DYNAMICS OF GREEN SPACES AND THEIR IMPACTS ON URBAN ECOSYSTEM SERVICES IN A CLIMATE CHANGE CONTEXT IN DAKAR REGION, SENEGAL

BY

CISSE, Mariama

PhD/SPS/FT/2021/13009

WEST AFRICAN SCIENCE SERVICE CENTRE ON CLIMATE CHANGE AND ADAPTED LANDUSE (WASCAL) CLIMATE CHANGE AND HUMAN HABITAT FEDERAL UNIVERSITY OF TECHNOLOGY MINNA, NIGER STATE

MAY, 2025

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DECLARATION

I hereby declare that this thesis titled: "**Dynamics of Green Spaces and their Impacts on Urban Ecosystem Services in a Climate Change Context in Dakar Region, Senegal**" is a collection of my original research work and it has not been presented for any other qualification anywhere. Information from other sources (published or unpublished) has been duly acknowledged.

CISSE, Mariama
PhD/SPS/FT/2021/13009
Federal University of Technology
Minna, Nigeria

____
Signature/Date

CERTIFICATION

The thesis, titled: "**Dynamics of Green Spaces and their Impacts on Urban Ecosystem Services in a Climate Change Context in Dakar Region, Senegal**" by CISSE, Mariama (PhD/SPS/FT/2021/13009) meets the regulation governing the awards of the degree of PhD of the Federal University of Technology, Minna and it is approved for the contribution to scientific knowledge and literary presentation.

Prof. O. O. Morenikeji
Major Supervisor
Signature/Date

Prof. Awa Niang Fall
Co-Supervisor
August 14, 2025
Signature/Date

Prof. Elke Mertens
Co-Supervisor
Elke Mertens August 14, 2025
Signature/Date

Prof. A. A. Okhimamhe
Director of WASCAL, Doctoral Research Programme (DRP) of Climate Change and Human Habitat (CC&HH)
Signature/Date

Prof. A. N. Saidu
Dean of Postgraduate School
Signature/Date

DEDICATION

I dedicate this work to my little late brother, Serigne Cissé, who left us at a young age, to my late grandmother Dior Seck, and to my late grandfather Serigne Faty Cissé, who once told me, “To become a good student, make solitude your companion”.

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ABSTRACT

Senegalese cities have undergone rapid urbanisation, resulting in significant landscape transformations. Dakar, one of Senegal's fastest-growing cities, is experiencing rapid urban expansion, leading to a substantial reduction in green spaces. These green spaces, essential for urban sustainability and resilience, are becoming increasingly scarce, negatively impacting the city's environment and the quality of life for its inhabitants. In this context of climate change, this study aims to assess the impacts of changes in the region's public green spaces on urban ecosystem services. To collect the data, several approaches were employed. These included a combination of methods, such as an itinerant inventory of public green spaces, surveys with questionnaires, and semi-structured interviews. Secondary data, such as Landsat satellite images, were also collected. Data analysis involved approaches such as geographic information systems, remote sensing, descriptive statistical analysis, and content analysis. This study also utilised new methods for evaluating ecosystem services, such as the InVEST model. The results obtained in this study revealed an interesting typology of public green spaces, characterised by low diversity, with Shannon and Evenness indices equal to 1.44 and 0.56, respectively. Furthermore, green spaces are unevenly distributed in the region, as revealed by the Gini coefficient of 0.59. In terms of quantity, the green spaces showed low density, with only 2 green spaces per square kilometre, a low coverage rate of 3.5 %, and a low ratio of 4.69 square metres per inhabitant. Qualitatively, the NDVI values are also relatively low for most green spaces. The spatiotemporal analysis from 1990 to 2022 showed a downward trend, with the total green space coverage decreasing from 13.36 % in 1990 to 9.54 % in 2022. This study also examined the three major green spaces in Dakar, revealing substantial changes in vegetation cover, accompanied by significant losses despite some observed gains. The primary factors contributing to these changes were anthropogenic, primarily due to the city's rapid urban expansion. The dynamics of green spaces directly impacted the selected regulatory services, particularly in the forest. The reduction in vegetation cover led to a decrease in carbon stocks, urban cooling capacity, and flood control. However, in the park and the reserve, the correlation was negative, suggesting that other factors influence ecosystem services. In light of this, this study conducted a suitability analysis to identify areas suitable for green space development. The results revealed significant potential for green space development in the Dakar region, with over 90% of the area being suitable, and moderately suitable being the most prevalent type. Consequently, this study highlights a critical issue with the integration of public green spaces in urban planning in Dakar, which has resulted in substantial loss of these spaces and the services they provide. To address this issue, this study recommends the expansion of green spaces and the implementation of a robust management policy for their proper conservation.

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LIST OF ABBREVIATIONS

AHP	Analytic Hierarchy Process
ANAT	National Agency of Territorial Planning
ARIES	Artificial Intelligence for Ecosystem Services
CICES	Common International Classification of Ecosystem Services
C	Carbon
CC	Cooling Capacity
CI	Consistency Index
CN	Curve Number
CO_2	Carbon Dioxide
Cr	Consistency Ratio
EbA	Ecosystem-based Adaptation
EbM	Ecosystem-based Mitigation
EROS	Earth Resources Observation and Science
ET	Evapotranspiration
FAO	Food and Agriculture Organisation
GEE	Google Earth Engine
GHG	Greenhouse Gases
GIS	Geographic Information System
Ha	Hectare
HMI	Heat Mitigation Index
HFZP	Hann Forest and Zoological Park
IPCC	Intergovernmental Panel on Climate Change
InVEST	Integrated Valuation of Ecosystem Services and Trade-offs
IUCN	International Union for Conservation of Nature
Kc	Crop Coefficient
LULC	Land Use and Land Cover
MCA	Multi-Criteria Analysis
MCF	Mbao Classified Forest
MEA	Millennium Ecosystem Assessment

NbS	Nature-based Solution
NDVI	Normalised difference vegetation index
NURGND	Natural Urban Reserve of Great Niaye and Dependence
PGS	Public Green Space
P (mm)	Precipitation in millimetres
Qgis	Quantum Gis
RI	Random Inconsistency Index
Ri	Runoff Retention Capacity
SCP	Semi-Automatic Classification Plugin
SDG	Sustainable Development Goal
TC	Tonne of carbon
T (ºC)	Temperature in degree Celsius
UHI	Urban Heat Island
UGS	Urban Green Space
USGS	United States Geological Survey
WASCAL	West African Science Service Centre on Climate Change and Adapted Land Use
WHO	World Health Organisation

CHAPTER ONE

1.0. INTRODUCTION

1.2 Background to the Study

Urban Green Spaces (UGS) are a vital part of cities, playing a key role in enhancing their resilience and sustainability (Sangwan *et al.*, 2022). These spaces are typically defined as areas that are either naturally or artificially vegetated, located within or on the outskirts of cities (Fratini and Marone, 2011). Urban green spaces include parks, forests, gardens, allotments, wetlands, and urban trees, which can be either public or private. They may be accessible directly or indirectly for various activities, such as active or passive recreation, and can have a positive effect on the urban environment (Mensah, 2014a). Since the nineteenth century, UGS have gained global importance, not only by improving the aesthetic appeal of urban areas but also by contributing to the livability and well-being of city residents (Swanwick *et al.*, 2003). Their value lies in the wide range of functions, services, and benefits they offer, called ecosystem services, which enhance the quality of life and promote urban sustainability (Bush *et al.*, 2021). These ecosystem services help address many urban challenges (Hurlimann *et al.*, 2021; Wolch *et al.*, 2014).

Cities are the main contributors to climate change, responsible for over 50 % of global greenhouse gas emissions (Walsh *et al.*, 2011; Govindarajulu, 2014). They are also the areas where the impacts of climate change are most pronounced, presenting more risks to both their sustainability and the well-being of their populations. The most significant consequences of climate change on societies and the environment include changes in extreme weather events, such as heatwaves, heavy rainfall leading to flooding, and droughts (Masson *et al.*, 2020; Swain *et al.*, 2020). Urban green spaces provide four main types of ecosystem services: supporting services, provisioning services, regulating services, and cultural services (Pantaloni *et al.*, 2022).

UGS are essential in both adapting to and mitigating the effects of climate change. These green spaces act as carbon sinks, absorbing carbon dioxide through photosynthesis and storing it as biomass (Nowak *et al.*, 2013; Oviantari *et al.*, 2018), which makes them important carbon reservoirs in urban areas (Nero *et al.*, 2017). Beyond mitigating carbon dioxide, UGS also help cool urban environments. By providing shade and enabling evapotranspiration, they create cooling zones that counteract urban heat, improving both air quality and overall well-being (Hamada and Ohta, 2010; Haq, 2011; Shishegar, 2015; Kadaverugu *et al.*, 2021). These spaces also have significant economic value, as they reduce energy costs by lowering the need for cooling buildings (Mathey *et al.*, 2011; Oliveira *et al.*, 2011; Peschardt *et al.*, 2012; Barrera and Reyes-Paecke, 2021). Green spaces help prevent flooding by capturing water with their canopy and stems, which aids water infiltration into the soil and root systems (Kim, 2016; Yang and Lee, 2021). Furthermore, UGS contribute to the physical and mental health of residents, supporting fitness, cognitive function, and immune health, and reducing mortality rates (Tzoulas and James, 2004; World Health Organisation, 2017). Overall, urban green spaces significantly enhance the quality of life by reducing air and noise pollution (Kothencz *et al.*, 2017).

Despite their vital role and the services, they offer, green spaces, mainly natural ones, are rapidly disappearing from urban areas due to the fast-paced urbanisation driven by population growth (Mensah, 2014b). In 2018, over half of the global population lived in cities (Bodo, 2019), and according to World Bank forecasts, this proportion is expected to rise to two-thirds by 2050 (Wahba *et al.*, 2020). The rapid urbanisation linked to population growth has led to significant changes, becoming a critical factor in the land use system (Weith *et al.*, 2021). This increasing demand for space has resulted in land shortages, prompting the conversion of agricultural land and forests into urban areas (Ramaiah and Avtar, 2019). Studies highlight the alarming rate at which forests and agricultural lands have been converted over the years, contributing to the significant growth of impervious surfaces (Zhong *et al.*, 2019). As a result, urban expansion directly leads to the loss of urban vegetation, which in turn diminishes the ecosystem services that green spaces provide. This decline exacerbates air and water pollution, urban heat islands, biodiversity loss, and increased carbon emissions, further worsening climate change (Puplampu and Boafo, 2021). The situation is particularly severe in towns in developing countries compared to those in Europe or America. In contrast, cities in Europe and America have adopted urban planning strategies that prioritise green spaces, leading to greener cities in developed regions than in Asia and Africa (Essel, 2017).

In Asia, China has seen a significant reduction in green spaces due to rapid urbanisation, a trend common across developing nations (Li *et al.*, 2020). In Beijing, for example, green space shrank by 47.05 square kilometres each year between 1992 and 2004. This loss is largely attributed to the widespread construction and development of transportation infrastructure in both the city centre and suburban areas. Furthermore, the influence of natural factors and the development of greening policies are also affecting the changes in green space dynamics (Wu *et al.*, 2023).

In Africa, rapid urbanisation has led to a continuous decline in green spaces, resulting in them occupying only a small fraction of available space in many urban areas (Mensah, 2014b). In sub-Saharan Africa, urban green spaces, blue spaces, and their benefits for residents are often overlooked or ignored (Lindley *et al.*, 2018). For example, Kumasi, the second-largest city in Ghana, was once known as a “garden city” of West Africa, celebrated for its abundant greenery. However, Kumasi has experienced the fastest urban growth in the country. It also functions as a transit hub for travellers entering and leaving

Ghana and is home to the largest open market in West Africa. These factors have contributed to the reduction of green space coverage, which is unevenly spread across the city (Mensah, 2014a). A study examining the dynamics of green spaces found a significant decline in their coverage, happening four times faster between 2009 and 2014 compared to the period from 1986 to 2002. Currently, green spaces in Kumasi cover only 33% of the area (Nero, 2017).

The degradation of vegetal resources has become a significant issue in Senegal (Sambou, 2004; Dieng, 2017), especially in urban areas. With the urban population growing rapidly and uncontrolled, from 725 831 in 1960 to 8 806 799 inhabitants in 2023 (https://data.worldbank.org), several challenges, including the loss of vegetation, have emerged. The expansion of built-up areas and infrastructures has placed tremendous pressure on green spaces, leading to their gradual reduction in both urban and surrounding areas, as seen in the Dakar region (Faye *et al.*, 2022). Dakar, the capital of Senegal and the country's smallest administrative region in terms of land area, is experiencing rapid urbanisation with a rate of 97.2%. This region is home to more than 20% of country's population (Regional Service of Statistics and Demography of Dakar, 2021). The region's unplanned expansion has led to the gradual encroachment on its natural and agricultural land, particularly in peri-urban areas (Sane and Ndiaye, 2006). Once famous for its lush greenery, Dakar, formerly known as the Cape Verde Peninsula, has seen a steady decline in its natural landscapes, with green spaces increasingly replaced by grey infrastructures (Diagne, 2008).

1.2 Statement of the Research Problem

Like many rapidly growing African cities, the Dakar region is grappling with the dual rapid urbanisation and climate change challenges. As urban expansion converts natural and semi-natural areas into impermeable urban surfaces (Yu *et al.*, 2019). The region faces increasingly severe climate impacts, including more frequent extreme events. For instance, annual flooding has caused significant damage to infrastructure, such as houses and roads, while exacerbating health risks like malaria and diarrhoea, and has affected the livelihoods of about 1.5 million people (Speranza *et al.*, 2019). To ensure that cities are inclusive, safe, resilient, and sustainable (SDG 11), it is crucial to reassess Dakar's urban green spaces. Ideally, the expansion and preservation of these spaces would play a central role in enhancing ecosystem services such as flood and heat mitigation and improved public health (Mathey *et al.*, 2011). Regular monitoring and integrating green spaces in urban planning policies are vital steps to ensure their ongoing contribution to the city's resilience and sustainability.

Green spaces in the Dakar region have undergone significant changes since independence, much like many other African cities (Shackleton and Gwedla, 2021). In the past, green space primarily consisted of tree planting along major avenues and boulevards, serving aesthetic, social and shading purposes, over time, additional types of green spaces were gradually introduced within the city (Diagne, 2008). Today, Dakar boasts a relatively diverse range of green spaces that require protection to maintain the services they offer. These include parks, forests, small gardens, green façades, grassed areas, trees, cemeteries, and car park façades (Tine *et al.*, 2021). However, similar to most African cities, rapid and uncontrolled urbanisation, coupled with the encroachment on public land, has led to a decline in green spaces, undermining the cities' original green character (Mboup, 2017). Research has shown that Dakar, like other West African cities, faces significant challenges in preserving urban vegetation primarily due to the rapid spread of urban development and infrastructure projects (Mensah, 2014b). These factors of land use and land cover dynamics have led to a significant loss of green space and pose a serious threat to the city's ecological balance, resulting in a decline in both the quantity and quality of the ecosystem services provided by these green spaces (Ahmad *et al.*, 2014; Kim and Kwon, 2021).

Land use and land cover changes are closely connected to the dynamics of urban green spaces and the ecosystem services they provide. Research has shown that as urbanisation progresses, with population growth and an increased built-up area, green spaces are gradually reduced, which diminishes their capacity to offer essential ecosystem services (Richards *et al.*, 2020; Xiao *et al.*, 2022). This issue has been particularly evident in China, especially in Huangyan, where the ecosystem services provided by green spaces have declined from 21.03% in 1992 to 19.56% in 2020 due to ongoing changes (Xiao *et al.*, 2022). In Addis Ababa, Ethiopia, studies have found a simultaneous rise in land surface temperature and degradation of vegetation (Abebe and Megento, 2016). When green spaces, which act as cooling islands, disappear, urban heat islands expand. Similarly, carbon sequestration is also affected by changes in green spaces. Research indicates that as green spaces increase in size, their carbon stocks grow, while their reduction leads to the release of carbon dioxide into the atmosphere (Han *et al.*, 2018; Ren *et al.*, 2019). Thus, the dynamics of green spaces impact all ecosystem services they provide.

There is, however, a lack of scientific research on the changes in ecosystem services due to the dynamics of green spaces, with most studies focused on Asia. In contrast, Africa, being the second most urbanised continent, lacks sufficient research to guide stakeholders and decision-makers on the importance of green space conservation and its integration into urban planning policies, leading to a shortage of scientific data. The unplanned urbanisation of African countries, particularly Senegal, has resulted in spatial inequalities, with green spaces being restricted to small areas (Ndiaye, 2015). Urban planning should not only address the built environment, such as housing and transportation networks, but should also incorporate green spaces into the urban landscape (Abebe and Megento, 2017). This is especially important in a context where Nature-based Solutions (NbS) are gaining attention as a way to address climate change, reduce vulnerability, and enhance the resilience of cities (Davis and Naumann, 2017). To overcome the challenge of limited data, it is essential to assess the current state of green spaces thoroughly to ensure they receive adequate attention. As Sambou (2004) emphasises, the sustainable management of natural resources requires a comprehensive understanding of these resources, both qualitatively and quantitatively. Therefore, this study, which focused on public green spaces (PGS), is conducted from this perspective to evaluate the changes in ecosystem services resulting from the dynamics of urban green spaces in Dakar, Senegal's most urbanised city, with the goal of promoting their protection, conservation, and expansion towards resilience and sustainability of this city.

1.3 Research Questions

1. What is the typology of PGS in the Dakar administrative region, and how are their features, such as diversity, spatial repartition, density, coverage rate, ratio, and quality, presented within the region?

2. How has the evolution of PGS in the Dakar region changed from 1990 to 2022, and what are the key factors that have influenced this dynamic?

3. What are the implications of PGS dynamics on urban ecosystem services, particularly climate regulation, in the Dakar region?

4. In a densely populated city like Dakar, where climate change poses significant challenges, where should PGS be developed to mitigate and adapt to these impacts?

1.4 Aim and Objectives

This study aims to evaluate the effects of PGS dynamics on the urban ecosystem services in the Dakar region, taking into account the context of climate change.

The specific objectives of this study are to:

1. Identify and classify the types of PGS in the Dakar administration region, and analyse their characteristics, including diversity, spatial distribution, density, coverage rate, ratio per inhabitant, and quality;
2. Analyse the spatial and temporal dynamics of PGS in the Dakar administrative region from 1990 to 2022, and identify the factors contributing to their degradation;
3. Assess the impacts of the dynamics of PGS on the urban ecosystem services in the Dakar administrative region, particularly their effects on climate regulation;
4. Determine suitable locations for future PGS in the Dakar region that consider ecosystem services and enhance access for underserved communities.

1.5 Research Hypotheses

Hypothesis 1: (a) Various PGS, such as forest, park, public garden, and squares, can be found throughout the Dakar administrative region;

(b) The presence of different types of PGS contributes to a high diversity of these spaces and would be important in ecosystem service provisioning;

(c) Green spaces are more concentrated in some areas than others;

(d) The spatial coverage of PGS in Dakar is limited, resulting in a low number of such spaces per square kilometre;

(e) The combination of a high population and limited spatial coverage leads to a low ratio of PGS per inhabitant;

(f) Green spaces with high NDVI (Normalised Difference Vegetation Index) values are considered to be of good quality, while those with low NDVI values are of poorer quality.

Hypothesis 2: (a)The steady increase in built-up areas between 1990 and 2022 has led to a gradual reduction in green spaces in the Dakar administrative region.

(b) Urban expansion driven by urbanisation is the main factor contributing to the degradation of green spaces in Dakar;

Hypothesis 3: PGS that experience a reduction in vegetation cover also see a decline in ecosystem services such as carbon storage, urban cooling, and flood mitigation;

Hypothesis 4: The Dakar administrative region still contains areas suitable for the development of public green spaces.

1.6 Justification for the Study

This study, conducted through the WASCAL centre, seeks to empower African policymakers in transforming cities into smart and resilient urban environments, especially in the context of climate change. It emphasises the development of green areas as a vital component for achieving the Sustainable Development Goals, particularly SDG 11, which focuses on inclusivity, safety, resilience, and sustainability. By offering a comprehensive guide, this research highlights the importance of UGS and their diverse ecosystem services in enhancing resilience in Senegalese cities. This study also draws attention to the harmful effects of the loss of green spaces on the urban population. In relation to climate change, it promotes the integration of urban green spaces into national adaptation and mitigation policies. Specifically, it supports Senegal's Ministry of Environment and Ecological Transition through its Division of Climate Change. The study explores the nature-based or ecosystem services approaches as solutions to climate change and its impacts. By providing scientific data to various stakeholders, the aim is to encourage the rational and sustainable management of green spaces and their ecosystem services.

