					
Botan Valley		✓		✓	✓	✓
Saklıkent NP				✓	✓	✓
Başkomutan Historical NP	✓	✓				
Aladağlar NP		✓		✓	✓	✓
Küre Mountains NP		✓		✓	✓	✓
Ilgaz Mountain NP		✓			✓	✓
Kop Mountain Defense NP	✓	✓				
Sarıkamış-Allahuekber Mountains	✓	✓				
Ağrı Mountain NP	✓	✓	✓	✓	✓	✓
Kaçkar Mountains NP		✓		✓	✓	✓
Akdağ NP (2)		✓	✓	✓	✓	✓
Nemrut Mountain NP	✓				✓	✓

Table 1.
 The values possessed by national parks in Turkey.

different symbol. Clicking on a protected area with the mouse opens a screen containing detailed information about that protected area. An example of this is shown in the image below (**Figure 3**).

Protected areas, which are areas where human activities are restricted or completely prohibited, do not always meet the expected conservation and development criteria [14]. Legal protection that provides passive protection management by restricting human activities is not always sufficient [15]. In particular, the granting of permits in recent years for projects that will damage natural resources in Turkey, under the guise of “investment,” threatens the future of protected areas [16]. However, the high ecological and cultural values of protected areas can conflict with economic objectives. Legal disputes frequently arise in these areas, particularly due to mining activities, energy investments, tourism projects, and development plans [16].

Among the disputes arising from actions and activities that violate the law, zoning issues in these areas come to the forefront. This is followed by concerns over permits granted for energy facilities, leasing of the areas, and disputes regarding authorization. It is observed that conflicts are predominantly resolved through court decisions

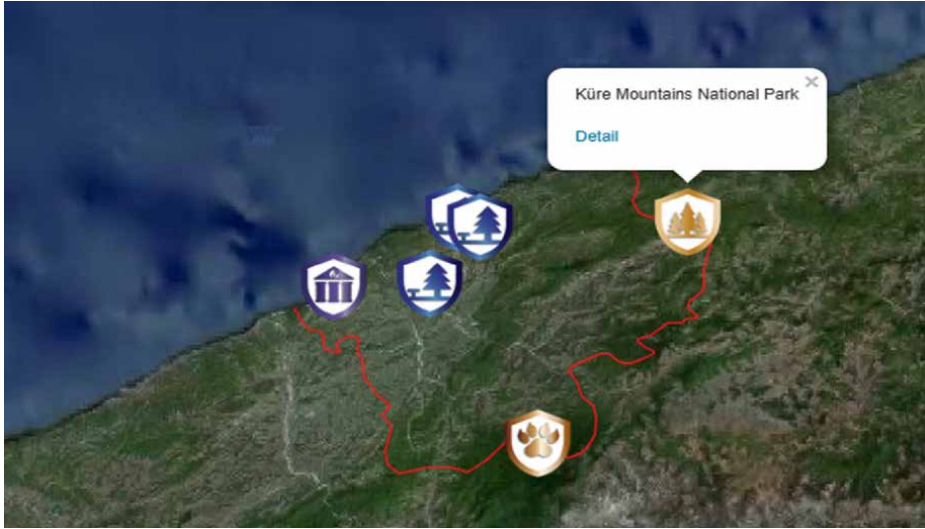


Figure 3.
An example of protected area monitoring with the national parks application.

[17]. The judiciary is not merely a supervisory mechanism, but has also become the guarantor of the sustainable management of protected areas [18].

Therefore, the classification of protected areas in Turkey and the values of these areas are not merely an ecological or cultural issue; they are also a dynamic process shaped by the law and judicial precedents. For this reason, the role of judicial decisions in the protection of protected areas is indispensable for the sustainability of environmental policies.

Previous studies on the subject have primarily focused on legislation, institutional structure, the balance between conservation and use, problems encountered, management, and the impact on local communities. Studies on judicial review also provide assessments based on interest, competence, and precedent in environmental cases. Qualitative research methods such as content analysis, legislation analysis, institutional analysis, and document screening are preferred in these studies.