The results of this study help the Ministry of Urbanism, Territorial Communities, Territorial Planning, the Ministry of Environment and Ecological Transition of Senegal, and urban planners to develop a comprehensive database of green spaces in the Dakar region. This database will serve as a key resource for creating and implementing a strong policy to manage these spaces both in the capital and nationwide. Furthermore, this research can provide valuable guidance on the most suitable types of green spaces for different contexts. By examining the primary functions of these spaces, it will be possible to identify strategies for mitigating climate change impacts and integrating these spaces into urban planning. Additionally, the findings can be used by local authorities, such as mayors, to improve to enhance the quality of life for their residents by offering scientific recommendations derived from this research.

In Africa, numerous studies on urban green spaces have been conducted, with South Africa being the leading region. However, in West Africa, research on urban green spaces mainly focuses on ecosystem services such as carbon sequestration, the dynamics of these spaces, their degradation due to urbanisation, and public perception of them. Senegal, however, stands out as one of the African countries with limited research on green spaces. This lack of scientific data creates significant challenges for managing these spaces, as it is difficult to effectively manage a resource that is not well understood. As such, this study makes a valuable contribution by exploring the effects of diminishing green spaces on urban ecosystem services in the Dakar region, particularly in the context of climate change. It is important to advocate for the integration of green spaces into urban planning, especially as they are increasingly emphasised in global climate policies focused on sustainability. This research addresses the challenges in this area, highlighting the growing importance of urban green spaces in developing sustainable and livable cities, and also serves as a useful resource for future studies.

Finally, due to the lack of awareness regarding the importance of green spaces, local communities often exploit them, especially those located in peri-urban areas. In this context, this study can serve as an effective tool for communication and awareness-raising within the communities. Increasing understanding of the ecosystem services offered by UGS could provide valuable guidance for reforestation efforts led by local authorities, cultural or sports associations, and non-governmental organisations.

1.7 Scope of the Study

1.7.1 Temporal scope

The time intervals selected to analyse the spatio-temporal dynamics of green spaces in the Dakar region span from 1990 to 2022. This decision was made considering several factors, including the fact that, as per the National Agency of Statistics and Demographics, the population of the Dakar region experienced a significant increase starting from 1988 (Regional Service of Statistics and Demography of Dakar, 2021). In addition, around the 1990s, some climatic events were observed, such as drought and a considerable decrease in temperatures, leading to significant cold waves (Sagna, 1990). These factors, combined with the issue of satellite images, which are often unavailable for certain areas, led to the choice of 1990 as the reference year of this study.

1.7.2 Spatial scope

The Dakar study area was chosen because it is highly vulnerable to climatic risks. It faces issues like flooding, urban heat island effect, air pollution due to the outdated car park, industrial concentration, the presence of a coal-fired power station, waste incineration, and deforestation (Regional Service of Statistics and Demography of Dakar, 2021). At the same time, most of the population is concentrated in this area. Green spaces play a crucial role in addressing the challenges of urban living. They have been an integral part of the urban landscape since the colonial era.

1.7.3 Content scope

The study focuses on assessing the dynamics of green spaces and their impacts on ecosystem services within the designated area. It specifically examines natural and artificial public green spaces, as they are more susceptible to changes in the urban landscape compared to private green spaces and are more accessible to the general public.

1.8 Limitations of the Study

This work has not been conducted without some constraints. The main difficulties encountered were primarily related to access to high-quality satellite imagery. In fact, the study of urban green spaces requires very high-resolution imagery because these spaces are often small and difficult to detect in dense cities. This can lead to the overestimation or underestimation of these spaces. Additionally, due to limited access to commercial remote sensing software for this study, mapping software was used exclusively to conduct the spatiotemporal analysis of green spaces with integrated plugins. This made the work challenging and slow due to software bugs.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Conceptual Framework

2.1.1 Urban green space

The term "urban green space" is defined differently across various literature sources. Schipperijn *et al.* (2013) define it as "*all publicly owned and accessible open spaces with a high degree of vegetation cover, such as parks, woodlands, nature areas, and other green spaces*". Rasidi *et al.* (2012) define it as "*any piece of land covered in vegetation, often referred to as parks, golf courses, sports fields, and other open spaces within urban built-up areas, whether publicly accessible or not*". This definition refers to areas with mostly unsealed, permeable, and soft surfaces like soil, grass, shrubs, and trees, in urban areas. In addition, UGS can be either private, such as those located within institutions or public, meaning they are accessible to everyone without restriction. It also encompasses land that is awaiting planning, land already designated for green space usage, and land planned for future development (Yared *et al.*, 2019).

There are various types of urban green spaces. The French Cities Engineers Association identifies thirteen types of urban green spaces, including parks and squares, green spaces along roads, public buildings, industrial and commercial establishments, and green areas around social and educational institutions such as nursery gardens and retirement homes. Additionally, it includes green spaces in stadiums and sports centres, cemeteries, campsites, reception areas, holiday villages, allotment gardens, horticultural establishments (municipal greenhouses, horticultural colleges, etc.), landscaped natural areas, roadside trees, and grouped or not (Richard, 2013). Swanwick *et al.* (2003) propose an alternative typology that encompasses all green spaces forming the urban green network. They categorise these spaces using a hierarchical structure, taking into account factors such as their role, nature, location, and form, resulting in four distinct categories that represent various green space types, as shown in Table 2.1.

Table 2.1: Typology of urban green spaces (Swanwick *et al.*, 2003)

Main categories	Sub-categories	Green space types
Amenity green space	Recreation green space	Parks and gardens
		Informal recreation areas
		Outdoor sport areas
		Play areas
	Incidental green space	Housing green space
		Other incidental space
	Private green space	Domestic garden
Functional green space	Productive green space	Remnant farmland
		City farms
		Allotments
	Burial grounds	Cemeteries
		churchyards
	Institutional grounds	School grounds (including school farms and growing areas)
		Other institutional grounds
Semi-natural habitats	Wetland	Open/running water
		Marsh, fen
	woodland	Deciduous woodland
		Coniferous woodland
		Mixed woodland
	Other habitats	Moor/heath
		Grassland
		Disturbed ground
Linear green space		River and canal banks
		Transport corridors (road, rail, cycleways and walking routes)
		Other linear features (e.g. cliffs)

A similar typology has also been proposed by Lahoti *et al.* (2019), who, in addition to function, have considered access to green spaces as a criterion. The observation from these three typologies is that there is no single, universal typology for urban green spaces.

Most classifications are context-specific and depend on the city's specific needs and objectives.

Urban green spaces are often linked to aesthetics, recreation, and health because they provide numerous benefits to the urban population for their well-being (Kothencz *et al.*, 2017; Roberts, 2017; Veinberga and Zigmunde, 2019; Yan and Tang, 2021). The World Health Organisation (WHO) recognises the importance of green spaces in promoting health and emphasises the need for their accessibility and equitable distribution within cities (World Health Organisation, 2017). Geary *et al.* (2021) demonstrated that residing near high-quality urban green and blue spaces positively impacts physical and mental health, as well as child development, and therefore advocate for viewing these spaces not only as public health and social investments but also as an opportunity to reassess our relationship with nature to help mitigate future pandemic risks. Furthermore, it is crucial to recognise that contemporary urban health challenges are predominantly linked to climate change (Ebi *et al.*, 2021). It would be intriguing to explore beyond the health aspect to address the significant challenge posed by climate change in enhancing UGS.

Facing climate change, green spaces have gained significant attention in urban areas, especially with the growing emphasis on Nature-based Solutions (Kabisch *et al.*, 2016). As previously discussed, green spaces are recognised as a powerful tool to mitigate climate risks and enhance carbon sinks within cities and urban centres. Consequently, there has been a growing focus on urban green space planning for climate change adaptation and mitigation. The Intergovernmental Panel on Climate Change (IPCC) has recommended in its 5th report that green spaces should be expanded not only for carbon sequestration and reduced energy consumption through the cooling effect, but also for other related advantages such as increased property values, stormwater regulation, reduced air pollution, increased recreational space, provision of shade and coolness, interception and infiltration of rainwater, increased biodiversity, and improved quality of life (IPCC, 2015). All these benefits of green spaces are collectively referred to as ecosystem services.

2.1.2 Green space dynamics

Green spaces undergo spatiotemporal dynamics, reflecting their evolving characteristics over time. In contemporary urban environments, these spaces encounter numerous challenges that shape their transformation and, in some cases, their disappearance, despite their crucial role in cities and the well-being of their inhabitants. The spatial dynamics of urban areas play a significant role in this phenomenon. As per Ahmad *et al.* (2014), global changes in urban land use are a prevalent issue affecting almost every country worldwide. Consequently, these alterations in urban land use inevitably impact green spaces, both qualitatively and quantitatively.

Previous studies point to urbanisation as the main cause of these changes (Okikiola and Akintunde-Alo, 2020). This process of urbanisation is profoundly altering landscapes through urban expansion, population growth and migration, as well as economic development. Forests, meadows, and farmland are transformed into impermeable surfaces, disrupting the composition and structure of ecosystems (Zhang *et al.*, 2020). This has resulted in, according to Li *et al.* (2022), green spaces are gradually becoming a scarce resource.

Another cause also frequently cited in previous studies is climatic events commonly called extreme events, such as floods and droughts, which further accelerate their decline (Zhai *et al.*, 2024). For example, drought is generally associated with a reduction in vegetation productivity due to hydric and thermal stresses (Ma *et al.*, 2015). Besides, the dynamics can often indicate increases in green space cover over the years. Except for most of the studies, decreases are more commonly observed, thus affecting their ecosystem services (Zhang *et al.*, 2015).

2.1.3 Urban ecosystem services

Globally, the term ecosystem services is defined by Daily (1997) as the conditions and processes through which natural ecosystems, and the species that inhabit them, sustain and fulfil human life. For instance, they preserve biodiversity and the production of ecosystem goods like seafood, forage, timber, biomass fuels, natural fibres, and numerous pharmaceuticals, industrial products, and their precursors. However, this definition primarily focuses on natural ecosystems and may not be entirely suitable for this study, which also considers semi-natural and artificial ecosystems.

The Millennium Ecosystem Assessment (MEA) defines ecosystem services as the benefits people derive from ecosystems (Millennium Ecosystem Assessment, 2005). Costanza *et al.* (1997) further emphasises that these services can be provided directly or indirectly by ecosystems. This definition encompasses all types of ecosystems, both natural and artificial, and appears more suitable for this study, which is conducted in an urban setting. In urban areas, ecosystem services are delivered through what is known as ecological infrastructures, such as green and blue spaces, including parks, cemeteries, gardens, urban forests, single trees, wetlands, and green roofs, among others.

Globally, the MEA has categorised ecosystem services into four main groups (Millennium Ecosystem Assessment, 2005):

a) provisioning services which group services of production of food, water, timber, and fibre;

b) regulating services that affect climate, floods, diseases, waste, and water quality;

c) cultural services that provide recreational, aesthetic, and spiritual benefits;

d) supporting services that are soil formation, photosynthesis, and nutrient cycling.

Another classification is given by the Common International Classification of Ecosystem Services (CICES), which shows three main groups of ecosystem services. These are provisioning, regulating, and cultural services, thus eliminating supporting services (Haines-Young and Potschin, 2018).

Figure 2.1 illustrates the conceptual framework that connects the various key concepts of this study. It categorises public green spaces into different types and highlights the ecosystem services they offer. However, the dynamics of these spaces, influenced by urbanisation, land use changes, and climate change, lead to the loss of green spaces and their associated benefits.

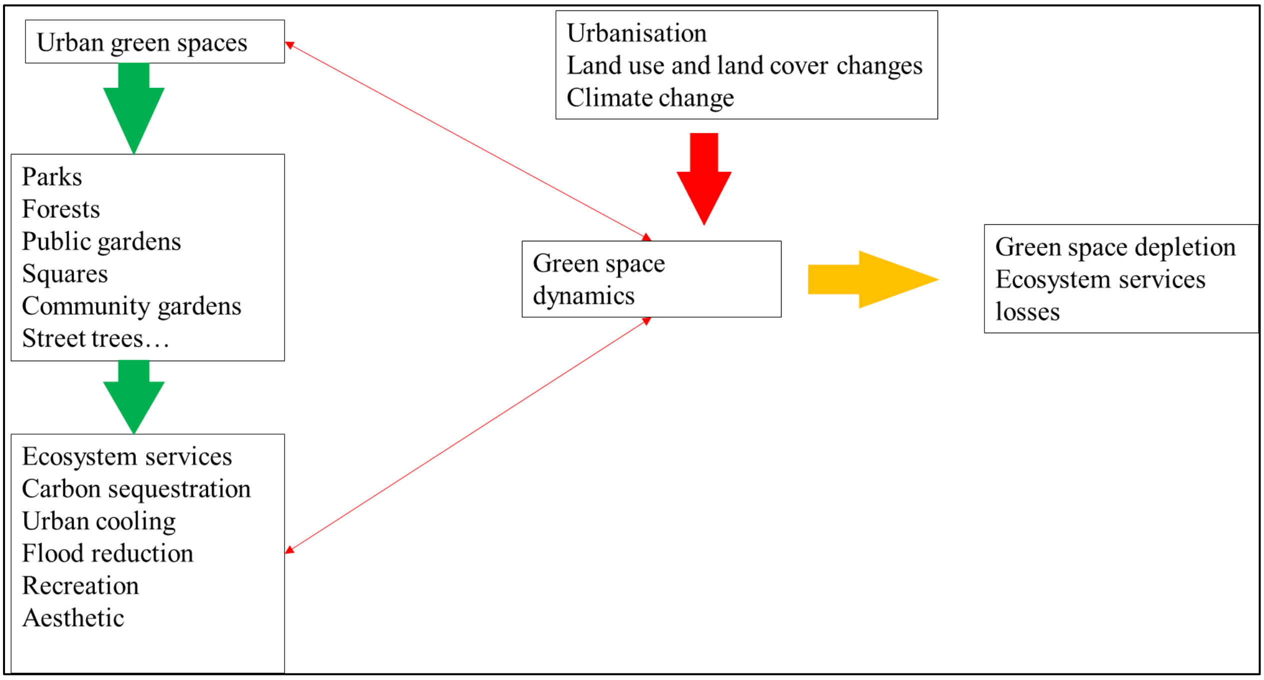

Figure 1.1: Conceptual framework

2.2 Theoretical Framework

Several theories exist about urban green spaces, which are based on valuing their benefits for the sustainability of urban areas, particularly in light of climate change. For instance, the ecosystem services valuation approach focuses on evaluating the services provided by ecosystems like urban green spaces. The objective is to persuade society to recognise the value of the services derived from ecosystems. This theory has emerged in a context where ecosystem services are becoming increasingly scarce (Liu *et al.*, 2010). Urban green infrastructure, a relatively new approach in research and planning policies, aims to create a network of green spaces that provide various benefits to urban environment and its inhabitants. This approach seeks to address pressing urbanisation issues, such as enhancing the quality of life, fostering social cohesion, and promoting environmental justice. Additionally, it aims to protect biodiversity, adapt to climate change, and support the transition to a green urban economy (Wright, 2011; Pauleit *et al.*, 2019). Thus, among all these theories, the two referred to in this study are Nature-Based Solutions (NbS) and land-use planning, which show how important it is to consider green space to tackle climate change.

2.2.1 Nature-based Solutions

The term Nature-based Solutions (NbS), developed by the International Union for Conservation of Nature (IUCN), is an umbrella concept defined by IUCN as "*actions to protect, sustainably manage and restore natural or modified ecosystems, which address societal challenges (e.g., climate change, food and water security or natural disasters) effectively and adaptively, while simultaneously providing human well-being and biodiversity benefits*" (Cohen-Shacham *et al.*, 2016). They are based on utilising nature and natural processes to provide infrastructure, services, and integrated solutions to the growing challenges of urban resilience. Natural solutions bring multiple benefits to cities, enabling them to address various societal challenges, such as reducing disaster risk and building climate resilience. Additionally, they contribute to restoring biodiversity, creating recreational opportunities, enhancing human health, ensuring water and food security, and supporting community well-being and livelihoods (World Bank, 2021).

In essence, NbS can enhance and simplify the implementation of urban landscape actions by considering the services provided by nature. The actions targeted under NbS encompass the development of UGS, such as parks and street trees, which can mitigate high temperatures in cities or regulate air and water flows. Additionally, allocating natural habitat spaces in floodplains can alleviate the effects of flooding. Furthermore, architectural solutions for buildings, like green roofs and walls, can reduce temperatures and conserve energy (Davis and Naumann, 2017). Note that NbS have different aspects depending on the objectives. In the context of climate change, two crucial approaches to NbS are Ecosystem-based Adaptation (EbA) and Ecosystem-based Mitigation approaches (EbM). EbA aims to support ecosystem services that counteract or moderate the impacts of climate change on people. On the other hand, EbM utilises ecosystem services to address the root causes of climate change by either reducing greenhouse gas emissions or enhancing their sinks. These approaches contribute to the objectives of the United Nations Framework Convention on Climate Change (Cohen-Shacham *et al.*, 2016).

This approach outlines the appropriate procedures for restoring nature and its various benefits to urban environments and their inhabitants.

2.2.2 Land use planning

The Intergovernmental Panel on Climate Change (IPCC), through its sixth assessment report (AR6 Working Group II), emphasises the significance of land use planning as a pivotal strategy for mitigating the impacts of climate change (IPCC, 2022). Land use planning, commonly known as urban planning in an urban context, is a deliberate and explicit intervention in the built environment. It involves the creation of plans, programs, and designs to shape and manage the use of land (Bush and Doyon, 2019). This theory posits that land use should align with the principles of zoning, which involves dividing the landscape based on different types of activities. IPCC emphasises that the most effective climate actions are achieved when combined with other planning measures, such as ecosystem-based adaptation. Urban planning plays a crucial role in mitigating current climate impacts by anticipating future scenarios and capitalising on opportunities. Many countries are currently undertaking efforts to organise their spatial planning in a manner that addresses climate risks. According to Jørgensen *et al.* (2014), adaptation based on urban planning has the potential to adapt over time the building stock, the infrastructure, the industrial and economic base, and the spatial patterns of urban development to the risks that may be caused by climate change.

The land use planning approach focuses on how the organisation of the urban landscape is increasingly important in climate change. This will also help to conserve, preserve and restore nature, such as green spaces in urban areas.

2.3 Review of Related Studies

Empirical researches are analysed to demonstrate the importance of green spaces. To do this, the various studies are organised into themes.

2.3.1 Urban green space and its ecosystem services facing climate change

The role played by UGS in dealing with climate change is now widely studied. Demuzere *et al.* (2014) have carried out a global study of the various services provided by green infrastructure, which is a network of green spaces in urban areas. Green spaces play a pivotal role in combating climate change by providing diverse ecosystem services. By absorbing and storing carbon in cities that emit substantial amounts of carbon dioxide, they significantly reduce their carbon footprint. Their importance extends beyond carbon sequestration; they also contribute to adapting to the global climate change phenomenon.

Green spaces serve as climate regulators, offering thermal comfort, mitigating the risk of flooding through runoff, and purifying water and air by enhancing their quality.

Specifically, Nero *et al.* (2017) assessed the quantities of carbon sequestration and storage by green spaces in the city of Kumasi in Ghana. To quantify the biomass and extract the carbon amount, they employed the non-destructive method, utilising allometric equations. There are two approaches to quantifying carbon stocks: the destructive method, which involves removing trees and obtaining samples, and the non-destructive method, which is more of an alternative to cutting trees. Kumasi's green spaces sequester and store significant amounts of carbon, as revealed by the findings, amounting to 211.28 tC/ha. This quantity is significant, especially in a context where cities are the primary contributors to greenhouse gas emissions, particularly carbon dioxide. Moreover, their findings reveal a disparity in stocks among different types of green spaces, with forests being the most abundant reservoirs. This underscores the importance of diversifying these spaces at the city level. Similar studies have been conducted in other countries, such as Burkina Faso, Togo, and Côte d'Ivoire, respectively (Gomgnimbou *et al.*, 2019; Fousseni *et al.*, 2020; Ouattara *et al.*, 2021).

Several studies have highlighted other advantages of green spaces, such as their ability to mitigate urban climate risks, as evidenced by Mees and Driessen (2011), who argue that green spaces are a no-regret adaptation strategy because they absorb rainfall, moderate temperatures, and simultaneously contribute to the sustainable development of urban areas. Mathey *et al.* (2011) have delved into the significance of urban green spaces in mitigating climatic conditions within urban areas, particularly in Germany. Their findings confirm the substantial potential of these spaces in providing cooling effects, especially in densely populated and hot cities. For instance, parks exhibit a significantly higher cooling effect compared to the built environment, particularly during the evening and night-time hours. This is attributed to the shade provided by vegetation, evaporative cooling, and the low heat storage capacity of the surrounding area.

It is not sufficient to focus solely on the services and functions of green spaces; it is equally important to conduct a thorough review of the tools and approaches used for their evaluation. Nowadays, numerous advancements are being made to facilitate the study of green spaces and their benefits (Neuenschwander *et al.*, 2014). In this context, remote sensing and geographical information systems techniques are widely employed to evaluate ecosystem services on both small and large scales. Numerous useful technologies have been developed in ecosystem services modelling, enabling visualisation of their spatial distribution, comparison with drivers of changes and other socio-ecological parameters, and modelling the impacts of changes in land use or land cover, land management, ecosystem and climatic conditions, and human population impact on the production and value of ecosystem services (Nemec and Raudsepp-Hearne, 2013; Nowak *et al.*, 2013; Villa *et al.*, 2014). Among the most widely used applications is i-Tree Eco, a free and peer-reviewed software developed by the Forest Service of the United States Department of Agriculture.

The i-Tree Eco is a part of the i-Tree software suite and is frequently employed in studies to assess the urban ecosystem services provided by entire urban areas (Scholz *et al.*, 2018). Its process involves five steps that are based on the relationship between biodiversity, ecosystem function, and human well-being. These steps generate the structure, function, services, benefits, and economic value of an ecosystem. i-Tree Eco is commonly used to define urban green growth models, assess a single ecosystem service like carbon storage or air quality improvement, evaluate the ecosystem services provided by an urban park or green spaces more broadly, and compare urban green design in terms of ecosystem provision (Rossi *et al.*, 2022). The i-Tree Eco model was employed to assess the role of various green spaces in the city of Porto in providing urban ecosystem services, particularly carbon sequestration. The findings corroborated the research results mentioned earlier by Nero. Notably, the study identified parks, public gardens, and woodlands as the green spaces with the highest carbon stocks compared to other types in the city (Graça *et al.*, 2018).

Another model commonly employed to study green spaces and their services is the Artificial Intelligence for Ecosystem Services (ARIES). Unlike the initial model, ARIES is an online tool designed to assess ecosystem services within urban environments. It offers supply and demand models for ecosystem services, utilising empirical data and models to generate more comprehensive flow representations (Arrogante-Funes *et al.*, 2022). ARIES maps the potential locations and quantities of services, human beneficiaries, and biophysical features that could reduce service flows (Villa *et al.*, 2014). This model was used by Capriolo *et al.* (2020) to evaluate the soil and vegetation's water retention capacity in Italy, the model aims to mitigate flooding by regulating excessive runoff caused by rainfall. To achieve this, the model incorporates the flood risk probability index, which considers the physical and bioclimatic factors that characterise the ecosystem's ability to manage potential floods.

The same service has been estimated by Kadaverugu *et al.* (2021) in Hyderabad City, India, using another model such as InVEST. Their research focuses on the role of urban green spaces and open land in mitigating floods by retaining rainwater. Their findings revealed that areas with a high green cover exhibit the highest retention values, followed by open spaces. Additionally, they employed the Runoff Resistance Index (Ri), which quantifies the proportion of runoff retained compared to precipitation, to pinpoint the areas with the highest resistance. Consequently, Ri values are high in pixels with vegetation land use, followed by open spaces.

The Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) is an open-source software developed by the Natural Capital Project and Stanford University that is suitable for ecosystem service assessment (Adelisardou *et al.*, 2021; Benra *et al.*, 2021; Sharp *et al.*, 2020). InVEST models can be used to assess and map the benefits provided by terrestrial and aquatic ecosystems. These models are spatially explicit and combine land use and land cover data with additional information such as soil type and climate data to provide output values of ecosystem services in biophysical and economic units. Initially, the model was designed to evaluate ecosystem services in natural and rural areas. Later, models specific to urban areas were integrated, such as urban cooling, urban stormwater retention, and urban flood risk mitigation (Veerkamp *et al.*, 2023). InVEST is a valuable model for studying environmental management and analysing changes in ecosystem services due to land use (Vigerstol and Aukema, 2011).

InVEST has also been widely used to evaluate the ecological services provided by urban green areas. Kadaverugu *et al.* (2021) have delved into the effects of vegetation cover on mitigating urban heat in Nagpur City, India. Their findings are based on the use of indices, and they've discovered that the concentration of heat mitigation indices is significantly higher in areas with dense green cover. Notably, their research reveals a direct correlation between the cooling effect and the size of urban green spaces. Moreover, the cooling distance is strongly linked to the canopy's density.

2.3.2 Urban green space changes

Due to the constant changes in land use and land cover, primarily caused by urbanisation, urban green spaces are experiencing significant impacts. Consequently, their quantity and quality are drastically reducing in many countries (Dallimer *et al.*, 2011). Xiao *et al.* (2022) argue that the green spaces in the outskirts of Chinese cities have been eroded, leading to a decline in biodiversity, due to the rapid expansion of urban areas by approximately. According to Theodorou (2022), urbanisation creates novel ecosystems with distinct abiotic and biotic characteristics that pose challenges to numerous organisms. Furthermore, the loss of biodiversity is not only a consequence of this phenomenon caused by habitat fragmentation, but it also leads to a decline in the types of ecological services provided, and globally, it negatively impacts environmental quality (Hu and Zhang, 2020). With the rapid changes occurring in green spaces, numerous studies are being conducted to enhance understanding and awareness, highlighting the need for more sophisticated assessment techniques and tools.

Huang *et al.* (2018) argue that remote sensing techniques have consistently been employed to evaluate changes in green spaces over time, utilising satellite imagery, particularly Landsat. The Google Earth Engine (GEE) platform is being developed to analyse larger scales, such as a country or a region. GEE is an open-access cloud computing platform that collects images, classifies them in a supervised manner, and assesses their accuracy using artificial intelligence and machine learning algorithms (Floreano and De Moraes, 2021). Using this platform, Zhai *et al.* (2024) are assessing the dynamics of green space coverage in 320 of China's most urbanised cities, researchers found a regressive trend, with these spaces shrinking at a rate of 1.14% annually over the past two decades. Geographic Information Systems (GIS) and remote sensing methods have become integral to land use and land cover studies, offering quick, effective, and cost-effective solutions. Now, plugins are being developed in GIS software like QGIS. These plugins include semi-automatic classification (SCP), which allows supervised classification to be achieved, from enhancing the quality of satellite images through land use and land cover production to the accuracy assessment of the results (Congedo, 2021). This technique, increasingly used in urban areas, is applied to analyse green space dynamics. For example, Vasenev *et al.* (2019) used it to study the change in land use in the city of Moscow. They realised that, like any urban expansion, green spaces suffer significantly, with losses recorded over the years.

2.3.3 Urban green space planning

In most cases, urban green spaces are meticulously planned and designed as public spaces, with a stronger emphasis on recreational activities (Yu *et al.*, 2017). Moreover, the multifunctionality of urban green spaces is no longer a subject of debate, as evidenced by Mehdi *et al.* (2018). This aspect is strongly emphasised in the development of urban plans. Semeraro *et al.*, (2021) defend the transdisciplinary approach to urban green infrastructure planning. They argue that planning should involve experts from various disciplines, including biologists who study ecosystems at multiple scales, from single plants to entire ecosystems, and urban planners who operate at different levels, such as micro, meso, and macro scales. The interaction and exchange of ideas between these disciplines through a multi-scale approach are crucial to maximising the benefits of green spaces. In essence, planners need to consider green spaces as a socio-ecological system where environmental conditions, economic objectives, and social needs interact strongly to identify ecosystem services issues. This is why the ecological approach is essential.

Nowadays, urban green space planning increasingly relies on land suitability analysis (Li *et al.*, 2020). Land suitability analysis involves selecting a suitable site from multiple alternatives. The goal is to create a map of a suitability index for the entire area (Bagheri *et al.*, 2013). The multi-criteria analysis (MCA) approach, when integrated with Geographic Information System (GIS), has become a widely used method for selecting suitable sites. MCA serves as a decision support tool for complex multicriteria problems that encompass both qualitative and quantitative aspects of decision-making (Garfì *et al.*, 2009; Ustaoglu *et al.*, 2021). It is one of the most widely used approaches to facilitate decision-making processes. Furthermore, there are various methods of MCA, and the analytic hierarchy process (AHP) is a robust and flexible method that is most commonly used in planning, selecting the best alternative, and allocating resources (Chen, 2006). The AHP allows for the calculation of the weight of factors or parameters and their comparison based on their relative significance in pairwise comparisons (Karna *et al.*, 2023).

The MCA approach has been used by Abebe and Megento (2017) and Gelan (2021) and in Ethiopia, to identify suitable sites for the development of green spaces. Several factors were considered, including the current land use and cover of the area, the slope, the proximity of residential areas, parks, and green spaces, the proximity of water sources and roads, the population density, and the soil types. After analysing these factors, the studies revealed that 49.76%, 4.15%, and 20.04% of the study area in Addis Ababa are classified as less suitable, highly suitable, and moderately suitable for green spaces, respectively. Similarly, 13.06%, 34%, 28%, and 18.9% of the study area in Sululta town are classified as highly suitable, suitable, moderately suitable, and poorly suitable for green spaces, respectively.

2.4 Examples from other Countries

The significance and relevance of integrating urban green spaces as nature-based solutions have been the subject of numerous studies worldwide, especially in light of the pressing issues of climate change and rapid urbanisation. Saudi Arabia, among the countries with the highest energy consumption and third-highest CO^2 emissions per capita, ranks seventh globally. Like other regions, Saudi Arabia is highly vulnerable to climate change due to its delicate ecosystem, characterised by frequent flooding and limited freshwater resources. As per the Global Climate Risk Index, it ranks 84th. In response to this alarming situation, Jeddah city has embraced nature-based solutions as a means of adaptation and mitigation against climate change. To achieve this, the various ecosystem services associated with two key aspects of climate change within green spaces are being evaluated. The most crucial of these is the collection of public perceptions, which plays a vital role in green space planning. Therefore, the findings of this study aim to assist planners and decision-makers in comprehending and implementing nature-based solutions to combat and cope with the challenges posed by climate change (Maghrabi *et al.*, 2021).

The most crucial takeaway from this experience is the importance of adopting a bottom-up approach in green space planning processes by involving the local community. However, it is not always enough, and it would be beneficial to educate the population about the multifaceted role of green spaces beyond their recreational and aesthetic benefits.

In Europe, countries are ahead in designing and implementing Nature-based Solutions (NbS) as a means to combat climate change. Floods and heat waves are two big challenges caused by the changing climate that Germany is experiencing (Dushkova and Haase, 2020). According to these authors, based on the experience of the severe floods in the country, German stakeholders have recognised the limitations of technological solutions such as dams, particularly given the challenging climatic conditions and the increasing duration of heavy rainfall events. To mitigate the impacts of these disasters, NbS are being increasingly explored and implemented. Furthermore, in the more specific context of urban greenery, Leipzig, having understood the importance of mixing and strengthening green infrastructures such as urban green spaces, has implemented a strategy based on spatial planning (Schwarz *et al.*, 2011). For example, there are a significant number of types of NbS in Leipzig, Germany. Among these are wildness patches and recreational areas in the former mining landscape and central parts of the city, the renaturation of rivers especially those that were heavily polluted during industrialisation, and the creation of green and blue urban infrastructure interconnected by bicycle paths such as green roads and green wall (Dushkova and Haase, 2020).

2.5 Overview and Discussion of the Key Issues

2.5.1 Overview

Climate change has been a fundamental concern of global scientific and political agendas since 1979, even though the problem was first identified in the 19^{th} century. This was followed by multiple scientific and political conferences, including the establishment of the Intergovernmental Panel on Climate Change (IPCC) in 1988 and the United Nations Framework Convention on Climate Change in 1992, which emphasised mitigation and recognised that climate change is anthropogenic (Gupta, 2010). On the other hand, year after year, despite numerous international efforts, the problem of climate change is still persistent. With this alarming rate of change, adaptation is necessary, as highlighted in the first report of IPCC. For both strategies, the use of urban green spaces as a means for climate change adaptation and mitigation was recommended by the IPCC in its fifth report (IPCC, 2015).

The fact that urban areas are complex socio-ecological systems, as well as centres of challenges and innovative actions to address these challenges, one of the most recent approaches that could reveal environmental issues holistically is conceptualised as nature-based solutions (Zwierzchowska *et al.*, 2022). This new trend has brought urban green spaces back from the place in the major preoccupations facing climate change and into a context where they had their natural status in planning. Furthermore, the potential of urban green spaces to provide ecosystem services depends on their management as a global system of urban green infrastructure or as isolated islands under the responsibility of different actors (Feltynowski *et al.*, 2018), which involves the protection and planning of green spaces.

2.5.2 Discussion of the key issues

Since ratifying the United Nations Framework Convention on Climate Change, Senegal has adhered to all subsequent conventions up to the Paris Agreement and has developed strategies to adapt and mitigate climate change across various sectors in fulfilment of its commitments (Republic of Senegal, 2020). In addition, it is important to integrate the regreening of Senegalese cities. Nevertheless, some initiatives have been taken for the creation and protection of green areas in Dakar, the capital of the country and the most urbanised city. Among them is the Master Plan for the Development and Safeguarding of the Niayes and green areas of Dakar.

Green spaces are regulated by the urban planning code of Senegal. Article A 172 of the bill states that "urban planning must provide for green spaces and public spaces to ensure that every resident of the city has an appropriate environment to meet their recreational needs and to have a healthy breath" (Republic of Senegal, 2009). The types highlighted in this code are parks, public gardens, public squares, playgrounds, stadium lawns, green cuts and roadway plantings. All modalities related to their development are declining. This provision is supported by the Environment Code, which, in Article L 28, related to human settlements, clearly states that "urban agglomeration must include recreational land and green space areas by a proportion laid down in the planning documents" (Republic of Senegal, 1998). As part of these two regulations, green spaces lack specific planning texts. The number of per capita green spaces is not fixed by these codes since there are no national standards. This often leads to challenges in implementing the laws, as the textual content doesn't always align with reality. In contrast, the New Urban Agenda of Senegal aims to enhance cities' inclusivity, safety, resilience, and sustainability. To achieve this, the role of nature in cities will be reevaluated through green spaces, including their creation and protection, whether natural or artificial (Republic of Senegal, 2021).

In essence, this section primarily focused on the fundamental concepts of the study and existing research on the topics it addresses. Numerous studies have already been conducted in various countries, particularly in Asia, underscoring the significance of urban green spaces and their ecosystem services. However, there has been limited research conducted in Africa, specifically in Senegal. This disparity emphasises the need to generate scientific data to inform public policymakers. In this regard, several methods have been developed. In this study, the SCP plugin integrated with Qgis is utilised to analyse green space dynamics. Additionally, the InVEST models and the MCA employing AHP are employed to evaluate ecosystem services and identify potential areas for future green space development in Dakar. The widespread application of these approaches demonstrates their effectiveness and adaptability.

CHAPTER THREE

3.0 MATERIALS AND METHODS

This chapter represents the methodological part of this study. It shows the process or approach used, from data collection to data processing and analysis.

3.1 Description of the Study Area

3.1.1 Geographical location and map of the area

The region of Dakar, capital of Senegal, is located in the far western part of Senegal (West Africa), between longitudes 17°10 and 17°32 West and latitudes 14°53 and 14°35 North. It is bordered to the east by the region of Thies and by the Atlantic Ocean to the north, west, and south (Figure 3.1). The region spans an area of 550 km^2, which is approximately 0.28% of Senegal's national territory (Regional Service of Statistics and Demography of Dakar, 2021). The Dakar administrative region is divided into departments, arrondissements, and districts.

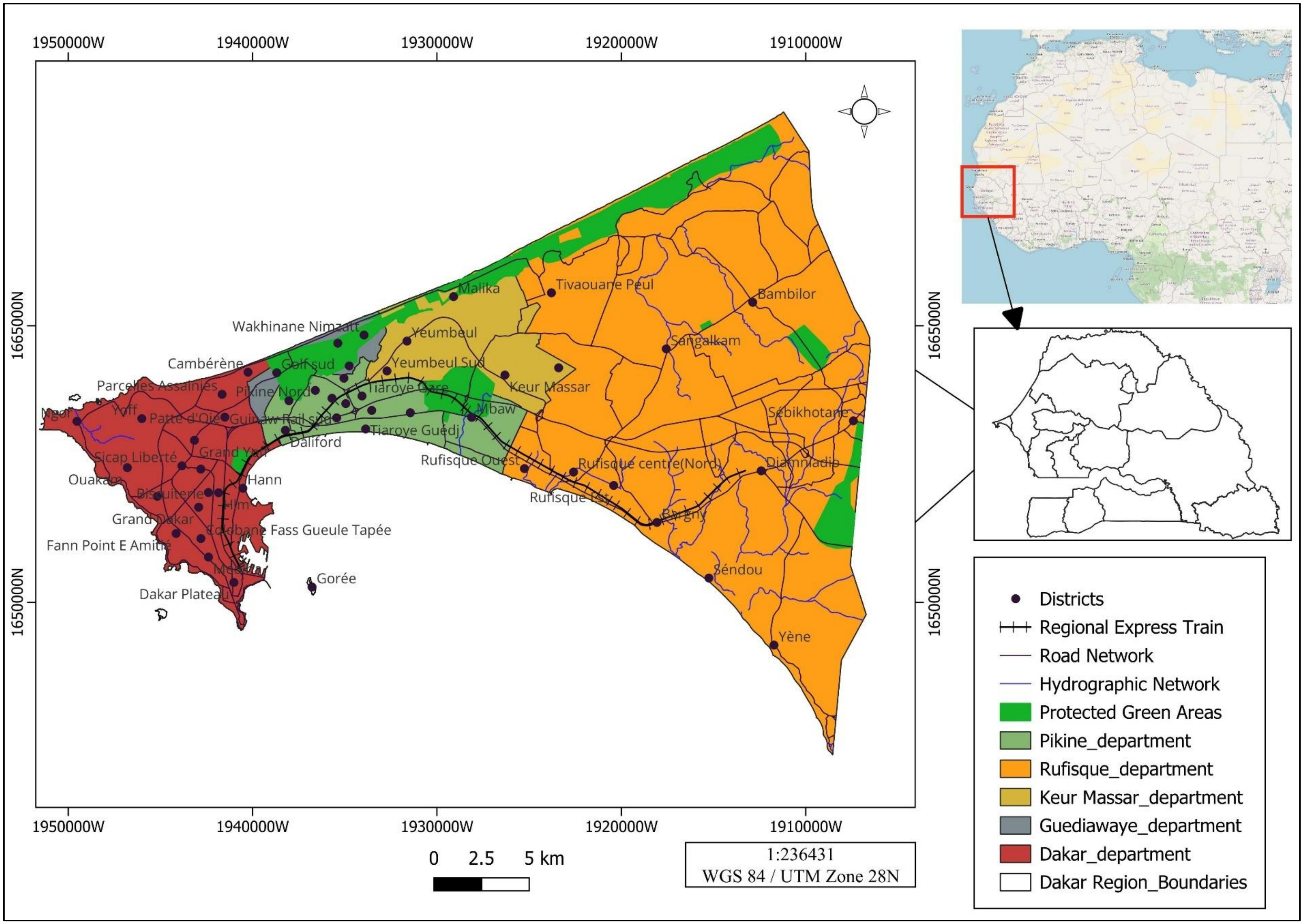

Figure 3.1: Presentation of the study area

3.1.2 Climate of the area

Dakar, a city in Senegal, falls under the Sahelian domain but boasts a canary-type climate. Its climate is relatively mild compared to the rest of the country, thanks to its geographical location and the influence of oceanic winds. This unique combination gives the region its distinctive character. For most of the year, the Dakar region experiences a microclimate influenced by the maritime trade winds from the Azores high-pressure system and a relatively high humidity level of around 25%. Temperatures range from 17° C to 25° C from December to April and from 27° C to 30° C from May to November. Rainfall is characterised by a relatively short rainy season, lasting between three and four months (July and October) (Faye, 2019).

The dominant winds in this region include the trade winds during the dry season and west and southwest winds during the rainy season. The most prominent is the maritime trade wind, a constantly humid wind filled with salt-water-saturated spray. Despite its predominance, the Harmattan, a Saharan continental trade wind, is also present but is less pronounced as you move away from the coast. Additionally, the particularly humid monsoon is the flow that adds to this and brings the potential for precipitation to the region (Regional Service of Statistics and Demography of Dakar, 2021).