This study differs from other studies in that it analyzes and categorizes disputes arising in protected areas following the incorporation of statutory provisions. Unlike other studies, the main material of this study on protected areas consists of court decisions.

2. Materials and methods

This study examines the laws governing protected areas in Turkey, along with the legal disputes arising from activities that violate these laws. The first step involved classifying protected areas in Turkey according to the relevant legislation. Next, the prohibitions regarding activities in these protected areas were analyzed. The study then reviewed and categorized case law related to protected areas by frequency. The judiciary's stance on this jurisprudence was assessed. Additionally, the research considered the international agreements it has ratified under the Climate Law to forecast the future approach to protected areas in Turkey.

2.1 Legislation analysis

In the first phase of the study, the legal classification of areas with protected area status was carried out. Within this scope, protection statuses in Turkey were systematically classified based on the Forest Law No. 6831 [5], National Parks Law No. 2873 [3], Cultural and Natural Heritage Protection Law No. 2863 [7], Land Hunting Law No. 4915 [4], and Environmental Law No. 2872 [6]. In this classification process, the defining criteria for the areas, the competent authorities, and the planning obligations for implementation were identified as the primary evaluation criteria.

2.2 Comparative assessment of prohibited activities

In the second stage, the types of activities prohibited in areas granted protected status were examined. The analysis aimed to determine the extent to which prohibitive or restrictive provisions in each piece of legislation were applied in practice. It was supported by case studies based on court decisions.

2.3 Content analysis of judicial precedents

In the third stage, the decisions of the Council of State, Regional Administrative Courts, and Administrative Courts were evaluated through document analysis. Twenty-nine judicial decisions issued between 2015 and 2024 were examined using content analysis methods. The frequently encountered issues of disagreement in decisions were coded thematically and classified under main themes, including “conflicts of authority,” “violation of the planning hierarchy,” “inconsistency with protection status,” “lack of institutional opinion,” and “lack of environmental sustainability.” Additionally, the courts’ grounds for annulment, their level of reference to constitutional foundations, and their normative interpretation preferences were analyzed.

2.4 Integration of policy documents and international agreements

Finally, the study evaluates the harmonization relationship between Turkey’s national and international environmental policies and judicial decisions. In particular, Turkey’s international obligations (e.g., Paris Agreement, Convention on Biological Diversity, European Landscape Convention) are taken into consideration within the Climate Law. In line with these documents, inferences have been made regarding the extent to which the existing jurisprudence of the judiciary will overlap with future normative regulations.

3. Results

3.1 Legislative provisions on protected areas in Turkey

Planning activities for protected areas are based on a multi-layered and intersecting legislative structure in Turkey. The main legal provisions where zoning plans in these areas are frequently evaluated for compliance with the law in judicial review are as follows;



Figure 4.
Classification of protected areas in Turkey.

Figure 4 shows the classification of protected areas according to the relevant laws. **Table 2** contains the definitions and management units of these protected areas.

Table 2 provides an overview of the definitions and management units of protected areas classified according to different laws. This facilitates a better understanding of the conflicts of authority that arise in court decisions. **Table 3** contains the actions prohibited in the areas in question.

Table 3 provides a comparative overview of activities prohibited in protected areas under relevant laws. This table highlights the similarities and differences between various regulations.

3.1.1 Law No. 2873 on national parks

Areas with nature protection status, such as national parks, nature parks, nature monuments, and nature conservation areas, are defined and protected under this law. The law requires planning for these areas to be carried out within the framework of a “Long Term Development Plan (LTDP)”. It is frequently emphasized in judicial decisions that the LTDP cannot be implemented until it is approved and that it constitutes the basis for sub-scale plans.

3.1.2 Law No. 2863 on the protection of cultural and natural assets

Archaeological and natural protected areas are protected under this law, and all kinds of planning and implementation in these areas can be valid with the approval of the Cultural Assets Protection Boards. Judicial decisions clearly state that the approval of the board is the “constituent element” of conservation zoning plans and that plans cannot be executed without this approval.