Figure 3.2 shows the Umbrothermal diagram used to identify the dry period (when the temperature curve is above the rainfall) and the wet period (when the temperature curve is below the rainfall) for the Dakar region by using the National Civil Aviation and Meteorology Agency data from 1991 to 2021. An analysis of this diagram over the past three decades reveals a prolonged dry period that surpasses the wet period. The dry period spans 10 months, commencing in October and concluding in July. During this period, the average rainfall amounts to 9.04 millimetres, while the average temperature stands at 37°C. In contrast, the wet period is characterised by a brief duration of only two months, namely August and September, which are the wettest. During these months, the average rainfall reaches 161.51 millimetres, while the average temperature is 42°C.

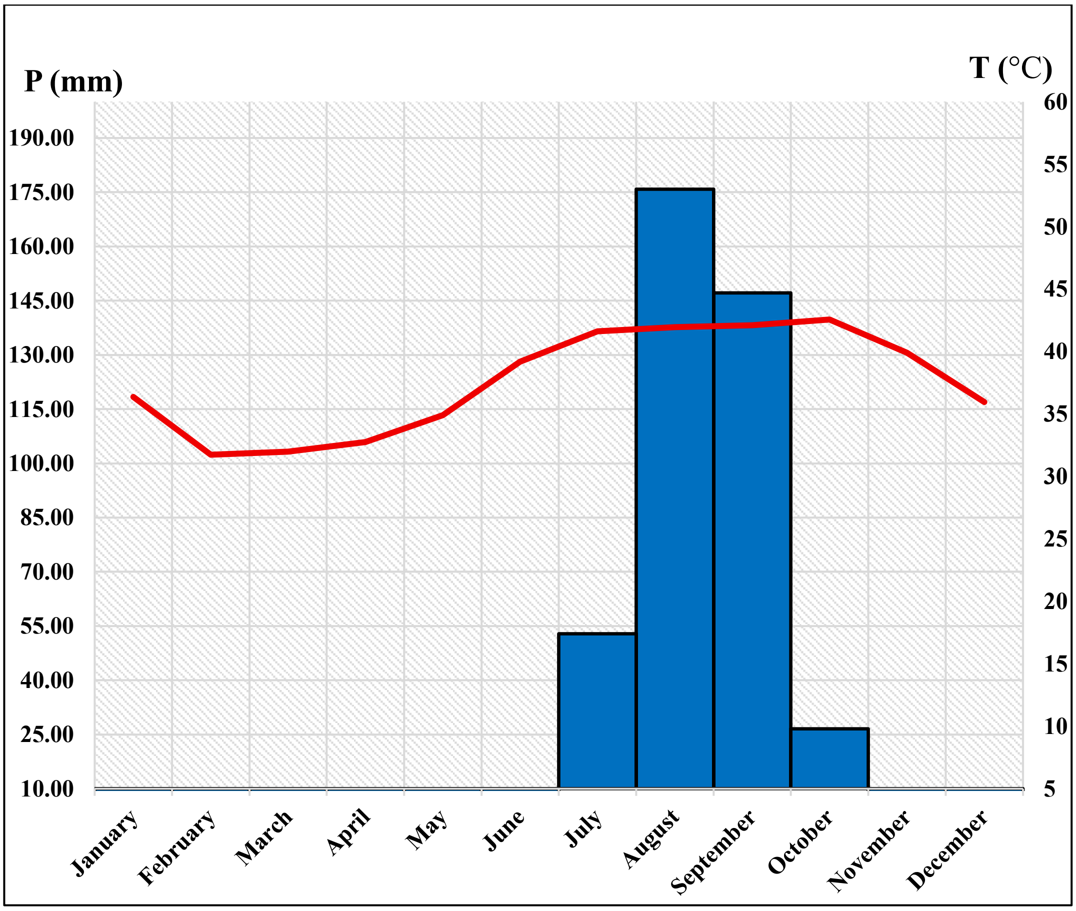

Figure 3.2: Umbrothermal diagram of Dakar from 1991 to 2021

3.1.3 Soil, vegetation and hydrology of the area

The region of Dakar has a variety of soil types. Generally, the soils are ferruginous with little or no leaching and are not very evolved (Diagne, 2008). Overall, vegetation in Dakar has been severely degraded due to increasing construction. However, some protected areas remain, such as the Mbao Classified Forest, covering 724 hectares, and the Hann Forest and Zoological Park, covering around 60 hectares. These areas are composed primarily of mono-specific plantations and exotic species, such as *Anacardium occidentale*, *Casuarina equisetifolia, Melaleuca Leucadendron,* and *Leucaena leucocephala*, along with some native species such as *Adansonia digitata*, *Detarium* *senegalense*, and *Balanites aegyptiaca*. Most streams and rivers in the region are intermittent, with more artificial drainage channels for discharges (Bassel, 1996). Furthermore, the hydrological regime of the Dakar region is mainly composed of a few marshes and temporary ponds, but also lakes such as the "Lac Retba", commonly called the Pink Lake, covering 300 hectares, and Warouwaye lack with 64 hectares (Cissé, 2021; Regional Service of Statistics and Demography of Dakar, 2021).

3.1.4 Demography and socio-economic activities of the area

According to Senegal's fifth General Census of Population and Housing, the population of Dakar is projected to reach 5 933 914 inhabitants by 2050. In 2025, the population is estimated to be 4 157 756 inhabitants, with a population density of 7 280 inhabitants per square kilometre (National Agency of Statistics and Demography, 2024). The population of Dakar is predominantly young, with the largest age groups being 25-29, 30-34, and 15-24 years old. Economic activities in the region are relatively diversified, including agriculture, fishing, industry, livestock farming, trade and more (Regional Service of Statistics and Demography of Dakar, 2021).

3.2 Description of Materials

Different types of data have been collected to achieve the objectives, including both primary and secondary data.

3.2.1 Primary data

The primary data in this study comprises two types: qualitative and quantitative. Qualitative data were gathered from various sources, including the State's technical services such as the Direction of Urban Landscapes and Public Spaces, the Direction of the Forest and Zoological Park of Hann, the Forestry Sector of Pikine and Guediawaye, and the Direction of the Natural Urban Reserve of Great Niaye and Dependence.

Quantitative data was collected from neighbourhood delegates and an inventory of green spaces.

3.2.2 Secondary data

Secondary data are data gathered from various sources. The main sources of these data include scientific articles, theses, and study reports found on the internet or in university libraries, as well as reports provided by technical services. Time series remote sensing data, such as the collection of Landsat satellite images, are obtained from the Earth Explorer website of the United States Geological Survey (USGS/EROS). Additionally, climatic data, including temperature and rainfall information, is collected and utilised from the National Agency of Civil Aviation and Meteorology of Senegal. Finally, socio-economic data is gathered from the National Agency of Statistics and Demography of Senegal.

3.3 Methods of Data Collection

This study involves analysing the spatiotemporal distribution of public green spaces using satellite images. An itinerant inventory was employed to identify the existing public green spaces. Subsequently, quantitative data were collected from the neighbourhood delegates of Dakar using a questionnaire. Qualitative data were obtained from administrative authorities through interviews conducted with interview guides.

3.3.1 Itinerant inventory of green spaces

This itinerant approach consists of visiting sites to record the number and types of existing green spaces in the Dakar region (Amontcha *et al.*, 2017). First of all, the aim is to obtain a list of the green spaces that are supposed to already exist in the study area. To do this, three major institutions were targeted: the Direction of Urban Landscapes and Public Spaces and the Direction of Water, Forests, Hunting and Soil Conservation. They were chosen because these entities operate in almost the entire Dakar region. This permits it to cover a wide area. Once we have obtained the list, an itinerant inventory enables to check existing green spaces in the field. Once a site has been found, its geographical coordinates are recorded for mapping.

3.3.2 Semi-structured interview

Semi-structured interviews using interview guides (Dieng, 2017) have been conducted to collect qualitative data. The themes to be considered in the interview guides are as follows:

a) the typology of green spaces that exist in the Dakar region;

b) the different functions of green spaces;

c) the current trend and evolution of green spaces;

d) the factors of degradation;

e) the method used to manage green spaces;

f) proposals for better management of green spaces

g) the importance of green spaces in the context of climate change;

h) the integration of green spaces in the fight against the effects of climate change.

3.3.3 Surveys by questionnaire

By using a questionnaire administered to the neighbourhood delegates in Dakar, quantitative data have been collected to acquire information on the factors that lead to the degradation of green spaces. Other complementary information is taken into account, as mentioned below:

a) perceptions of green spaces

b) the benefits of green spaces

c) the spatial and temporal dynamics of green spaces

d) the design of green spaces

e) maintenance of green spaces

The Kobo Toolbox platform was used to design and administer the questionnaire.

3.3.4 Sampling

To carry out this study in the Dakar region, sampling is necessary. For this purpose, sampling by degrees was used, which consists of drawing samples at several levels (Diop, 2008). This approach, also known as multi-stage cluster sampling, involves dividing large populations into smaller clusters to enhance the effectiveness and efficiency of primary data collection. Clusters are typically formed based on well-defined administrative boundaries (Galway *et al.*, 2012). In this study, the districts of the Dakar region are considered as our clusters at the first sampling level. After the selection of the first level such as the districts, the second level consists of considering the neighbourhood unit where the neighbourhood delegates are targeted. To obtain the number of neighbourhood delegates to be surveyed, the sample size was randomly calculated using the Dagnelie (1998) formula (Equation 3.1) as cited by Natta *et al.* (2023), which is as follows:

$$n = \frac{p(1-p)U^2 1 - \alpha/2}{d^2} \tag{3.1}$$

Where n: is the sample size; p: 0.92 is the proportion of respondents; $U_{1-\alpha/2}$: 1.96 is the value of the normal random variable for a risk α equal to 5%; d: 5% is the margin of error for estimating parameters from the survey.

After the calculation, a total of 113 neighbourhood delegates to be surveyed was obtained. The people surveyed were distributed in two ways. Firstly, the districts were selected on a reasoned basis (Brun *et al.*, 2020). To obtain them, a layer of Dakar's district boundaries was overlayed using Google Earth Pro. After a visual interpretation focusing on the presence of green spaces, 10 districts were selected to administer the questionnaire. These are districts of Plateau, Fann/Point E/Amitié, Grand Dakar, Hann/Bel Air, Mermoz/Sacré-Cœur, Keur Massar, Mbao, Pikine Ouest, Golf Sud and Rufisque Est. Secondly, the choice of neighbourhoods is based on a random draw. Our sample of 113 neighbourhood delegates was randomly selected from the neighbourhoods of these 10 districts.

3.3.5. Satellite images collect

The satellite images used in this study are those from Google Earth Pro and the Landsat collection. Google Earth Pro aids in identifying existing public green spaces for digitisation. The Landsat scenes (Path 205, Row 50) are employed to analyse the spatio-temporal dynamics of public green spaces from 1990 to 2022 (Table 3.1). The same period of the year, which corresponds to the dry season, is chosen to minimise high cloud cover and ensure the consideration of permanent green spaces unaffected by rain.

Table 3.1: Satellite images chosen for the spatio-temporal dynamics analysis

Satellite	Path/Row	Sensor	Spectral bands	Acquisition date
Landsat 9	205/50	OLI_TIRS	11	09/04/2022
Landsat 7	205/50	ETM	8	31/05/2012
Landsat 7	205/50	ETM	8	18/04/2002
Landsat 5	205/50	TM	7	05/12/1990

3.4 Methods of Data Analysis

To analyse the primary and secondary data obtained from the field, different approaches are used depending on the research objectives.

3.4.1 Typology and characteristics of public green spaces in the region of Dakar

The typology of public green spaces in the Dakar region is based on the classifications existing in the literature (refer to chapter two, pages 17-19). After the itinerant inventory, during which the geographical coordinates of the visited spaces were collected, green spaces were digitised using Qgis software. This exercise was carried out by using Google Satellite as the basic image for identifying the green spaces; in addition, Open Street Map data were also used to add green spaces that have not been visited. After the digitising stage, a typology map is produced to show the types of green space in the Dakar region. Finally, the different types of green spaces are classified based on the main function they provide. Other criteria are also considered, such as location and access (Nor and Abdullah, 2019).

The characteristics of the public urban green spaces in the Dakar region, which have been determined, are the diversity of public green spaces, the spatial distribution within the area, the density of green spaces, the coverage rate, the ratio per inhabitant, and their quality, as measured using the Normalised Difference Vegetation Index (NDVI). The diversity of green spaces is assessed using the Shannon index (H') and Pielou's Evenness index (E). These two indices are calculated based on the following formulas (Equations 3.2 and 3.3) (Sambou, 2017):

$$H' = -\sum_{i=1}^{S} Pi * \ln Pi \tag{3.2}$$

Where Pi = ni/N: ni, the number of green spaces for a given type i; N: the total number of green spaces recorded; S: specific richness. With H' $\geq$ 4 corresponding to high diversity; 2.5 $\leq$ H'< 4 is moderate diversity; H' < 2.5 corresponding to low diversity (Honvou *et al.*, 2021).

$$E = \frac{H'}{H'max} \quad (3.3)$$

Where H'max = log2 S. The Pielou index ranges from 1 to 0. When it approaches 0, there is green space types dominance and it approaches 1 when the number of green spaces is evenly distributed among the different types.

To obtain the results, both indices were computed in RStudio using the vegan package.

The Gini coefficient, used to express the coefficient of equality, is applied to measure the spatial distribution of public green spaces. It is calculated using the Lorenz curve. The Gini coefficient ranges from 0 to 1, with 0 meaning equal distribution and 1 representing unequal distribution (Yao *et al.*, 2014; Ke *et al.*, 2023). The ineq package in RStudio was utilised for the analysis. The input data were derived from the green spaces digitised and the shapefiles of departmental boundaries in the Dakar region. Other parameters are obtained from these formulas (Equations 3.4, 3.5, 3.6, and 3.7) (Amontcha *et al.*, 2017):

$$D = \frac{N}{S} \quad (3.4)$$

Where D: is the density of green spaces in a city; N: is the number of green spaces in a city; and S: is the surface of the city.

$$CR = \frac{s}{S} * 100 \quad (3.5)$$

Where CR: coverage rate of green spaces of a city; s: surface of all green spaces of a city; S: surface of the city.

$$RGS = \frac{S}{PS} \quad (3.6)$$

With R: ratio of green spaces per inhabitant; S: surface of all green spaces; PS: population size.

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{R}}{\mathrm{NIR} + \mathrm{R}} \tag{3.7}$$

Where NDVI: is the Normalised Difference Vegetation Index; NIR: is the Near Infrared band; and R: is the red band.

3.4.2 Spatio-temporal dynamics of green spaces 1990-2022 and the factors of degradation

3.4.2.1 Land use and land cover classification from 1990 to 2022

The SCP plugin integrated into mapping software has been utilised to conduct supervised categorisation of land use and land cover from remotely sensed images (Seremane *et al.*, 2023). The image classification process has been implemented in a structured manner within the SCP plugin.

The initial step involved image preprocessing, which aimed to enhance image quality for accurate interpretation. This was achieved by using the image conversion option within the plugin. This option provided both atmospheric and radiometric corrections. Afterward, the study area was extracted using another option called “clip raster bands.”

The supervised classification method was used to create land use and land cover maps using the SCP plugin with the band processing option. After preprocessing the image and extracting the study area, a false colour composition was created using bands. This colour composition helped identify five land cover classes in the Dakar region, as shown in Table 3.2. Then, training inputs were assigned to each class in the SCP dock. Finally, the classification was performed using the Random Forest algorithm, a machine-learning approach that involves multiple decision trees (Tempa and Raj, 2022). After classifying the land use and land cover maps, an accuracy assessment was conducted using the Overall accuracy and Kappa coefficients, which are widely utilised in remote sensing.

The results seem satisfactory, with overall accuracy coefficients ranging from 75.15% to 96.99% and Kappa coefficients varying from 0.66 to 0.95.

Table 3.2: Land cover classes description

Land use and land cover types	Description
Green space	All areas of vegetation, including public and private green spaces.
Water	Areas of water like lakes, rivers, and ponds.
Agriculture land	Cultivated areas such as fields and market gardens area.
Bare land	Areas devoid of vegetation or bare soil, rocks, and tannins.
Built-up	Impervious areas, including buildings and roads.

The detection of land use and land cover change was done using the cross-classification option in the SCP plugin. For this, a two-two crossing of the maps was conducted involving 1990-2002, 2002-2012, 2012-2022, and 1990-2022.

Figure 3.3 represents the procedure to be undertaken to realise the land cover maps covering these periods.

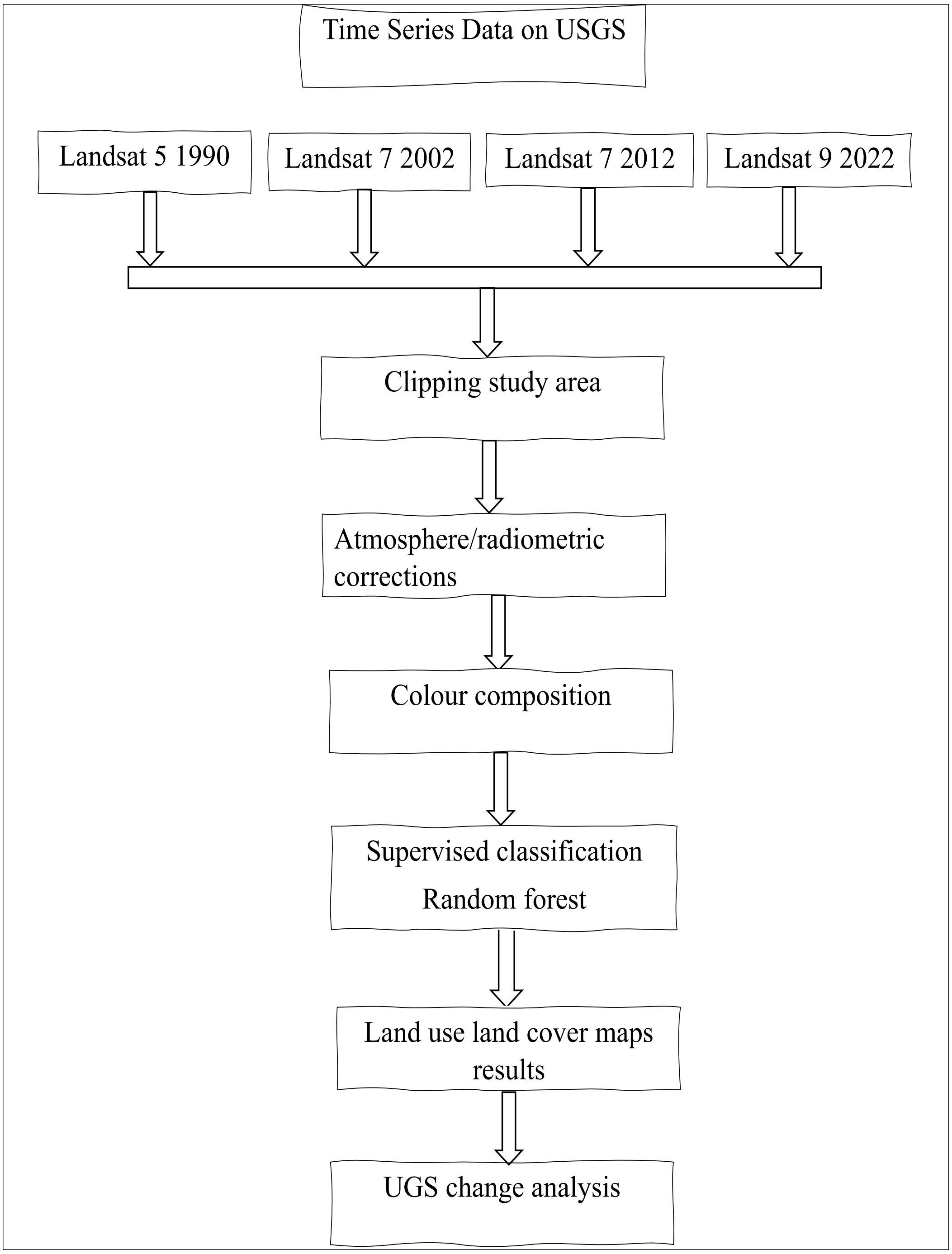

Figure 3.3: Flowchart of processing Landsat data

3.4.2.2 Factors of the deterioration of public green spaces in the Dakar region

The factors leading to their disappearance have been identified by analysing the dynamics of public green spaces. This was made possible through surveys conducted with neighbourhood delegates and individual interviews with the managers of some protected green spaces. The quantitative data obtained from the surveys were analysed descriptively, focusing on the frequency of responses. The qualitative data collected from semi-structured interviews were transcribed and analysed using RStudio software with the word cloud package to visualise the frequency of words.

3.4.3 The impacts of green spaces dynamics on urban ecosystem services in the Dakar region

The InVEST model was used to monitor the evolution of urban ecosystem services offered by public green spaces between 1990 and 2022. Given the study's focus on climate change, only ecosystem services related to climate are being examined. The MEA classification of ecosystem services is employed to identify the services under study, which encompass regulating services such as carbon storage and sequestration, the urban cooling effect, and flood regulation provided by green spaces.