3.1.3 The Law No. 2634 on tourism incentives

Grants the Ministry of Culture and Tourism the authority to make and approve plans for tourism centers and Culture and Tourism Protection and Development Zones. However, if there are also areas with protection status in these regions, conflicts may arise between the protection measures introduced by Laws No. 2873 and 2863 and the planning authority, leading to the problem of conflict of norms. In the decisions of the Council of State, this situation is frequently evaluated in the context of “ambiguity of authority” [19].

Law No. 2873 on National Parks [1]		
Class	Definition	Authority
National park	From a scientific and esthetic point of view, natural and cultural resources that are rare both nationally and internationally, with conservation, recreation, and tourism areas	Ministry of Agriculture and Forestry
Nature park	Natural areas with vegetation and wildlife that are suitable for public recreation and enjoyment within the landscape integrity	
Natural monument	Natural areas that possess characteristics and scientific value created by nature and natural phenomena, and are protected under national park principles	
Nature reserve	Natural areas that contain rare, endangered, or threatened ecosystems, species, and natural phenomena of scientific and educational importance, and which require absolute protection and are reserved for scientific and educational purposes only	
Law No. 4915 on Land Hunting [2]		
Wildlife development area	Areas where game and wild animals and wildlife are protected and developed, game animals are introduced, measures are taken to improve their habitat, and hunting is permitted when necessary within the framework of a special hunting plan	Ministry of Agriculture and Forestry
Forest Law No. 6831 [3]		
Conservation forests	Forests in areas exposed to the danger of landslides and rain erosion, as well as inhabited areas, highways, and railways, which are protected against dust and sandstorms and prevent riverbeds from silting up, or which are considered necessary for national defense and are therefore set aside, and areas covered with maquis or scrubland	Ministry of Agriculture and Forestry
Gene protection forest	Natural forests managed for the purpose of conserving the genetic diversity of a species in its natural environment (in situ)	
Seed stands	Areas designated and managed by the Ministry for the purpose of producing seeds from forest trees and shrubs	
Seed gardens	Gardens cultivated to produce high-quality, abundant seeds	
Forest parks	Forest park with and without accommodation	
Law No. 2863 on the protection of cultural and natural assets [5ba]		
Site areas	Cities and city ruins that have been around since prehistoric times and reflect the social, economic, architectural, and other characteristics of the periods they lived in, places that have been the subject of social life with a high concentration of cultural assets or where significant historical events took place, and areas with identified natural features that need to be protected	
Environmental Law No. 2872 [4]		
Wetlands of local importance	Areas that are of particular value for maintaining the ecological and genetic diversity of a region due to the characteristics and quality of their wetland flora and fauna	Ministry of Agriculture and Forestry
Wetlands of national importance	Areas of national importance that are not included in the list of wetlands and Ramsar sites approved by the General Directorate	
Ramsar Sites	Wetlands included in the Ramsar List by being declared in accordance with Article 2 of the Ramsar Convention	

Table 2.
Classes, definitions, and management units of protected areas.