3.4.3.1 Carbon storage and sequestration

Carbon storage and sequestration, one of the InVEST models, has been used to model the carbon sequestration and storage capacity of green spaces in the Dakar region from 1990 to 2022. The analysis spans twelve to ten-year intervals, such as 1990, 2002, 2012, and 2022. Additionally, like land use change detection, the years are divided into pairs, like 1990-2002, 2002-2012, and 2012-2022. The model calculates carbon stocks by summing the carbon densities of four reservoirs, such as above-ground biomass, below-ground biomass, soil, and dead organic matter carbon pools (Equation 3.8). To run the model, input data is provided, including land use and land cover maps for each year and carbon pools associated with each land use type. In this study, data on green spaces' carbon pools were obtained from previous studies in the area, while default values were used for other land cover types (Table 3.3) (Sharp *et al.*, 2020).

$$C_{total} = C_{above} + C_{below} + C_{soil} + C_{dead} \tag{3.8}$$

Where C_{total} is the total carbon storage, C_{above}, C_{below}, C_{soil}, and C_{dead} represent the carbon stored in the above-ground biomass, below-ground biomass, soil, and dead organic matter pools, respectively.

Table 3.3: Biophysical table for the carbon storage and sequestration model (tC/ha)

lucode	LULC_name	C_above	C_below	C_soil	C_dead	Source
1	Green space	85.32	10.89	0	0	(Cissé, 2021; Niang *et al.*, 2023)
2	Water	0	0	0	0	
3	Agriculture land	15	35	30	4	Model
4	Bare land	0	0	7.61	0	(Woomera *et al.*, 2004)
5	Built-up	0	0	0	0	

Lucode: land use, land cover code from the raster; LULC_name: name of each land use, land cover; C_above: carbon density of aboveground biomass (t/ha); C_below: carbon density of belowground biomass; C_soil (t/ha): carbon density of soil (t/ha); C_dead: carbon density of dead matter (t/ha).

3.4.3.2 Urban cooling

The InVEST urban cooling model was used to calculate the heat mitigation index of green spaces in the Dakar region between 1990 and 2022. The model estimates the heat mitigation based on the biophysical properties assigned to each land cover category, such as a shade factor (ranging from 0 for no tree cover to 1 for full tree cover over 2 metres in height), normalised evapotranspiration factor (ETfactor), and albedo (ranging from 0 to 1) (Sharp *et al.*, 2020). For each pixel (i), the cooling capacity (CC_i) is computed as a weighted average of the shading factor, ETfactor, and albedo (Equation 3.9). The heat mitigation index incorporates not only the pixel's cooling capacity but also the cumulative effect of nearby green spaces (j) larger than 2 hectares. This influence is evaluated within a defined search radius (d_{cool}) and is calculated as a distance-weighted average of the cooling capacities (CC_j) of neighbouring green spaces (Equation 3.10). If a pixel's cooling capacity value is higher than the cumulative cooling effect of surrounding green spaces, its local cooling capacity value is used as the heat mitigation (Equation 3.11) (Ronchi *et al.*, 2020).

$$CC_i = 0.6 * \mathrm{Shade} + 0.2 * \mathrm{Albedo} + 0.2 * \mathrm{ETfactor} \qquad (3.9)$$

$$CC_{UGS} = \sum CC_j * \exp\left(\frac{-d_{i,j}}{d_{cool}}\right) \qquad (3.10)$$

$$HMI = \begin{pmatrix} CC_i & \\ CC_{UGS} & if\ CC_i > CC_{UGS}\ or\ Area\ of\ UGS\ < 2ha \end{pmatrix} \qquad (3.11)$$

Where CC_{UGS}: cooling capacity of urban green space; HMI: heat mitigation index

The same approach used for carbon sequestration was applied to this model. The necessary input data are:

a) land use land cover maps for each year;
b) reference evapotranspiration (https://earlywarning.usgs.gov/fews/product/461</onlink);
c) biophysical table (Table 3.4);
d) areas of interest, such as the shapefiles of green spaces;
e) air temperature blending distance (500 m) (default value from the model);
f) reference air temperature, which is 30 °C (default value from the model);
g) cooling distance from the vegetation of area >2 ha (d_{cool}) corresponding to 2000 m;

h) Urban heat island (UHI) effect, which is 3.5°C (https://yceo.users.earthengine.app/view/uhimap)

Table 3.4: Biophysical table for the urban cooling model

lucode	Kc	Green_area	Shade	Albedo
1	1	1	1	0.15
2	1	1	1	0.06
3	0.7	0	1	0.2
4	0.3	0	1	0.2
5	0.05	0	0.05	0.18

Lucode: land use, land cover code from the raster; Kc: crop coefficient; Green_area: 1 is when it is green space and 0 when it is not green space; Shade: proportion of area covered by tree canopy; Albedo: proportion of solar radiation that is directly reflected by the land use type.

3.4.3.3 Urban flood risk mitigation

The InVEST Urban flood risk mitigation model was used to assess the contribution of green spaces in Dakar towards mitigating flooding, through rain interception by vegetation cover and the enhancement of soil storage and infiltration (Zimmermann *et al.*, 2016). First, the model estimates the runoff Q (mm) for each pixel, defined by its land cover type and soil characteristics. This runoff represents the amount of water retained per pixel for a given volume of precipitation, calculated using the curve number method (Equation 3.12) (Sharp *et al.*, 2020; Kadaverugu *et al.*, 2021).

$$Q_{p,i} = \frac{(P - \lambda S_{max,i})^2}{P + (1-\lambda)S_{max,i}} \quad if \ > \lambda . S_{max,i}, otherwise\ Q_{p,i} = 0 \qquad (3.12)$$

Where P is the design storm depth in mm; Smax, i is the potential retention in mm, which is a function of the curve number (CN), an empirical parameter that depends on land use and soil characteristics (Equation 3.13); and λ. Smax is the rainfall depth required to initiate runoff, also referred to as the initial abstraction (λ = 0.2 for simplification).

$$S_{max,i} = \frac{25400}{CN_i} - 254 \tag{3.13}$$

Then, the model calculates the runoff retention per pixel, Ri (Equation 3.14), as well as the runoff retention volume per pixel, R_m^{3}i (Equation 3.15), and the runoff volume (flood volume) Q_{m3i} (Equation 3.16).

$$Ri = 1 - \frac{Q_{p,i}}{P} \tag{3.14}$$

$$R\_m^3 i = \mathrm{Ri} * \mathrm{P} * \mathrm{pixel.area} * 10^{-3} \quad \text{with pixel. area in m}^2 \tag{3.15}$$

$$Q_{m^3 i} = Q_{p,i} * \mathrm{pixel.area} * 10^{-3} \tag{3.16}$$

The model necessitates input data, including land use and land cover maps, a hydrologic soil group raster layer, and a biophysical table that provides the curve number for each soil type within the study area (Table 3.5) (Kadaverugu *et al.*, 2021).

Table 3.5: Biophysical table for the urban flood risk mitigation model

lucode	CN_A	CN_B	CN_C	CN_D
1	0	40	54	63
2	100	100	100	100
3	0	80	87	0
4	0	50	62	0
5	0	81	85	87

Lucode: land use, land cover code from the raster; CN_A: curve number value for this LULC type in the soil group code A; CN_B: curve number value for this LULC type in the soil group code B; CN_C: curve number value for this LULC type in the soil group code C; CN_D: curve number value for this LULC type in the soil group code D.

Once the three ecosystem services had been evaluated, the Spearman rank model was employed to establish a correlation between the vegetation cover of the three green spaces and the three ecosystem services assessed. To accomplish this, the R programming language was utilised to execute the model.

3.4.4 Identification of suitable areas for future development of public green spaces in the Dakar region

The multi-criteria analysis (MCA) approach is employed to identify the most suitable locations for green space planning in the Dakar region (Mrówczyńska *et al.*, 2021; Ustaoglu *et al.*, 2021). This approach followed different steps.

3.4.4.1 Determination of criteria and sub-criteria for green space areas' suitability

The initial step in analysing suitable areas for developing public green spaces involves selecting the criteria that could potentially influence their development. This decision is informed by previous studies and interviews conducted with institutions responsible for managing public green spaces, such as the Direction of Urban Landscape and Public Spaces. The primary factors considered are land use and land cover, the distance to existing green spaces, the distance to roads, population density, slope, and soil types (Abebe and Megento, 2017; Gelan, 2021). The datasets used are shown in the following table.

Table 3.6: Basic data and their sources

Data	Source
Current land use/cover	Current study
Green space types	Current study
Population density	World Pop Hub database
Road network	National Agency for Spatial Planning (ANAT)
Slope	Open topography database
Soil type	World Soil Information database

3.4.4.2 Standardisation and mapping of criteria

Once the criteria or factors have been identified, the rate of the requirements is defined. This involves classifying the criteria according to a linear transformation scale ranging from 1 to 5. According to the FAO land suitability classification, there are five classes such as highly suitable (S1 = 5), moderately suitable (S2 = 4), less suitable (S3 = 3), not suitable (N1 = 2), and permanently unsuitable conditions (N2 = 1). This step is followed by the standardisation of the criteria using the linear transformation scale, which allows a score to be assigned to each sub-criterion (Verheye *et al.*, 1982).

3.4.4.3 Calculating the weight of the criteria

This stage involves making a judgment or a comparison between the different criteria to identify which criterion is more important than the other (Saaty, 2008). The Analytical Hierarchy Process (AHP) method is used in this study to calculate the influence weight of each factor (Chen, 2006; Gelan, 2021). Using the pair-wise comparison, each criterion is compared to another on a scale of 1 to 9 (Table 3.8), the higher the scale, the greater the importance (Ahmed *et al.*, 2011). This is accomplished by creating a pair-wise matrix.

Table 3.7: Pair-wise comparison of the criteria (Saaty, 2008)

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective.
2	Weak or slight	
3	Moderate importance	Experience and judgment slightly favour one activity over another.
4	Moderate plus	
5	Strong importance	Experience and judgment strongly favour one activity over another.
6	Strong plus	
7	Very strong importance	An activity is favoured very strongly over another, its dominance demonstrated in practice.
8	Very, very strong	
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation.

Once the criteria are compared, the pairwise matrix is normalised by dividing each column by the sum of all columns. Next, the criteria weights are calculated by averaging the rows of the normalised matrix. To assess the credibility of the weights, a consistency ratio (CR) is computed using the following formulas (Equation 3.17) for the pairwise comparison matrix. Furthermore, the CR must be less than or equal to 0.1 for the AHP analysis to proceed. However, if the CR exceeds 0.10, there are inconsistencies in the assessment process, and the AHP method may not yield meaningful results (Sharma *et al.*, 2022).

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{3.17}$$

Where CR: is the consistency ratio; CI: is the consistency index; and RI: is the random inconsistency index, which depends on the number of criteria obtained from Table 3.9.

The consistency index was obtained from this formula (Equation 3.18):

$$CI = \frac{\lambda max - n}{n - 1} \tag{3.18}$$

Where λmax: is the average value of the consistency vector; n: is the number of criteria.

Table 3.8: Random inconsistency index

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

3.4.4.4 Weighted overlay analysis

The final stage of analysing suitable areas for green space development involves a weighted overlay of the criteria. This process aggregates the standardised layers by adding up all the criteria and multiplying them by their respective weights, which were determined in the previous phase. This method generates the final map of suitable sites for green spaces in the Dakar region. All the analysis is conducted using ArcMap 10.7 software.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 Results

4.1.1 Typology and characteristics of public green spaces in the region of Dakar

4.1.1.1 Typology of public green spaces in the region of Dakar

The itinerant inventory, combined with images from Google Earth and OpenStreetMap, has enabled the digitisation of various types of public green spaces in Dakar, Senegal's capital. A total of 836 public green spaces, including flat green spaces, have been digitised. These spaces are categorised into 1 urban forest (Mbao Classified Forest), 1 urban park (Hann Forest and Zoological Park), 23 wetlands, the most prominent being the Natural Urban Reserve of the Great Niayes and Dependence, 11 woody plantation blocks (Filao bands), 53 public gardens, 87 squares, 1 botanical garden, 14 cemeteries, 499 accompanying green spaces (such as schools, universities, hospitals, public institutions, and roads), 5 vegetated parking areas, 11 playgrounds, 46 allotments, and 84 informal green spaces (vacant land). Additionally, street trees and trees island have also been identified in the area. The accompanying photos (Plates I, II, III, IV, V, VI, VII, VIII, IX, and X) illustrate some of these green spaces.

These flat green spaces have been categorised into thirteen (13) distinct types as illustrated in Figure 4.1. These green spaces are further classified into six groups based on their diverse functions, which align with the four categories of ecosystem services identified by the MEA: ecological functions, provisioning services, supporting services, and cultural services. The detailed results are presented in the accompanying table (Table 4.1).

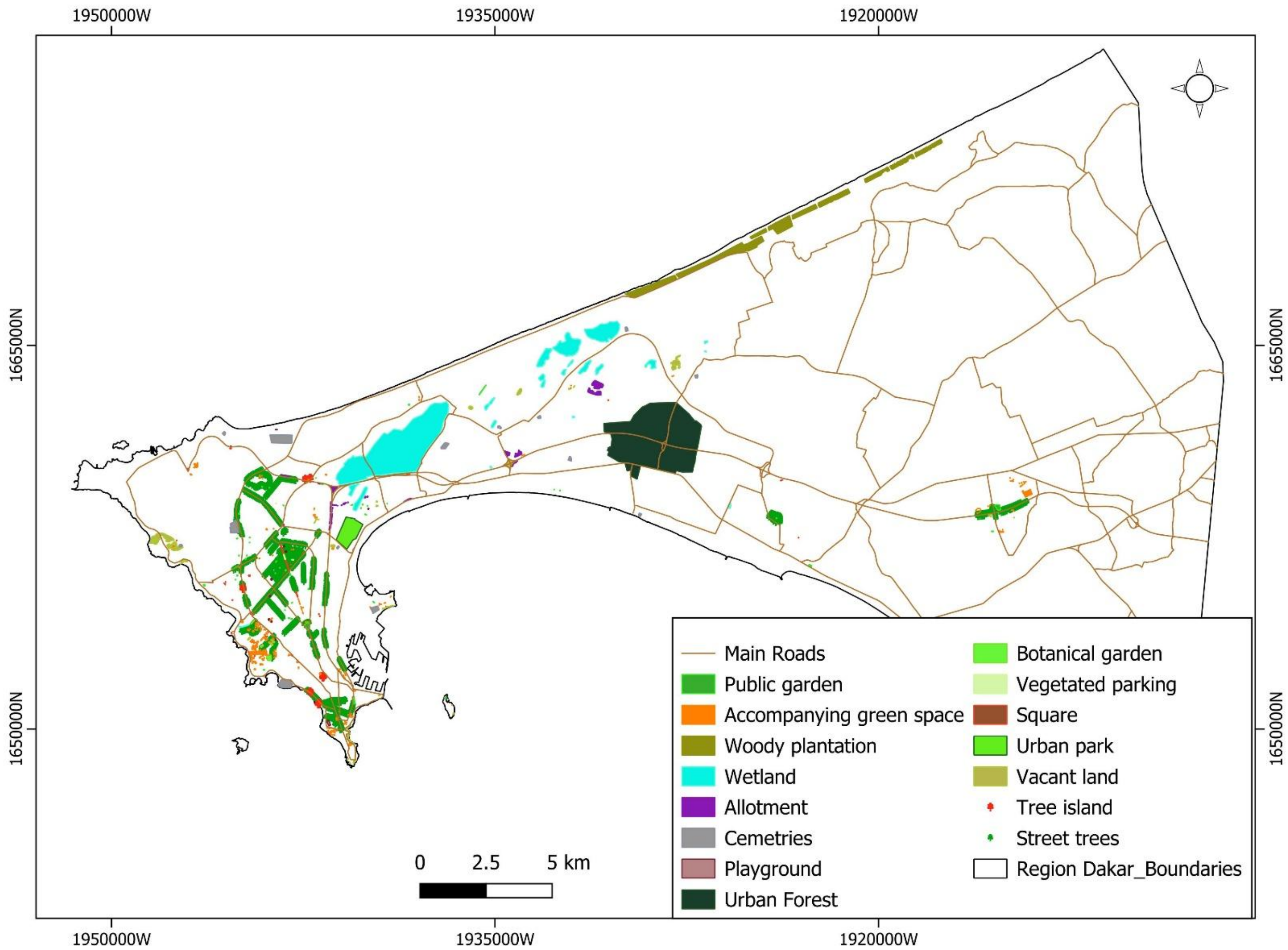

Figure 4.1: Typology map of public green spaces of the Dakar region

Plate I: Promenade along Dakar's cornice

Plate II: Public garden of the Independence Place

Plate III: Mbao Classified Forest

Plate IV: Hann Forest and Zoological Park

Plate V: Green space at a traffic circle

Plate VI: Green space accompanying a public establishment

Plate VII: Public garden of the National Place

Plate VIII: Alignment trees on the centenary boulevard

Plate IX: Green space along the VDN road (A) and (B)

Plate X: Natural Urban Reserve of Great Niaye and Dependence (C) and (D)

Table 4.1: Classification of public green spaces in the region of Dakar

Nº	Functions	Nº	Public green space types	Description
1	Ecological function	1.1	Urban forest	Biodiversity conservation, carbon sequestration, air purification, soil enrichment, collecting rainwater with a retention basin, and sea spray control.
		1.2	Urban park	
		1.3	Wetland	
		1.4	Woody plantation	
		1.5	Botanical garden	
2	Recreational function	2.1	Public garden	Places for relaxation, leisure, and playing.
		2.2	Playground	
3	Aesthetic function	3.1	Street trees	Beautification of public institutions (ministry, school, university, hospital, museum, stadium, residence of the president), along roadways, spaces between roads, and junctions.
		3.2	Accompanying green spaces	
		3.3	Trees Island	
		3.4	Vegetated parking	
		3.5	Square	
4	Worship function	4.1	Cemetery	Burial sites of missing persons.
5	Productive function	5.1	Allotment	Production sites for ornamental plants and market gardens.
6	No specified function	6.1	Vacant land/informal green space	Open spaces around residents or some monuments with the presence of vegetation.

4.1.1.2 Characteristics of public green spaces in the Dakar region

(a) Diversity of public green spaces in the Dakar region

The analysis of the variety of public green spaces in the Dakar region reveals Shannon and Pielou's Evenness indices of 1.44 and 0.56, respectively. The Shannon index, not exceeding 2.5, indicates a low level of diversity in the types of public green spaces in Dakar, suggesting the existence of a few distinct types. On the other hand, the Pielou index suggests a moderate dominance of certain green space types, indicating that some green spaces are more prevalent than others in the region.

(b) Spatial distribution of public green space in the Dakar region

The spatial distribution of public green spaces in the Dakar administrative region reveals an unequal distribution. The Gini coefficient of 0.59 indicates that green spaces are significantly concentrated in certain areas while scarce in others. This coefficient shows that 59% of green spaces are unevenly distributed. Figure 4.2 clearly illustrates this coefficient, with the Lorenz curve (blue line) representing inequality and moderately distant from the equality curve (red line). Figure 4.3 further highlights the high concentration of green spaces in the Dakar department. This can be explained by the presence of most public institutions, such as schools and Dakar's major university, as well as the efforts made by Dakar City Hall and the Direction of urban landscape and public spaces to create green spaces. The largest Natural Urban Reserve of Great Niaye et Dependence spans across the departments of Dakar, Guediawaye, and Pikine, with the majority located in Pikine. Additionally, the Mbao Classified Forest, an urban forest, is situated in this area. However, the department of Rufisque has the fewest public green spaces.

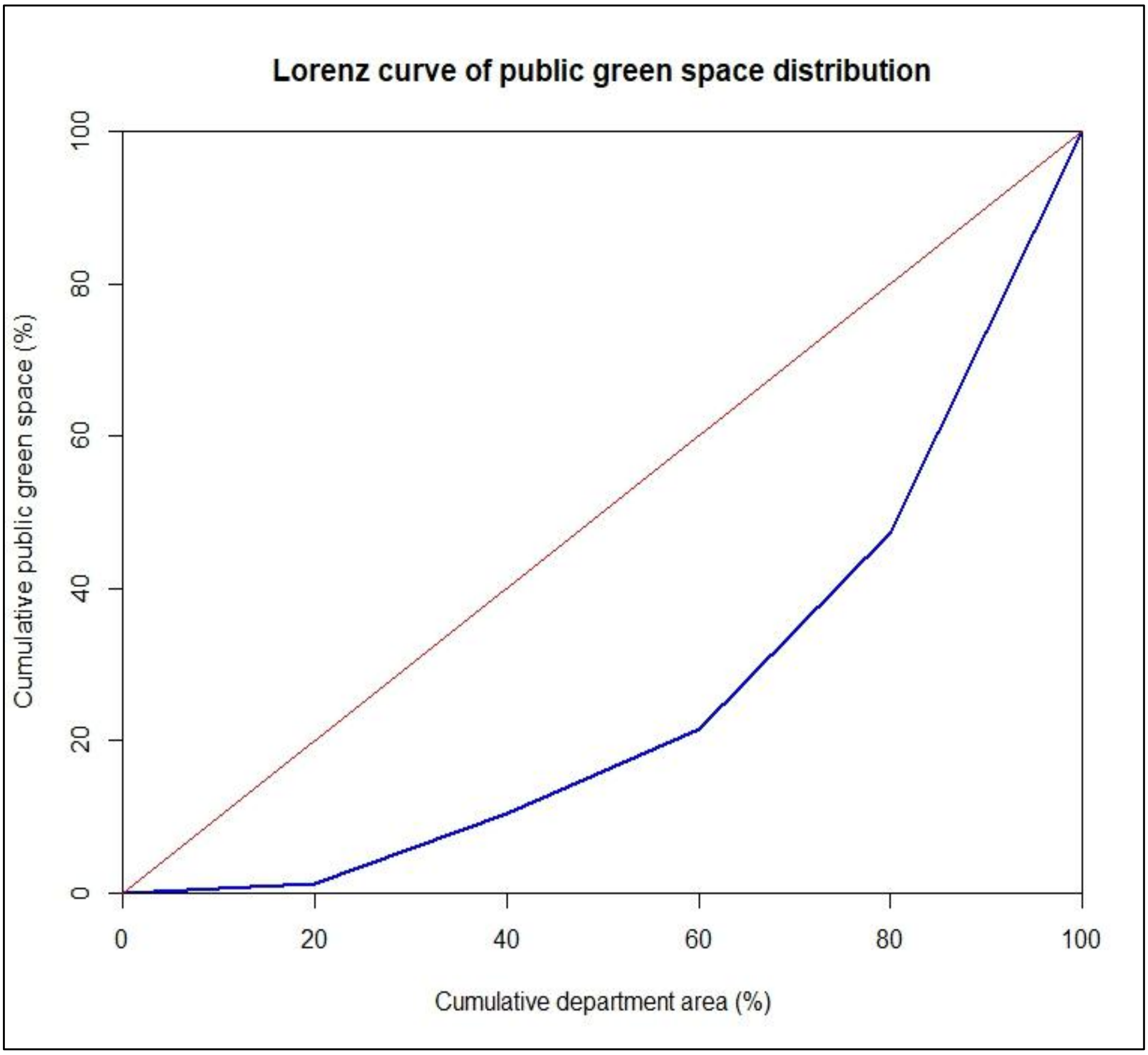

Figure 4.2: Lorenz curve of public green space distribution

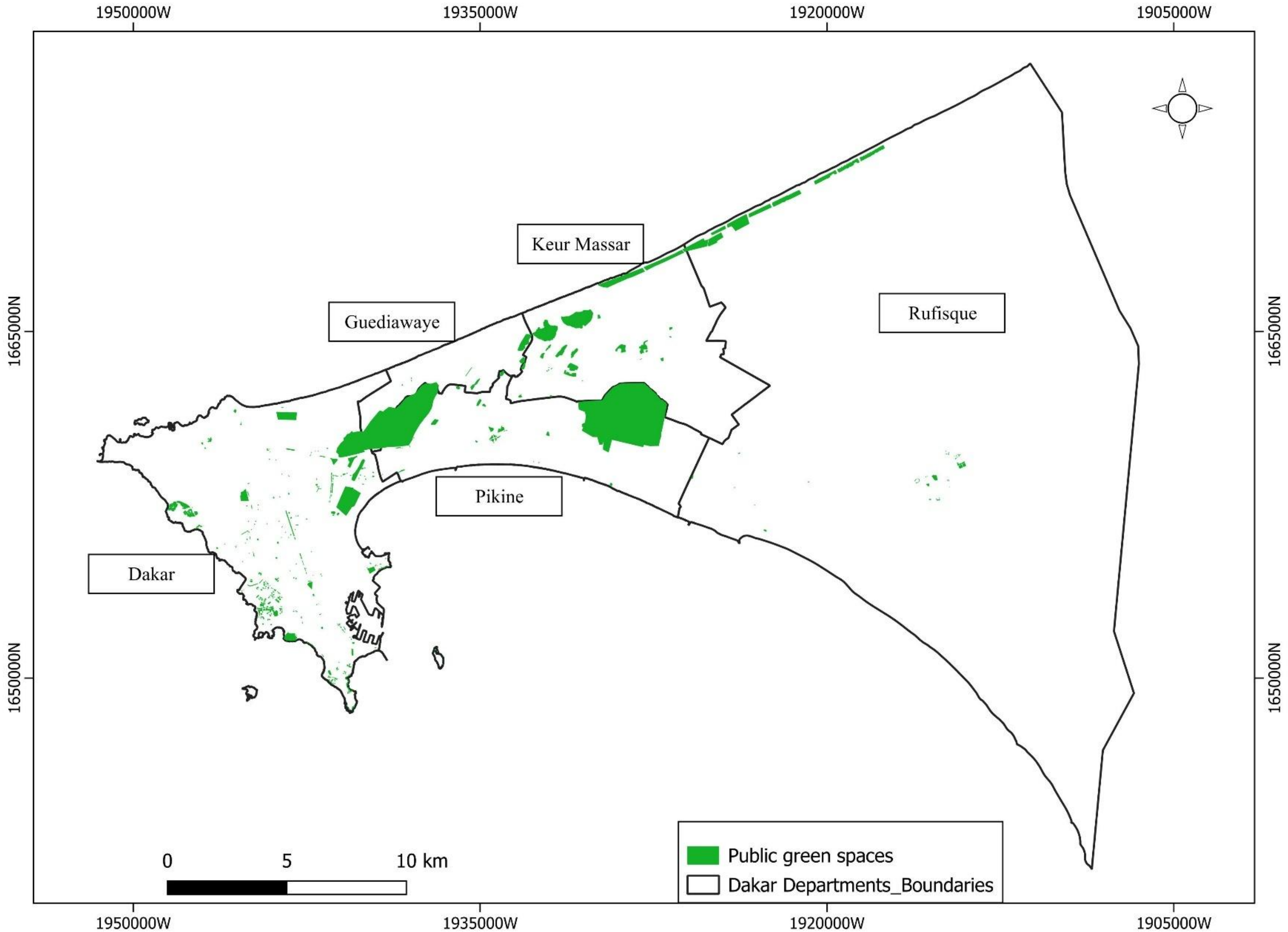

Figure 4.3: Spatial distribution of public green space within the region of Dakar

(c) Density of public green spaces of Dakar region

The density calculation only considers flat spaces, excluding street trees and tree islands, as this study focuses on this type of space. The results show that the density of public green spaces in the Dakar region is 2 green spaces per square kilometre. This density appears low for the densest region of Senegal. Moreover, there is a difference in density among the various types of green spaces. Figure 4.4 below illustrates the density of each type of public green space. Notably, accompanying green spaces, such as those found in public institutions like schools and universities, public hospitals, ministries, presidential palaces, administrative buildings, places of worship (mosques and churches), sports facilities, and roads, are well-represented, with a density of 26 green spaces per square kilometre. This highlights the importance given to the aesthetic and beautification role of green spaces in the Senegalese capital. Unlike urban parks, public gardens play a crucial role in enhancing the quality of life for residents, while urban forests are underrepresented in the Dakar administrative region.

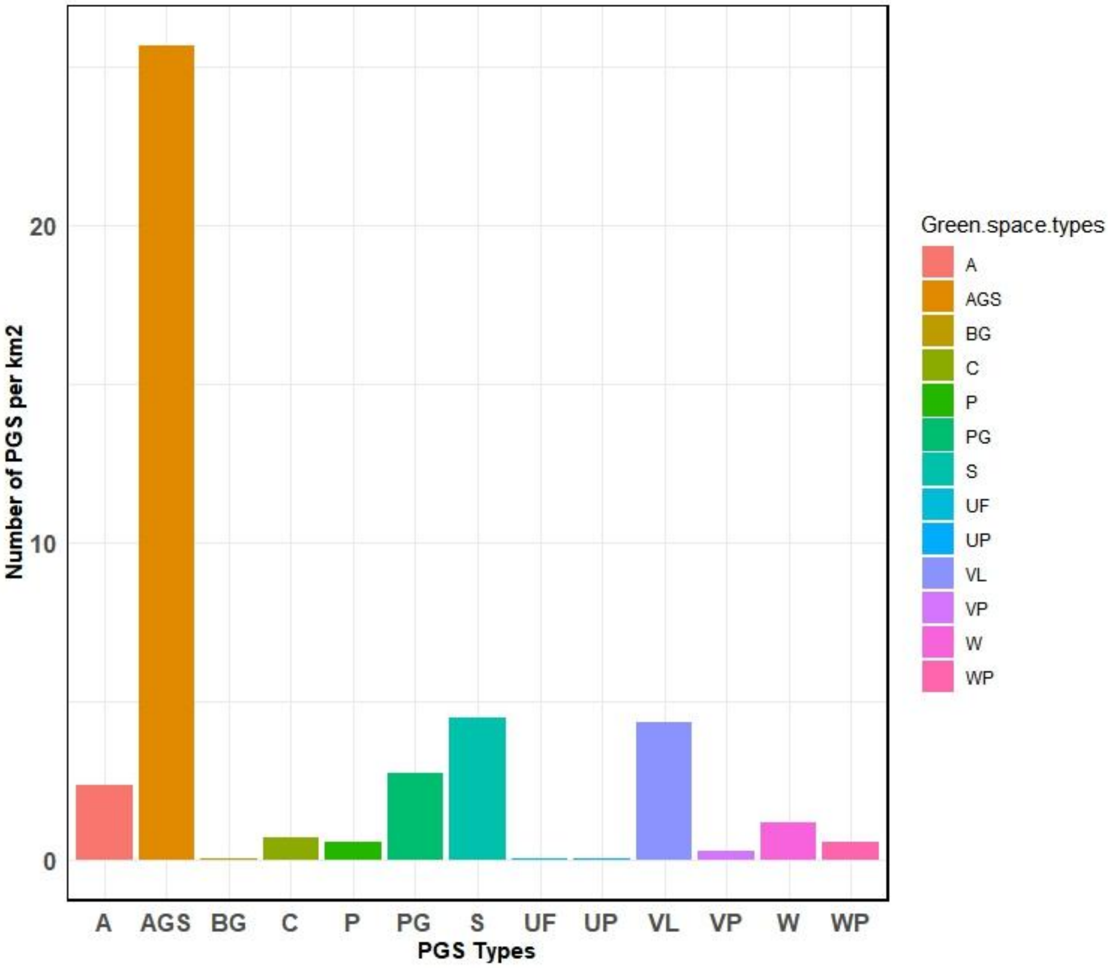

Figure 4.4: Density by public green space types in the region of Dakar

A allotments; AGS accompanying green spaces; BG botanical gardens; C cemeteries; P playgrounds; PG public gardens; S squares; UF urban forest; UP urban park; VL vacant land; VP vegetated parking; W wetlands; WP woody plantation.

In terms of density repartition in the different departments of the Dakar region, the department of Dakar is by far the most provided with 9 public green spaces per square kilometre (Figure 4.5). Contrarily, the department of Rufisque has a null density of public green spaces.

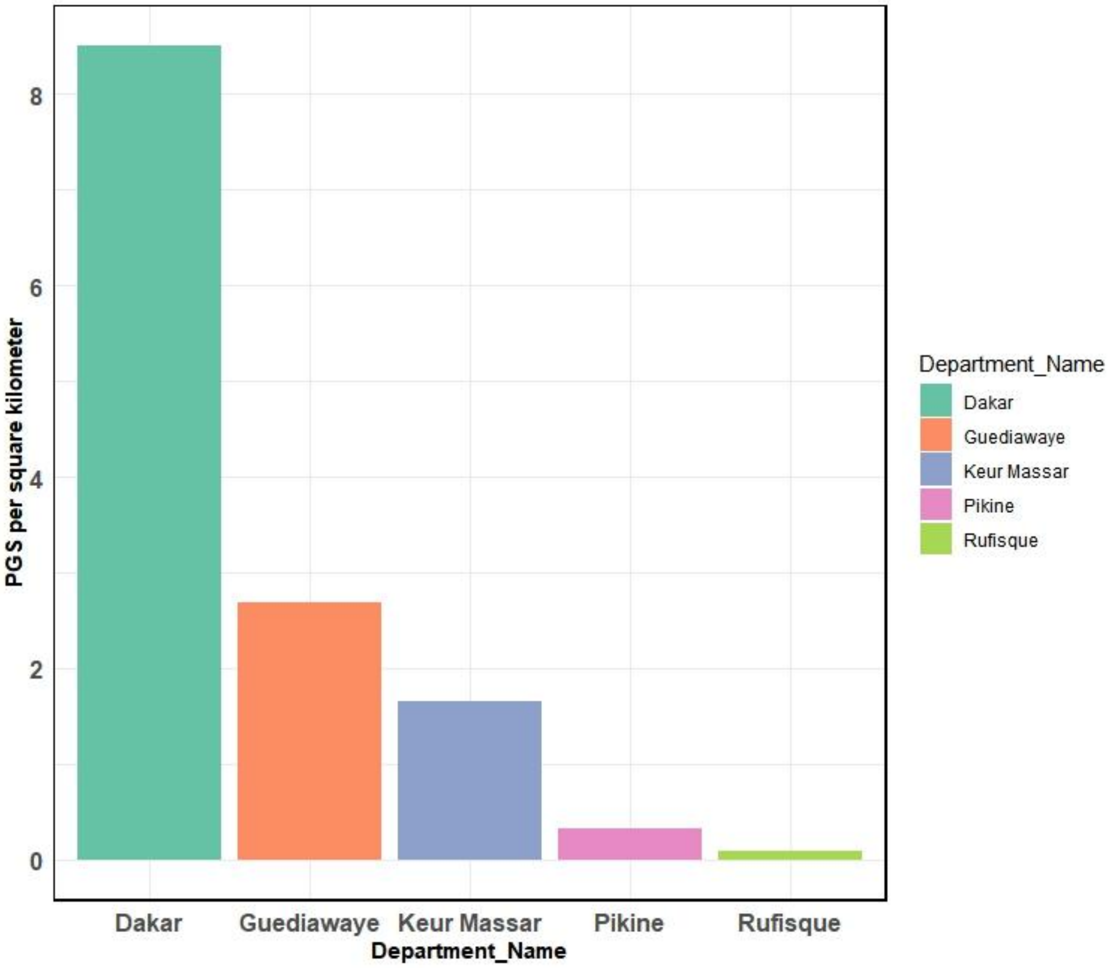

Figure 4.5: Density of public green spaces per department of Dakar

(d) Rate of coverage of public green spaces of Dakar

The coverage rate of all types of public green spaces in the Dakar region is estimated to be 3.5%, or 19.45 square kilometres. This rate of coverage varies from one type of green space to another (as shown in Figure 4.6). These green spaces can be categorised into two groups based on their spatial coverage. First, green spaces with a coverage rate of less than 10 % of the total spatial coverage, which include types such as vegetated parking, playgrounds, botanical gardens, public gardens, squares, and park. Secondly, there are green spaces with a coverage rate greater than 10 % of the total coverage. These green spaces are types such as woody plantations, wetlands, and forest. The low coverage of public gardens and park, which play significant ecological and recreational roles, highlights the need of revise the public green space planning policies in this region to improve the quantity of these valuable spaces.

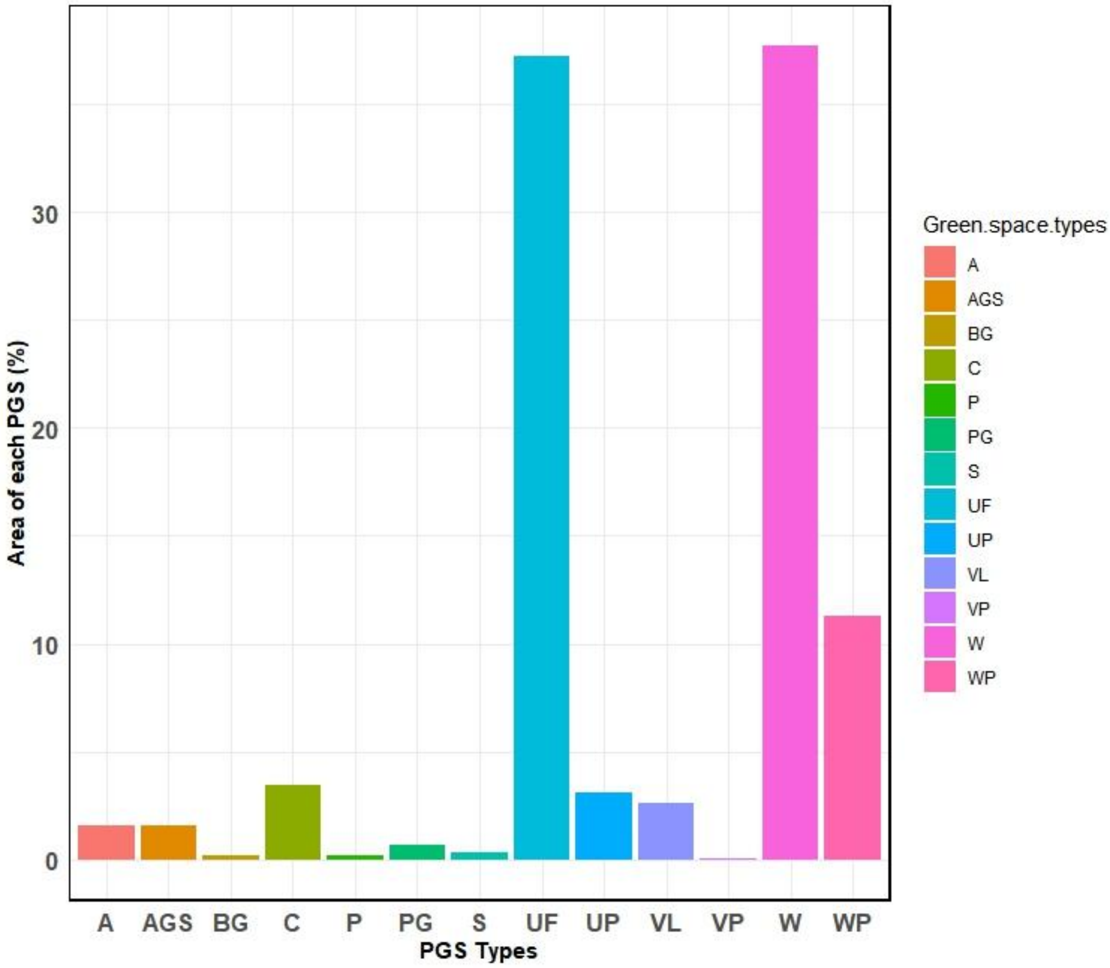

Figure 4.6: Cover rate by public green space types

A allotments; AGS accompanying green spaces; BG botanical gardens; C cemeteries; P playgrounds; PG public gardens; S squares; UF urban forest; UP urban park; VL vacant land; VP vegetated parking; W wetlands; WP woody plantation.

The coverage of public green spaces varies from one department to another, with the department of Pikine having the highest rate at over 20 %, representing 10.68 km^2 of its area, despite its low number of green spaces (15 public green spaces). In contrast, Rufisque, the largest department in the Dakar region, is almost devoid of public green spaces, with 0.47 % of its territory, or 1.68 km^2. The observation is that despite having the largest number of green spaces, the department of Dakar has a low coverage rate of 4.05 %. (Figure 4.7).