Prohibited activities in protected areas	
2873 Article 14	The natural and ecological balance and the value of the natural ecosystem shall not be disturbed. Wildlife shall not be destroyed. All kinds of interventions that cause or may cause the loss or alteration of the characteristics of these sites, as well as works and operations that cause soil, water, and air pollution and similar environmental problems, shall not be carried out. Any production of forest products, hunting, and grazing that could disturb the natural balance cannot be carried out. Except for the structures and facilities specified in the approved plans and those necessary for the defense system required by the General Staff, no structures or facilities may be constructed or operated by any means, unless there is an indispensable and definite necessity in terms of public interest, or settlement may not be made in these areas outside the existing settlement areas.
4915 Article 4	Wildlife cannot be destroyed in wildlife protection and development areas. The ecosystem shall not be disturbed, Facilities that hurt wildlife conservation and development areas and breeding stations, even outside these areas, shall not be permitted. Waste from existing facilities, if any, cannot be left untreated. No structures or facilities other than those shown on the approved plans may be constructed. Easements may not be established. Additional prohibitions may be imposed by the Department in these areas as necessary. Prohibitions cannot be imposed by other public institutions and organizations without the opinion of the Ministry. The openings created as a result of burning, cutting, uprooting, strangling, pruning for any reason in public openings and existing trees and vegetation in wildlife protection and development areas, as well as the areas to be obtained by leveling the land, cannot be occupied or used. All kinds of structures and facilities cannot be built in these places, and these structures and facilities cannot be registered in the title deed. Such structures and facilities will be confiscated directly by the Ministry without any registration or conditions. The expenses related to the improvement works to be carried out by the Ministry due to the negative interventions that destroy wildlife and the deterioration of the ecosystem in these areas shall also be compensated by those who caused them.
6831 Article 2 Article 16 Article 111	Areas that completely lost their forest qualities prior to December 31, 1981, may be designated for various agricultural uses such as fields, vineyards, gardens, orchards, olive groves, hazelnut and pistachio farms, or lands deemed suitable for animal husbandry, including pastures and winter pastures. However, this provision does not apply to conservation forests, national park areas, nature parks, and nature conservation areas, as long as these areas maintain their conservation status. (Article 2) In accordance with Article 16, The Ministry of Agriculture and Forestry may permit the construction of necessary facilities, roads, energy, water, communication, and infrastructure for mining exploration and activities within state forests, subject to a fee. However, exploring and operating mines in state forest areas that contain seed stands, gene conservation areas, conservation forests, productive forest areas, forest parks, or endemic and rare ecosystems requiring protection must receive consent from the Ministry of Agriculture and Forestry, although rights acquired during the license period, including appropriations, will be preserved. Pursuant to Article 111: In conservation forests and national parks, penalties for individuals committing forest-related crimes will be doubled.
2872 Article 9	It is essential to protect the natural structures and ecological balances of wetlands. Land cannot be gained through the filling or drying of wetlands. Should land be gained in violation of this provision, the area in question must be restored to its original state by the activity owner.

Table 3.
Prohibited activities in protected areas.

3.1.4 Zoning Law No. 3194

This law, which sets the framework for the entire spatial planning system, regulates the preparation, approval, and implementation processes of zoning plans. Although it does not include special regulations for protected areas, the upper and lower scale plans must be harmonized and regulated by the principle of gradual unity of plans [20].

3.1.5 Regulation on the making of spatial plans (2014)

This regulation details the procedures and principles, such as scientific analysis, public institutional opinions, and ensuring the plan hierarchy in planning processes. Failure to support the plans made in protected areas with planning reports, environmental analyses, carrying capacity, and ecosystem sustainability data is grounds for annulment in judicial decisions [21].

3.1.6 Regulation on plans to be made in protected areas

This regulation, dated 2012, sets out the procedures and principles for plans of all types and scales to be made in protected areas, national parks, and areas with other natural protection status. The regulation requires these plans to be prepared by an interdisciplinary team, to be consulted by conservation boards, and to be based on scientific principles. In judicial decisions, violations of this regulation often constitute the grounds for plan annulment [22].

3.1.7 Amendment to Law No. 2634 by Law No. 7334 (2021)

With this amendment, a reconciliation mechanism has been introduced to eliminate confusion of authority where protected areas and tourism areas overlap. With the coordination to be carried out between the Ministry of Culture and Tourism and the Ministry of Environment, Urbanization, and Climate Change, it is aimed to finalize the plans to be made in these areas by taking the opinion of both ministries. However, it is observed that this regulation has not been sufficiently established in practice, and jurisdictional disputes continue in judicial decisions [23].

This legislative framework reveals that the planning processes in protected areas are multi-actor, multi-scale, and often complex. This structure forms the basis for the disputes that are frequently subject to legal justifications in judicial review and, as will be detailed in the second part of the study, is directly reflected in the content of judicial decisions.

3.2 Linking legislation and judicial decisions on protected areas in Turkey

Planning procedures in protected areas are subject to not only technical but also a multi-layered legal review process. In this context, judicial decisions examine both the implementation of the relevant legal regulations and the extent to which these practices are compatible with the principles of urbanism and environmental planning. Below, an assessment of the seven legislations taken as a basis for the decision analysis is presented, together with sample judicial decisions.