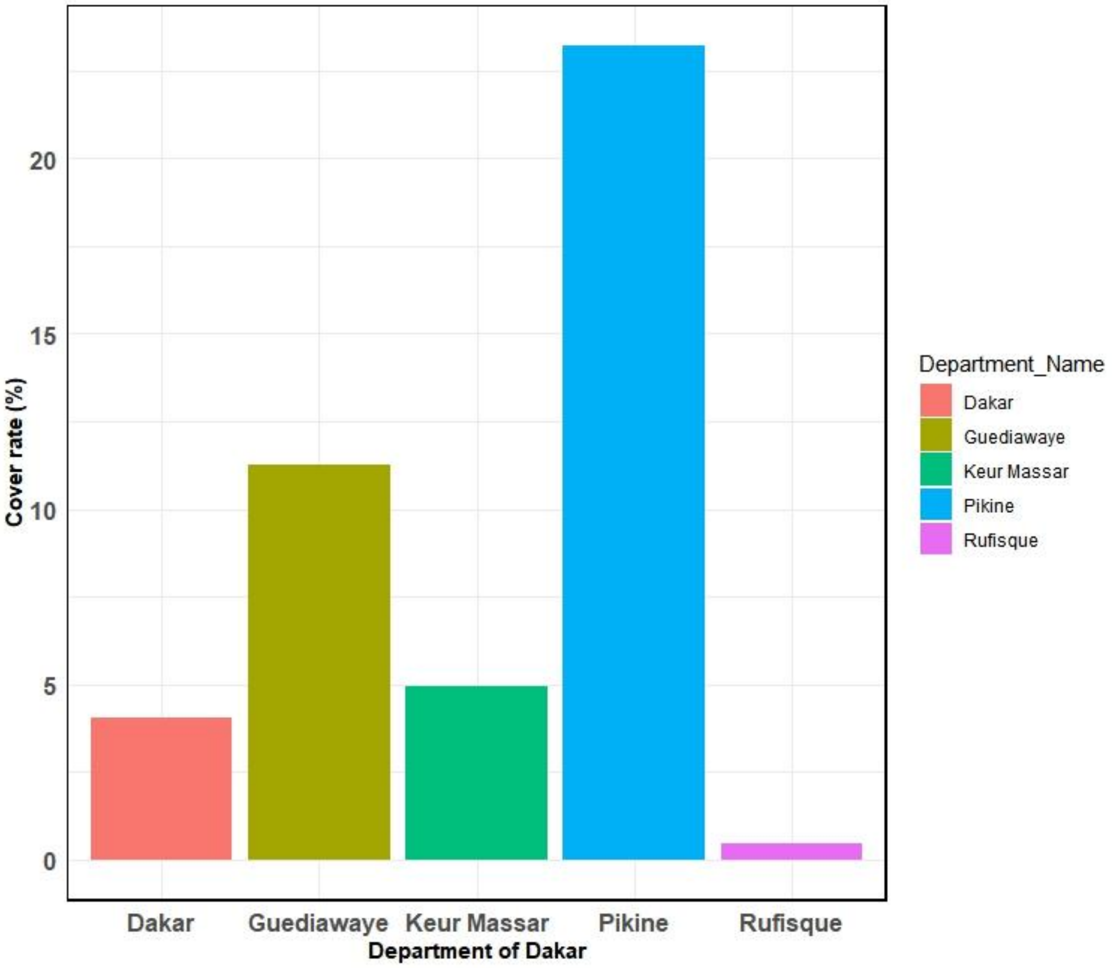

Figure 4.7: Cover rate of public green spaces by department

(e) Green space ratio per inhabitant of Dakar region

According to the Director of Urban Landscape and Public Spaces, Senegal lacks a national green space ratio and falls significantly short of the World Health Organisation's standard of 10 square meters per inhabitant. The Dakar region's results reveal a ratio below the international standard, with only 4.69 square metres of public green space per inhabitant. This finding underscores the region's considerable distance from achieving its green space target. Figure 4.8 illustrates the distribution of the ratio of public green spaces across the five departments of the Dakar region. The department of Pikine stands out with the highest ratio of 12.66 square metres per inhabitant, primarily due to its extensive coverage of public green spaces. However, it's worth noting that Pikine also boasts the highest green space coverage rate among all departments. On the other hand, the department of Dakar, despite its largest population, exhibits a low ratio of 2.22 square metres per inhabitant, indicating the limited spatial coverage of these green spaces within this department.

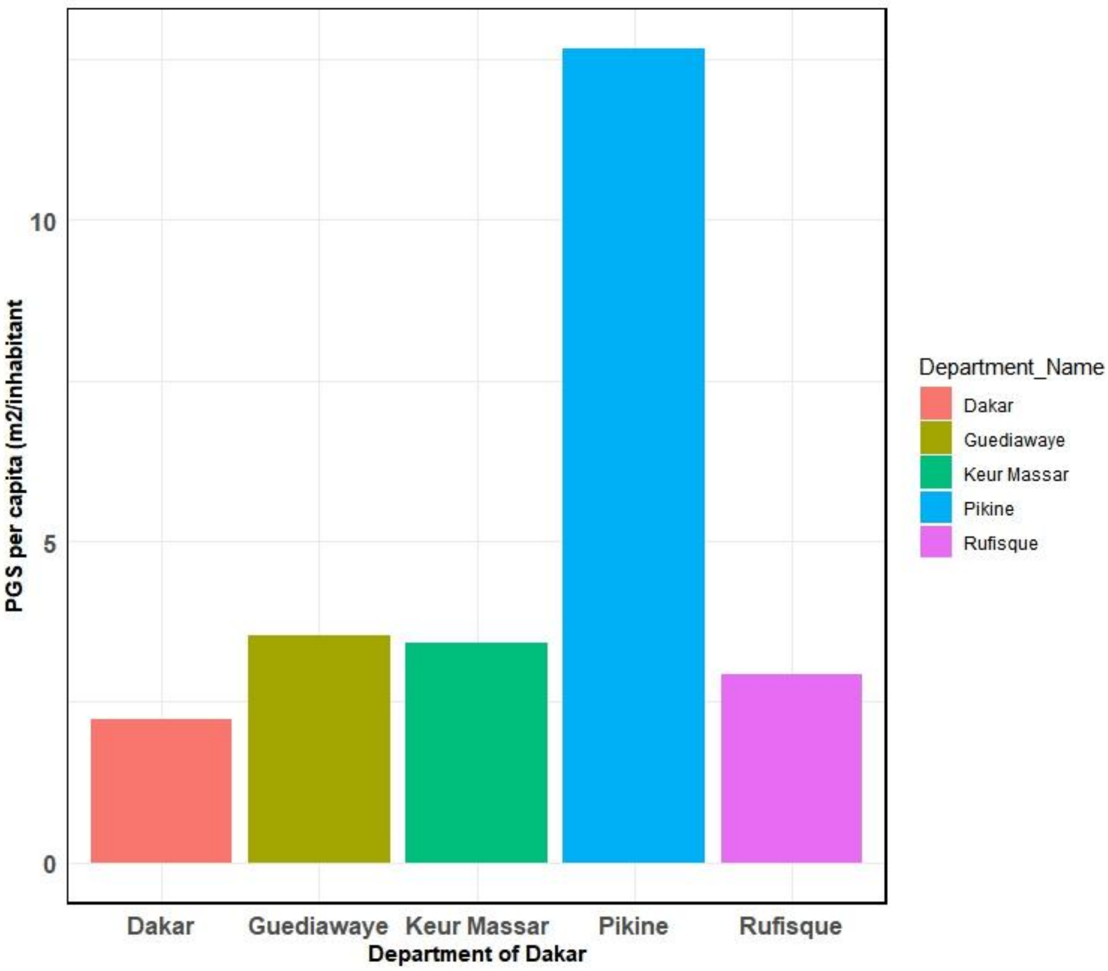

Figure 4.8: Per capita ratio of public green spaces per department of the Dakar region

(f) Quality of public green spaces of Dakar region

The Normalised Difference Vegetation Index (NDVI) was employed to assess the quality of public green spaces in the Dakar region. The primary focus is on the vegetation cover within these spaces. Figure 4.9 presents the NDVI map of the Dakar region, with a minimum value of -0.25 and a maximum of 0.61. A negative value indicates the absence of vegetation, such as buildings and water bodies. Conversely, a higher value signifies the presence of more vegetation in these areas. The analysis reveals that the majority of public green spaces exhibit low NDVI values, ranging from 0.18 to 0.61. Smaller green spaces such as gardens, squares, and accompanying green spaces have the lowest NDVI values at 0.18. However, larger green spaces like parks, forests and wetlands have much higher NDVI values, reaching 0.61. Moreover, in these green spaces, low values of NDVI have also been noted in places showing the low density of vegetation or the presence of buildings or water.

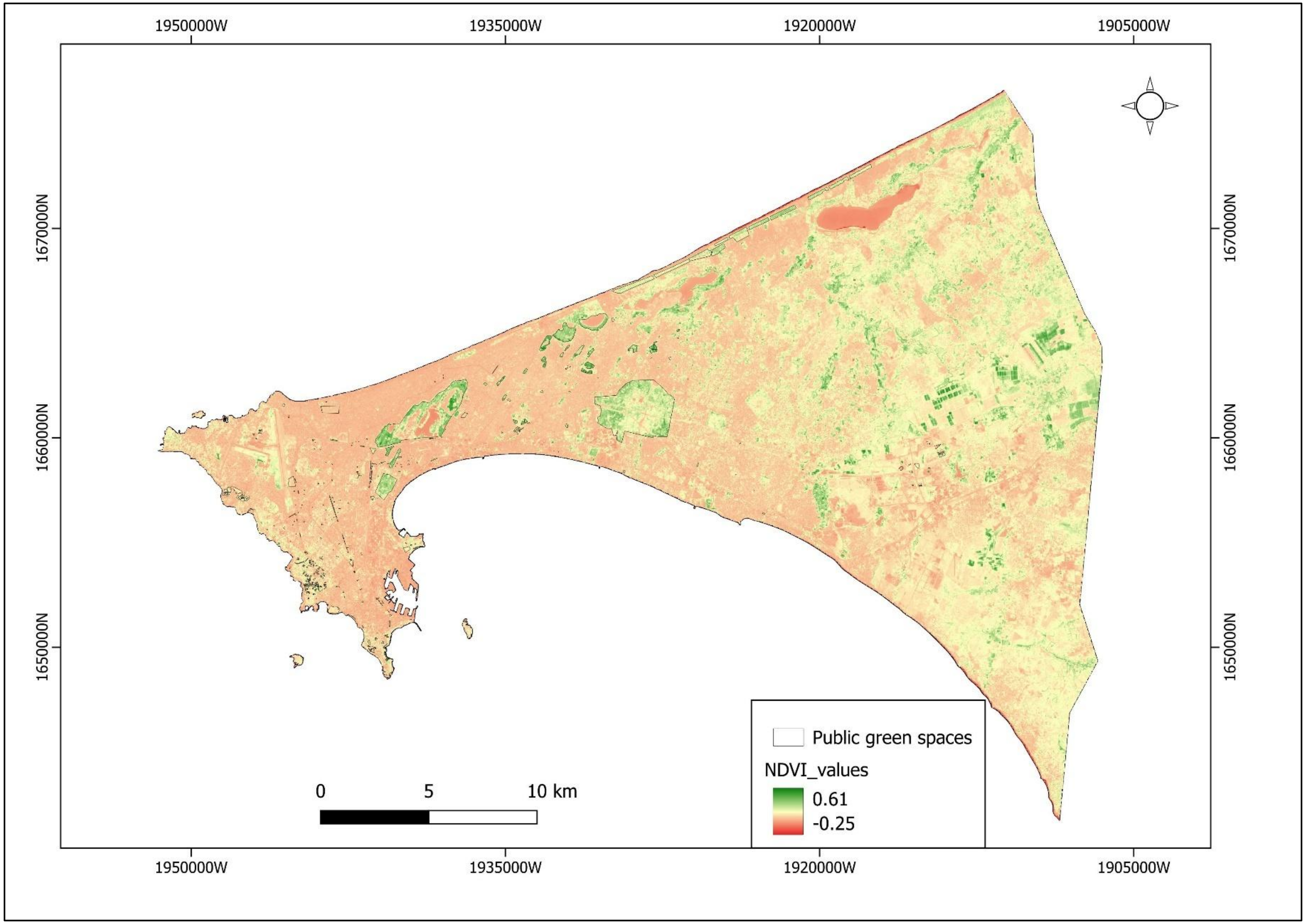

Figure 4.9: NDVI map of the region of Dakar

4.1.2 Spatio-temporal dynamics of green spaces in the Dakar region and the factors drivers of their degradation

4.1.2.1 Spatio-temporal dynamics of green spaces in the Dakar region

(a) Global land use and land cover of the region of Dakar from 1990 to 2022

The analysis of land use and cover in the Dakar region over the period from 1990 to 2022 reveals a dynamic spatial pattern. The region is predominantly dominated by two main classes: bare land and built-up areas. Figure 4.10 illustrates this trend, while Table 4.2 provides further details. In 1990, bare land accounted for 46.3% of the total area, covering 25 116.4 hectares. Agriculture land followed with 19.4%, occupying 10 486.4 hectares, and built-up areas held 19.2%, spanning 10 424.5 hectares. Green spaces and water areas collectively accounted for 13.4% (7 242.8 hectares) and 1.7% (931.3 hectares), respectively.

Notably, the proportions of green spaces and water areas declined significantly over the 12-year period. In 2002, these two classes had decreased considerably. Indeed, green space represented only 7.9 % of the total area of Dakar or 4 269.6 ha, a reduction of 2 973.24 ha of vegetation. Water had also decreased by 1 % or 528 ha with a reduction of 403.29 ha. This reduction in space was also evident in the agriculture land class, with 15.2 % (8 232.9 ha) with a decrease of 2 253.42 ha. On the contrary, bare land and built-up area increased in surface area by 52.3 % (28 325.3 ha) with an increase of 3 208.95 ha and 23.7 % (12 845.5 ha) with a rise of 2 421 ha respectively.

The built-up area continued to expand in 2012, covering 29.1% (15 791.6 hectares) of the Dakar region's land area, an increase of 2 946.06 hectares. This development has progressed primarily in one direction, from west to east. The departments of Dakar, Pikine, and Guediawaye are entirely occupied by the built-up areas, to the detriment of other land covers. In contrast to previous years, the vegetation in the region exhibited a slight increase in cover. In fact, in 2012, vegetation cover represented 12.5% (6 794.4 hectares), a modest increase of 2 524.77 hectares. This increase is also evident in the water surface, which saw a rise of 1.6% (855.7 hectares), with an additional 327.69 hectares. Agricultural land, however, experienced a significant decline during this period. Its area was reduced to 5.3% (2 894.9 hectares), representing a drastic reduction of 5 338.08 hectares. This declining trend is also observed in the bare land class, with a reduction of 460.44 hectares, resulting in a coverage of 52.4% (27,864.9 hectares).

In 2022, the overall land cover types experienced a decline, except for the built-up area, which continued to expand at an impressive pace. Notably, the built-up area now occupies 39.3% (21 311.3 hectares) of Dakar's total surface area. This growth rate is remarkable, representing an increase of 10.19% (5 519.7 hectares) in just ten years. In the department of Rufisque, in the west, where the built-up area was initially smaller, land has gradually been converted into built-up space. This continuous expansion of the built-up area has led to the creation of the fifth department, Keur Massar. However, the vegetation cover regressed once again, experiencing a 9.5% decline (5 170.6 hectares), resulting in a loss of 3% (1 620.75 hectares). The water area, agriculture land, and bare land classes collectively account for 1.6% (853 hectares), 4.3% (2 324.6 hectares), and 45.3% (2 4541.9 hectares), respectively.

Table 4.2: Land cover of the Dakar region from 1990 to 2022

Land cover types	1990		2002		2012		2022	
	ha	%	ha	%	ha	%	ha	%
Green space	7,242.8	13.4	4,269.6	7.9	6,794.4	12.5	5,170.6	9.5
Water	931.3	1.7	528	1	855.7	1.6	853	1.6
Agriculture land	10,486.4	19.4	8,232.9	15.2	2,894.9	5.3	2,324.6	4.3
Bare land	25,116.4	46.3	28,325.3	52.3	27,864.9	51.4	24,541.9	45.3
Built-up	10,424.5	19.2	12,845.5	23.7	15,791.6	29.1	21,311.3	39.3
Total	54,201.4	100	54,201.4	100	54,201.4	100	54,201.4	100

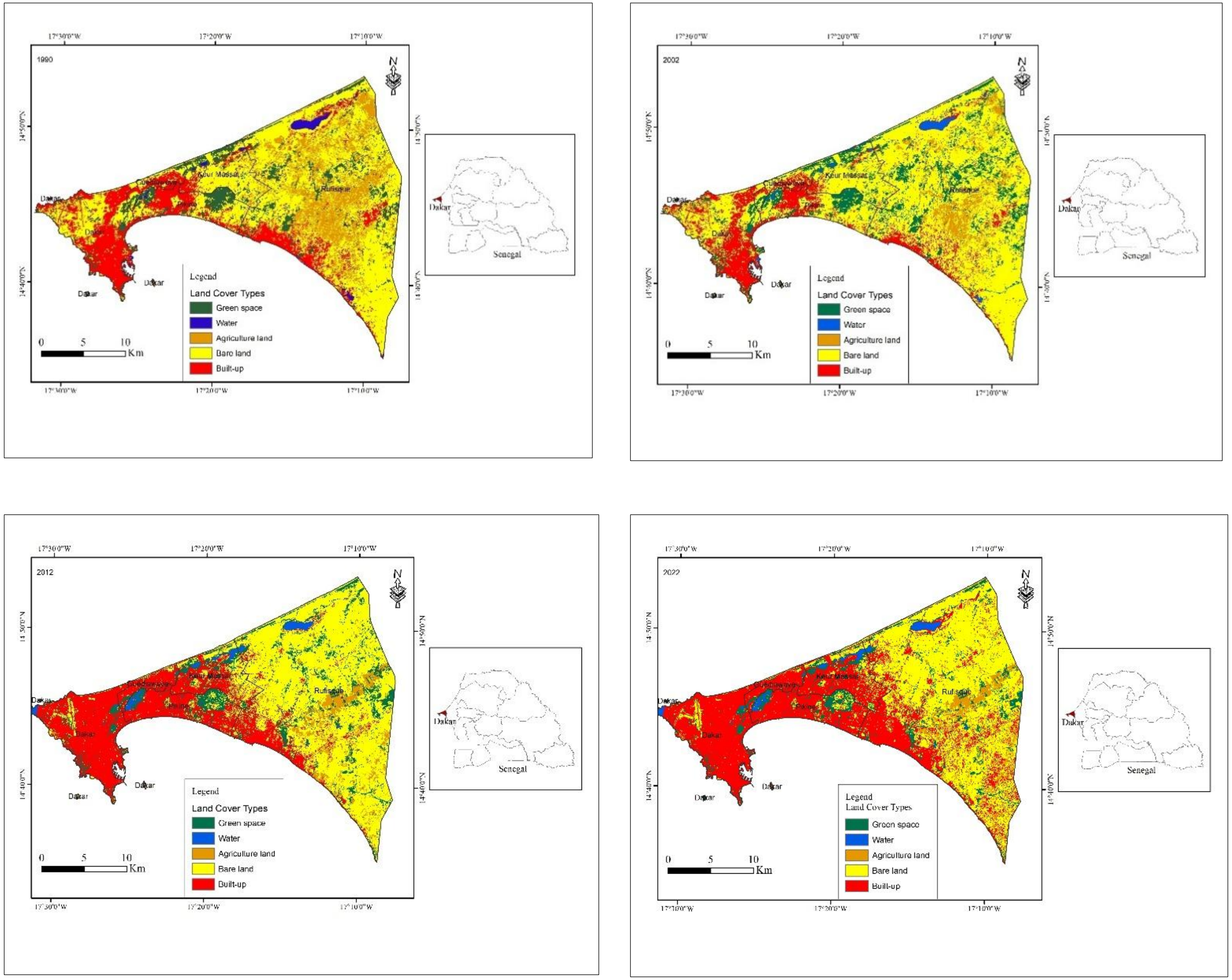

Figure 4.10: Land cover map of the Dakar region from 1990 to 2022

(b) Global change in land cover in the Dakar region from 1990 to 2022

The results show a significant change in the land cover of the Dakar region over the period studied. All classes experienced a substantial transformation between 1990 and 2022 (Figure 4.11), with these changes profoundly impacting the vegetation cover. The matrix table generated enabled us to illustrate the modification of land cover classes over the years studied. The matrix results indicate a high degree of instability in green spaces in the Dakar region, marked by their conversion into other land use types. Between 1990 and 2002, only 11.14 % of green spaces remained stable (Table 4.3). Furthermore, vegetation cover lost a substantial portion of its area, with 3.07 % converted to agricultural land. During the same period, another 1.77 % was converted to bare land, highlighting the extent of vegetation cover degradation, with an overall loss of 5.2 %. The agricultural land increased in the area, particularly in the department of Rufisque, west of Dakar, with 9.25 % of bare land converted to agricultural use. In contrast, bare land decreased as it converted to farmland and built-up areas. Built-up areas gained 5.14 % at the expense of bare land, representing a 5.4 % increase in built-up area.