Table 4 shows the most common types of disputes encountered in court decisions examined between 2015 and 2024. The table reveals which legal issues are prominent in protected area planning.

Sequence	Court - division	Merit - decision no	Date of decision	Subject of dispute
1 [24]	6th Council of State	M. 2016/7609, D. 2019/14223	16.12.2019	Uncertain plan decisions/ unpredictability
2 [25]	6th Council of State	M. 2018/275, D. 2022/4533	12.04.2022	Lack of institutional opinion/ status differences
3 [26]	6th Council of State	M. 2018/545, D. 2022/3799	29.03.2022	Confusion of authority (Ministry of Environment, Urbanization and Climate Change- Ministry of Culture and Tourism)
4 [27]	6th Council of State	M. 2018/2832, D. 2022/6005	23.05.2022	Use decisions contrary to the protection status
5 [28]	6th Council of State	M. 2018/4863, D. 2022/6099	24.05.2022	Forest area plan boundary incompatibility
6 [29]	6th Council of State	M. 2018/3348, D. 2022/3130	16.03.2022	Mixed protection statuses/ incompatibility of authority
7 [30]	6th Council of State	M. 2019/495, D. 2022/8531	11.10.2022	Conflict of norms/lex specialis analysis
8 [31]	6th Council of State	M. 2020/9886, D. 2022/2340	01.03.2022	Carrying capacity, lack of environmental monitoring
9 [32]	6th Council of State	M. 2019/19495, D. 2021/8444	17.06.2021	Lack of conservation board approval
10 [33]	6th Council of State	M. 2020/5512, D. 2024/3137	20.05.2024	Irregularities in the form of form in the suspension process
11 [34]	4th Council of State	M. 2024/839, D. 2024/1817	14.03.2024	Re-evaluation of the protection status of the area
12 [35]	4th Council of State	M. 2024/1622, D. 2024/3165	16.05.2024	Mining activities in protected areas and legal and ecological evaluation of the EIA process
13 [36]	13th Council of State	M. 2023/3752, D. 2024/393	31.01.2024	Tender procedure and leasing process in protected areas
14 [37]	8th Council of State	M. 2015/12935, D. 2019/10892	28.11.2019	Lack of public interest in energy projects
15 [38]	14th Council of State	M. 2015/9326, D. 2016/1173	25.02.2016	Irregularities in discovery notification in the hydroelectric power plant (HPP) project
16 [39]	Plenary session of the administrative law divisions	M. 2020/2139, D. 2021/310	17.02.2021	Wind power plant prohibition in a sensitive area to be strictly protected
17 [40]	10th Council of State	M. 2013/8106, D. 2019/6402	08.10.2019	Re-evaluation of the degree of protection
18 [41]	Istanbul District Administrative Court	M. 2020/1381, D. 2020/2008	08.12.2020	Organize industrial zone area status and suitability assessment
19 [42]	6th Council of State	M. 2024/1481, D. 2024/2252	16.04.2024	It is imperative to avoid conflicts of authority between the two ministries

Table 4.
Disputes arising in judicial decisions.

3.2.1 The basic principles adopted by the judiciary in disputes arising in judicial decisions

6th Council of State M. 2018/275, D. 2022/4533 12.04.2022 [25]; It is concluded that the plans are contrary to the principles of urbanism, planning law and protection legislation due to the following reasons: Preparation of the plans without taking into account the protection statuses, absence of upper-scale plans, approval without obtaining the opinions of the relevant administrations, including regulations that will open natural and cultural heritage areas for construction, contrary to the plan grading and public interest. In this decision, it was emphasized that the envisaged construction in the area with national park status was contrary to the legislation on the grounds that the NPP was not prepared; it was stated that the plans were approved in violation of the principle of “gradual unity”.

6th Council of State M. 2019/19495, D. 2021/8444 17.06.2021 [32]; Although a conservation zoning plan was prepared, the plan was put into effect without the approval of the board, which was considered by the judiciary as a lack of constituent action, and the plan was canceled.

6th Council of State M. 2018/545, D. 2022/3799 29.03.2022 [26]; The approval of the plan by the Ministry of Environment in the areas within the Cappadocia Culture and Tourism Conservation and Development Zone was found unlawful by the judiciary on the grounds of jurisdiction.

6th Council of State M. 2020/9886, D. 2022/2340 01.03.2022 [31]; The zoning plan, which was not based on upper-scale plan decisions, was canceled. The judiciary emphasized that the planning was far from spatial integrity and analysis-based decision-making.

6th Council of State M. 2018/2832, D. 2022/6005 23.05.2022 [27]; It is foreseen that no license can be issued without determining basic technical criteria such as carrying capacity, building approach distances, and number of floors in the plans.

6th Council of State M. 2018/3348, D. 2022/3130 16.03.2022 [29]; The conservation zoning plan, which was prepared without interdisciplinary teamwork, was canceled because it was found to be contrary to planning principles and regulations.

6th Council of State M. 2024/1481, D. 2024/2252 16.04.2024 [42] It is a decision that shows that the new memorandum of understanding introduced to resolve jurisdictional conflicts is not effective in practice and still causes disputes. In the case of overlapping protected areas and tourism centers, it is imperative to avoid a conflict of authority between the two ministries.

6th Council of State M. 2021/3806, D. 2022/6046 24.05.2022 [43]; According to the Constitutional provision regulating the legality of the administration, since authority is a matter of public order, an authority in public law must be exercised only by the authority granted by law.

8th Council of State M. 2015/12935, D. 2019/10892 28.11.2019 [37]; If there is public interest and necessity in the presence or construction of all kinds of places and facilities related to energy on State forests, permission may be granted to real and legal persons by the Ministry of Agriculture and Forestry in return for a fee. In the transaction subject to the lawsuit, it is understood that the General Directorate of Forestry has determined that the integrity in terms of forestry works has been disrupted by the evaluation made by the General Directorate of Forestry. It is concluded that there is no public interest in building an energy facility in the state forest.

4th Council of State M. 2024/1622, D. 2024/3165 16.05.2024 [35]; It reveals that the environmental impact assessment (EIA) process should be based not only on formal

compliance but also on ecological risks. In particular, principles such as the protection of biological diversity, ecosystem integrity, and the non-disruption of the habitats of protected species have been evaluated by judicial bodies within the framework of the supremacy of environmental law norms.

14th Council of State M. 2015/9326, D. 2016/1173 25.2.2016 [38]; This decision shows that formal procedural errors in administrative proceedings may also have an impact on the merits. Particularly in technical and multi-actor cases such as EIA, the effective participation of the parties in the discovery process is important not only for procedural but also for ensuring substantive justice. Therefore, if the date of discovery is not notified to all parties in a timely and proper manner, this deficiency may cripple the proceedings.

6th Council of State M. 2020/5512, D. 2024/3137 20.05.2024 [33]; The decision provides an important case law on the legal nature of long-term development plans for protected areas. The approach is that such plans are not included in the spatial plan cascade, but are a separate planning tool according to nature conservation legislation and cannot be directly subject to the same legal procedure as zoning plans. This provides clarity in administrative practices.

Plenary session of the administrative law divisions M. 2020/2139, D. 2021/310 17.02.2021 [39]; This decision sets out a clear approach that new energy investments can be restricted in strictly protected sensitive areas where environmental protection priorities are high, but that legal certainty should be respected for existing investments. It is recognized that the principal decision remains within legal limits in terms of balancing both environmental protection and investor rights.

These judicial decisions not only resolve concrete disputes, but also shed light on the shortcomings and normative inconsistencies of planning practice regarding protected areas in Turkey. These decisions provide a basic framework for understanding how legal and urban planning principles have shaped the judicial evaluations, which will be elaborated on in the next stage.

3.3 Turkey's protected area policies in the context of international platforms

Protected areas are not only for nature conservation but also priority areas where ecosystem-based solutions are implemented to combat climate change. When protected area planning in Turkey is evaluated on the basis of judicial decisions and legislative review, it is seen that the fragmented structure of the legal framework, institutional authority conflicts, and practices that do not sufficiently include planning principles stand out. This situation points to an implementation gap between Turkey's international commitments and national practices.

3.3.1 The problem of harmonization with international policies

Turkey is a party to many international environmental and nature protection regimes such as the United Nations Convention on Biological Diversity (CBD), the Paris Agreement, the EU Green Deal, the Bern Convention, and the Ramsar Convention. All of these conventions envisage effective management of protected areas, sustaining biodiversity, preventing the destruction of natural habitats, and integrating climate adaptation strategies with spatial planning. However, in planning practices in protected areas in Turkey, the principle of conservation-use balance is frequently violated, the planning process is not based on scientific, interdisciplinary, and participatory principles, and most importantly, parameters such as carrying

capacity, climate risks, and carbon sink areas are not taken into account in planning decisions.

This situation indicates that the global policy texts that Turkey has undertaken obligations regarding protected areas are not reflected at the implementation level in domestic law.

3.4 Evaluation of planning activities in protected areas within the framework of Turkey's climate law

The following provisions are included in Articles 5 and 6 of Turkey's Climate Law [44].

“Measures shall be taken by relevant institutions and organizations to prevent carbon sink losses in forests, agriculture, pastures, and wetlands in order to offset emissions to achieve the net-zero emission target, and it shall be ensured that sinks and protected areas are protected and increased.”

“Measures shall be taken by relevant public institutions and organizations to mitigate the impacts of climate change on ecosystems and biodiversity and for sustainable ecosystem management. The quality and ratio of protected areas shall be increased by ensuring the conservation of marine and terrestrial protected areas, and land destruction shall be balanced in areas affected or likely to be affected by climate change. Sustainable management of sinks created in non-forest areas within the scope of combating desertification and erosion, as well as afforestation and soil conservation, is ensured to be in line with the net-zero emission target.”

In the judicial decisions examined within the scope of the research, it was found that environmental impact analyses of plans are inadequate, carrying capacity calculations were not made, construction is carried out without relying on upper-scale conservation plans (e.g., UDGP), and the approval process was carried forward without consultation with institutions. Such shortcomings are in clear contradiction with the Climate Law's holistic ecosystem approach and preventive planning principles.

4. Conclusion and recommendations

Sub-scale plans without a top-scale plan (e.g. UDGP), tourism, energy, and mining-oriented developments in national parks, forests, and wetlands, conflict of authority between the Ministry of Culture-Tourism and the Ministry of Environment and Urbanization, lack of environmental analysis and monitoring processes in plans, and disregard of ecosystem services in areas with endemic species are incompatible with legislation and principal decision.

The following policy recommendations have been developed within the scope of these evaluations made in the light of judicial decisions.

A unified planning framework should be established for protected areas; a holistic spatial planning approach covering all protection statuses should be adopted.

The Climate Law should clearly define the role of protected areas as carbon sinks, ecosystem service providers, and climate adaptation mechanisms.

Legal arrangements should be made to provide a permanent solution to the conflicts of authority between the Ministry of Culture and Tourism and the Ministry of Environment, Urbanization, and Climate Change.

In order to prevent the cancelation of plans, a plan approval system should be designed in which institutional opinions are made mandatory and binding.

Environmental impact and climate sensitivity assessments should be made mandatory for all plans prepared in protected areas.

When examining court rulings and legislation related to protected areas in Turkey, it is evident that both national environmental policies and international obligations must be implemented within a more integrated framework in the future. The objectives introduced by the Climate Law to protect carbon sink areas, ensure the continuity of biological diversity, and prevent land degradation indicate that new standards will emerge in the management of protected areas. In the medium and long term, criteria such as climate sensitivity, carrying capacity, ecosystem services, and participation are expected to become mandatory in planning processes. Furthermore, resolving conflicts of authority between administrative authorities will not only reduce the workload of the judiciary but also increase predictability in planning processes. In this context, the future of protected areas will be shaped not only by nature conservation but also as a cornerstone of climate change adaptation policies.

Judicial decisions impose practical obligations such as basing plans on higher-level plans to prevent their cancelation, mandating institutional opinions, and integrating ecological analyses into reports. Furthermore, stricter oversight processes are envisaged to allow energy, tourism, and mining investments in protected areas. In this regard, the study's findings will contribute not only to academic discussions but also to practitioners in reducing legal risks and making planning processes more transparent and scientifically grounded.

5. Limitations of the study

The main limitation of the study is that the number of judicial decisions analyzed is limited and based only on selected court decisions. Moreover, since the policy documents have not yet been fully reflected in practice, the predictions remain at an interpretative level.

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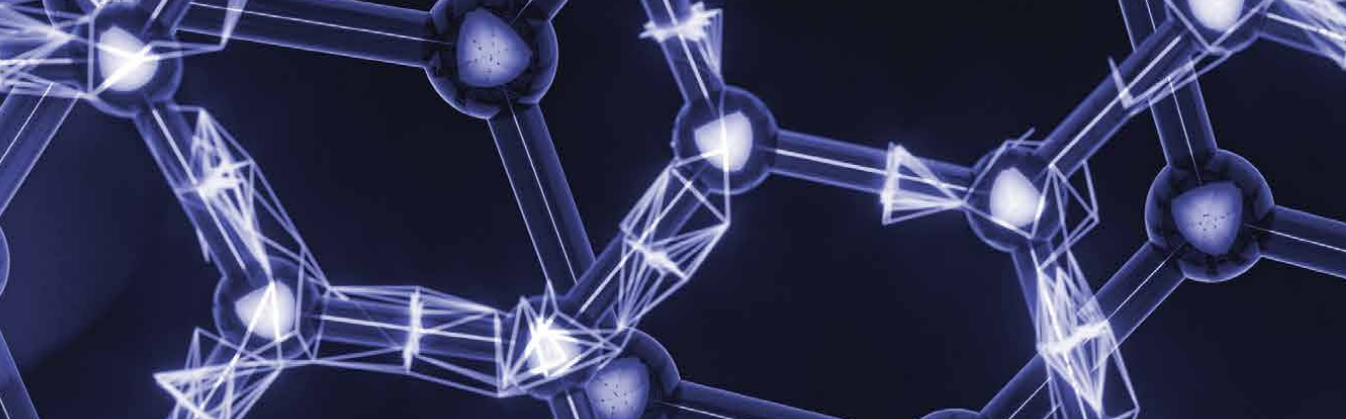
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Edited by Ilda Vagge

The book *National Parks and Protected Areas - Conservation, Biodiversity, and Climate Action* is a crucial resource for understanding the intricate relationship between conservation efforts and the pressing challenges posed by climate change. Comprising nine meticulously researched chapters, this volume examines the vital role protected areas play in preserving biodiversity and ecosystem resilience amid an increasingly volatile climate. Each chapter offers a unique perspective on the multifaceted challenges and opportunities across various national parks and reserves worldwide.

From the historical climate reconstructions in Cofre de Perote National Park to the pressing human-wildlife conflicts in Mkomazi National Park, the contributions collectively highlight the urgent need for adaptive management strategies that integrate ecological science with community engagement. Key themes include the importance of soil health as a foundation for biodiversity, the identification of climate-resilient biodiversity refuges in Spain, and the innovative landscape designs that balance human activity with ecological integrity in Iceland. The governance transformations at Tram Chim National Park illustrate the potential to reconcile conservation objectives with sustainable livelihoods, while legal perspectives on protected areas in Turkey underscore the need for robust regulatory frameworks to safeguard these vital ecosystems. As climate change continues to reshape our natural world, this book underscores the imperative for informed conservation action. It serves not only as a call to action but also as a guide for researchers, policymakers, and practitioners committed to fostering sustainable coexistence between human societies and the environment. By bridging the gap between scientific inquiry and practical application, this book offers valuable insights essential for navigating the complexities of conservation in a changing climate. This comprehensive examination of conservation strategies is timely and significant, reinforcing the critical importance of protected areas in the global fight against biodiversity loss and climate change.

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