Changes continued between 2002 and 2012, with vegetation decreasing dramatically, leaving only 5 % relatively stable (Table 4.4). On the other hand, 7.93 % of bare land and 2.63 % of built-up areas were converted to green space, resulting in a 4.07 % increase in their surface area. However, this period also saw the greatest loss of vegetation: 4.75 % of green space was converted to bare land, while agricultural land and built-up areas gained 1.18 % and 1.22 % of vegetation, respectively. The built-up area shrank significantly, losing over 10 % of its surface to bare land, though it saw a slight increase in other areas. Similarly, agricultural land expanded, claiming 4.94 % of bare land.

Unlike previous years, green spaces showed much greater stability between 2012 and 2022 (Table 4.5). Vegetation cover increased by 8.41 %, with only slight changes observed. During this period, the matrix table shows that small portions of green spaces were converted to water (0.02 %), agricultural land (0.07 %), bare land (0.85 %) and built-up (0.18 %). Additionally, there were gains in green spaces, with 3.05 % of bare land transformed into green space, reflecting efforts to develop green areas and reforest the region. In contrast to the green space, the water surface area continued to decline significantly. This reduction is also visible in the built-up area, which decreased slightly by 10.16 %. Indeed, the built-up area was reduced by 10.19 % in favour of the bare land class, leading to a 6.51 % increase in bare land.

The overall class transfer matrix from 1990 to 2022 showed very low stability for the green space class (Table 4.6). Only 3.66 % of the area remained as green spaces during this period. However, there were notable positive changes in favour of green space: 5.49 % of bare land was converted to green space, while 3.62 % of the built-up area also became vegetation. The water and agriculture land classes also contributed small portions to vegetation, with 0.31 % and 0.28 %, respectively. Conversely, green space experienced significant negative change, with 3 % of its space converted to bare land, 1.76 % to agricultural land, 0.97 % to built-up areas and 0.14 % to water. The class that declined the most was water, losing 7.8 % of its surface area between 1990 and 2022. In contrast, classes such as agriculture land, bare land and built-up area registered substantial increases in surface area, expanding by 15.06 % for agriculture, 1.05 % for bare land, and 20.09 % for built-up. Built-up areas, in particular, have become more sprawling over the years.

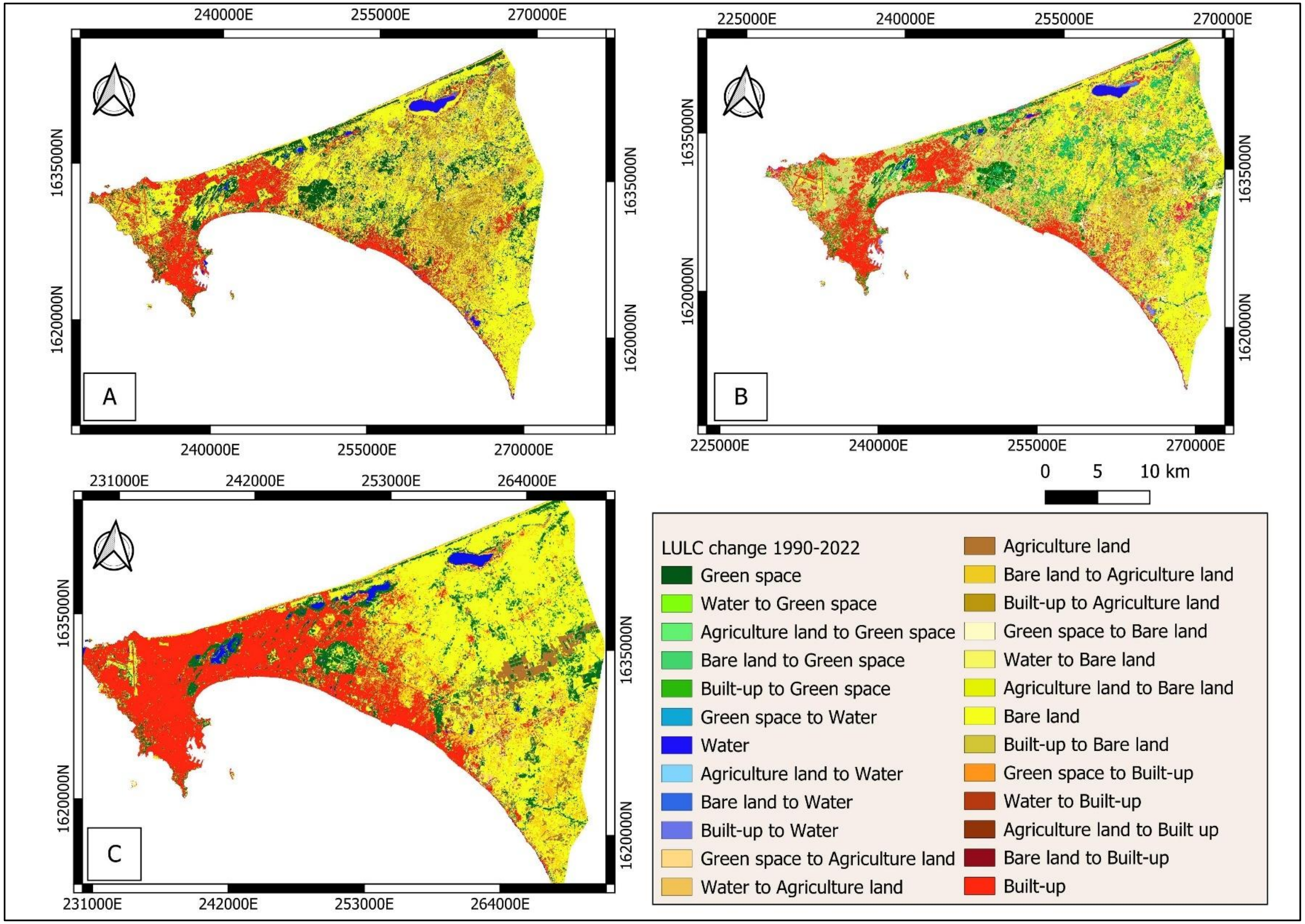

Figure 4.11: Land use and land cover change of the Dakar region of 1900-2002 (A), 2002-2012 (B), and 2012-2022 (C)

Table 4.3: Land use and land cover matrix from 1990 to 2002 in percentage

	Land cover types	1990					
		Green space	Water	Agriculture land	Bare land	Built-up	Total
2002	Green space	11.14	0.19	3.07	1.77	0.17	16.34
	Water	0.09	1.11	0	0.03	0.03	1.26
	Agriculture land	0.09	0.01	6.45	1.64	0.06	8.25
	Bare land	1.43	0.08	9.25	39.08	5.14	54.98
	Built-up	0.62	0.33	0.57	3.82	13.84	19.18
	Total	13.37	1.72	19.34	46.34	19.24	100.01

Table 4.4: Land use and land cover matrix from 2002 to 2012 in percentage

	Land cover types	2002					
		Green space	Water	Agriculture land	Bare land	Built-up	Total
2012	Green space	5	0.12	1.18	4.75	1.22	12.27
	Water	0.3	0.74	0.02	0.25	0.26	1.57
	Agriculture land	0.48	0.02	1.33	3	0.39	5.22
	Bare land	7.93	0.16	4.94	33.86	4.9	51.79
	Built-up	2.63	0.22	0.78	13.11	12.41	29.15
	Total	16.34	1.26	8.25	54.97	19.18	100

Table 4.5: Land use and land cover matrix from 2012 to 2022 in percentage

	Land cover types	2012					
		Green space	Water	Agriculture land	Bare land	Built-up	Total
2022	Green space	8.41	0.02	0.07	0.85	0.18	9.53
	Water	0	1.55	0	0.01	0.02	1.58
	Agriculture land	0.09	0	4	0.2	0	4.29
	Bare land	3.05	0	0.98	40.54	0.71	45.28
	Built-up	0.72	0	0.16	10.19	28.24	39.31
	Total	12.27	1.57	5.21	51.79	29.15	99.99

Table 4.6: Land use and land cover matrix from 1990 to 2022 in percentage

	Land cover types	1990					
		Green space	Water	Agriculture land	Bare land	Built-up	Total
2022	Green space	3.66	0.14	1.76	3	0.97	9.53
	Water	0.31	0.77	0.04	0.19	0.27	1.58
	Agriculture land	0.28	0.03	2.01	1.78	0.19	4.29
	Bare land	5.49	0.18	11.85	24.31	3.45	45.28
	Built-up	3.62	0.61	3.69	17.05	14.36	39.31
	Total	13.36	1.73	19.35	46.33	19.24	100

(c) Land use and land cover changes of three major public green spaces of the Dakar region

Three specific green spaces have been selected in the context of this study to monitor their vegetation cover. These are three public green spaces protected by presidential decrees. These green spaces are considered to be the green lungs of the Dakar region, hence their choice. These are the Hann Forest and Zoological Park, the Mbao Classified Forest, and the Natural Urban Reserve of Great Niayes and Dependence.

During the studied period, the Hann Forest and Zoological Park showed little evolution (Figure 4.12). In fact, in 1990, the vegetation cover of this urban park represented 58.58 ha, which decreased slightly in 2002 to 57.42 ha. However, in 2012, the vegetation cover grew to a surface area of 60.39 ha and will be maintained until 2022. Other classes have also been experiencing insignificant changes. The second dominant class of the park is the built-up area, which has increased over the years. In 1990, the built-up area occupied 1.71 ha, rising to 3.15 ha in 2002 and 4.32 ha in 2012, but in 2022, the built-up area has decreased very slightly to 4.23 ha. Water and bare land have also shown a general decline, and agriculture land has completely disappeared from the park in 2012 and 2022.

On the other hand, spatial dynamics are more intense in the Mbao Classified Forest than in the park (Figure 4.13). In 1990, the vegetation cover was 561.87 ha; this value decreased in 2002 to 579.06 ha. This slight decrease is observed until 2012 with a value of 522.81 ha. However, the greatest reduction in the vegetation cover of the forest was noted in 2022, with a value of 456.21 ha. The bare land class has increased considerably, showing the degradation of this forest. In 1990, the bare land was 97.38 ha, 104.76 ha in 2002, 157.14 ha in 2012, and 201.06 ha in 2022. The built-up area also increased during this period, recording 19.35 ha in 1990, 20.34 ha in 2002, 29.61 ha in 2012, and 47.25 ha in 2022. This trend illustrates the fragmentation experienced by the only urban forest of the Dakar region.

This fragmentation is more visible in the Natural Urban Reserve of Great Niayes and Dependence, which has seen its space change over the years. Indeed, Figure 4.14 shows that the vegetation cover declined between 1990 and 2002, with 280.62 ha and 271.98 ha. A slight increase in surface area was observed in 2012 with 296.01 ha and has continued to increase until 2022 with 304.11 ha. This growing trend is equally visible at the water surface, with 43.29 ha in 1990, 50.94 ha in 2002, 159.03 ha, and 304.11 ha in 2022. The built-up area increased in size between 1990 and 2002, with 26.37 ha and 30.6 ha, respectively, and in 2012, 65.25 ha.

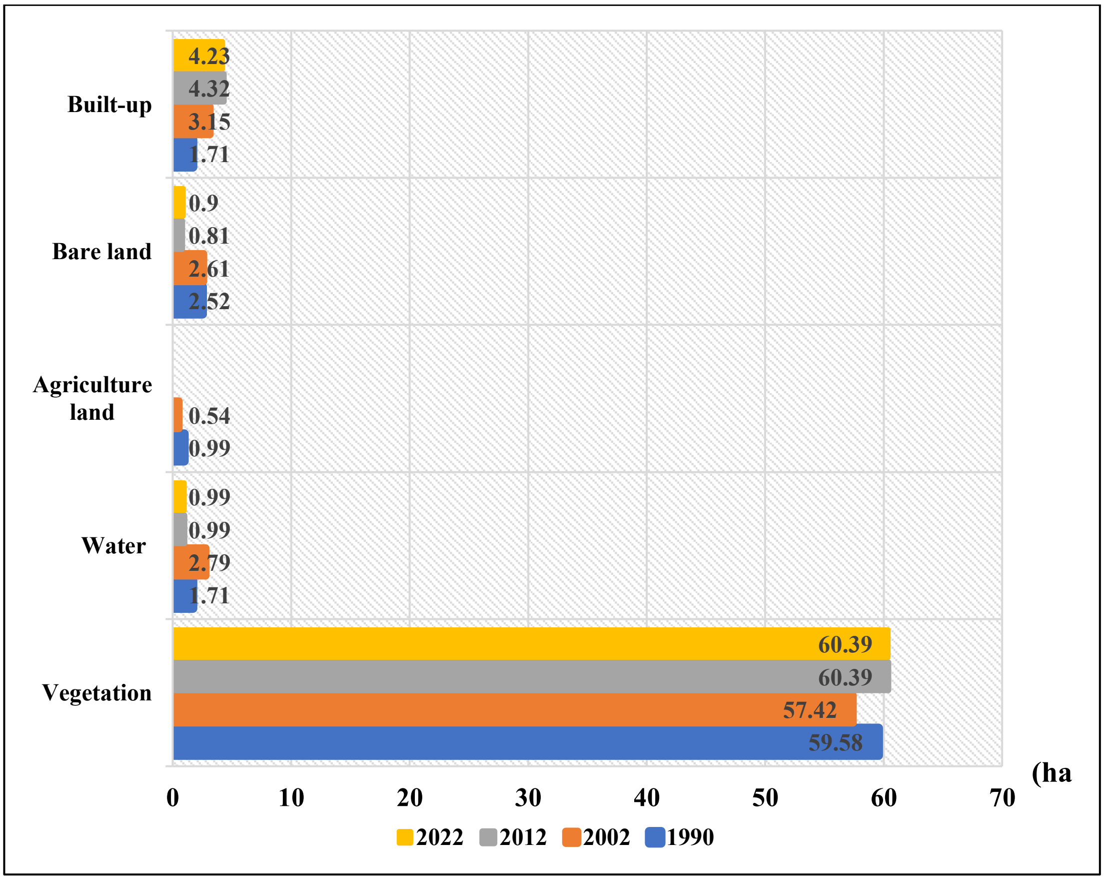

Figure 4.12: Land cover of Hann Forest and Zoological Park from 1990 to 2022

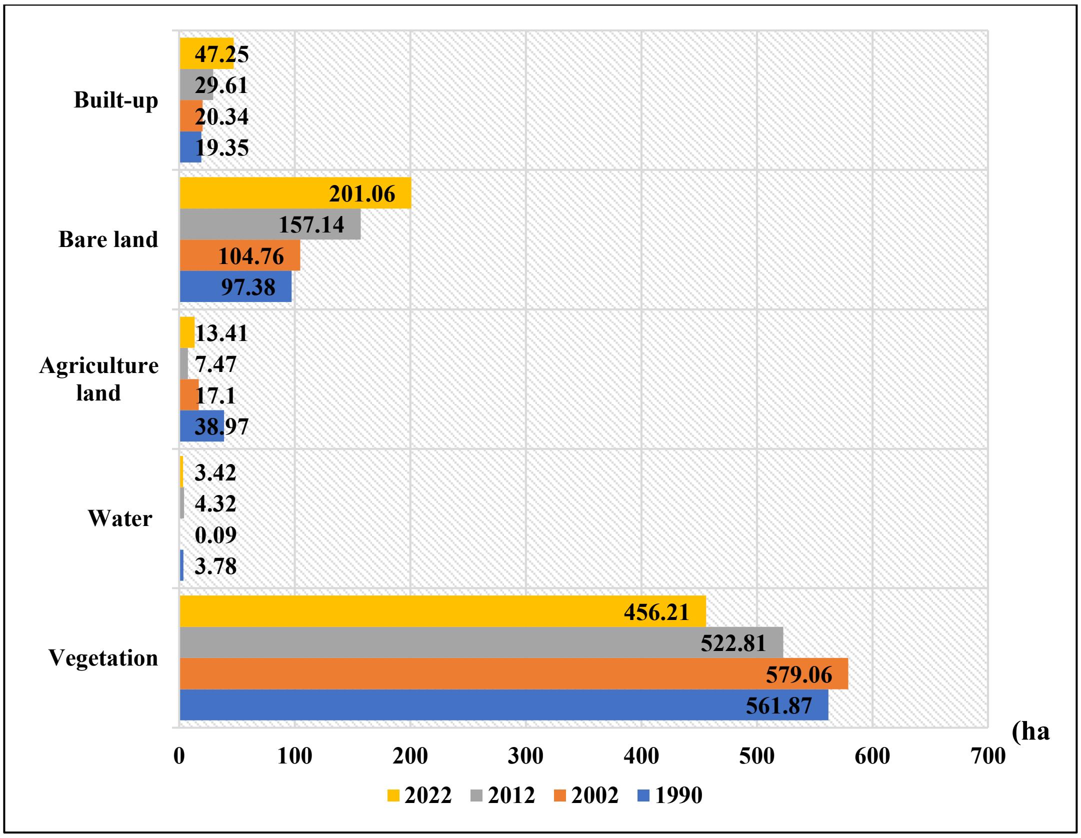

Figure 4.13: Land cover of Mbao Classified Forest from 1990 to 2022

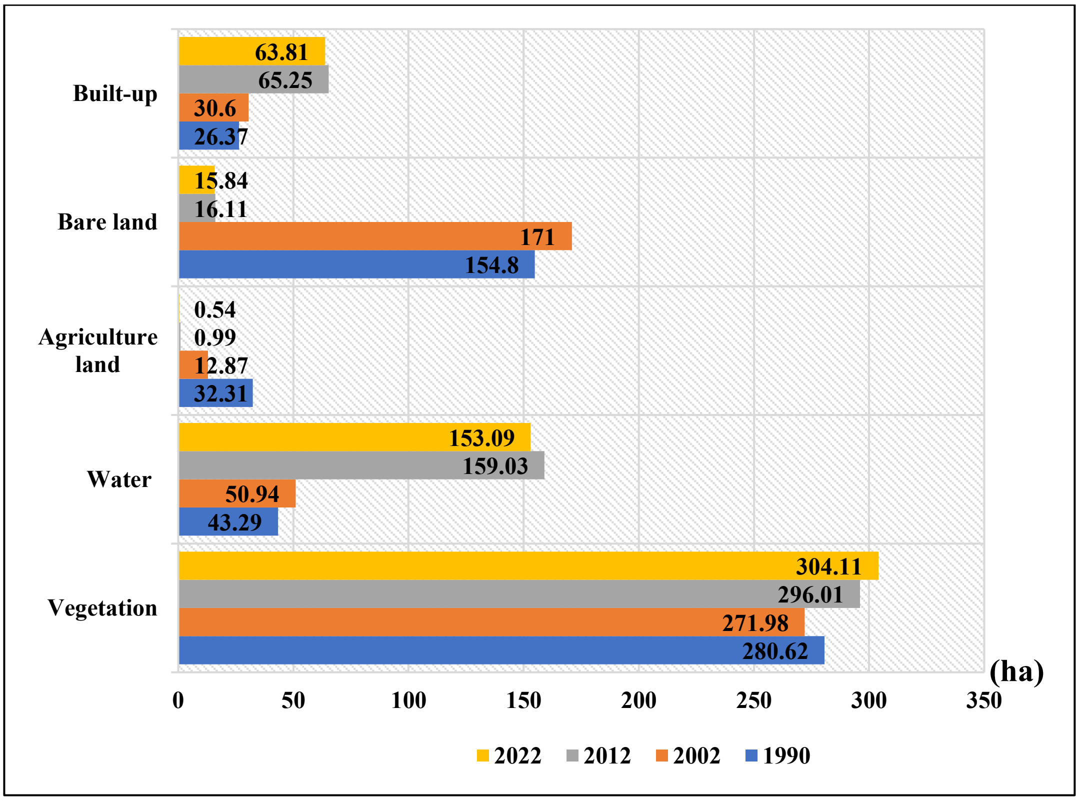

Figure 4.14: Land cover of the Natural Urban Reserve of Great Niayes and Dependence from 1990 to 2022

(d) Trend evolution of the vegetation cover in the three green spaces of the Dakar region

Figure 4.15 presents the linear regression models for the three green spaces selected in the Dakar administrative region to illustrate the evolution of their vegetation cover over time, with years as the independent variable and vegetation cover as the dependent variable. The analysis reveals a slight increase in vegetation cover in the Hann Forest and Zoological Park (HFZP), with an R^2 value of 0.21. A similar positive trend is observed in the Natural Urban Reserve of Great Niaye and Dependence (NURGND), where the R^2 value is 0.67, indicating a moderately stronger relationship than in the park. In contrast, a negative trend is observed in the Mbao Classified Forest (MCF), with a higher R^2 value of 0.74, suggesting a relatively strong linear relationship and indicating that vegetation cover has declined over the 32 years of observation.

However, none of the three models is statistically significant, with p-values of 0.14 for the forest, 0.53 for the park, and 0.18 for the reserve. This lack of significance is likely due to the small sample size, as the analysis includes only four years of data.

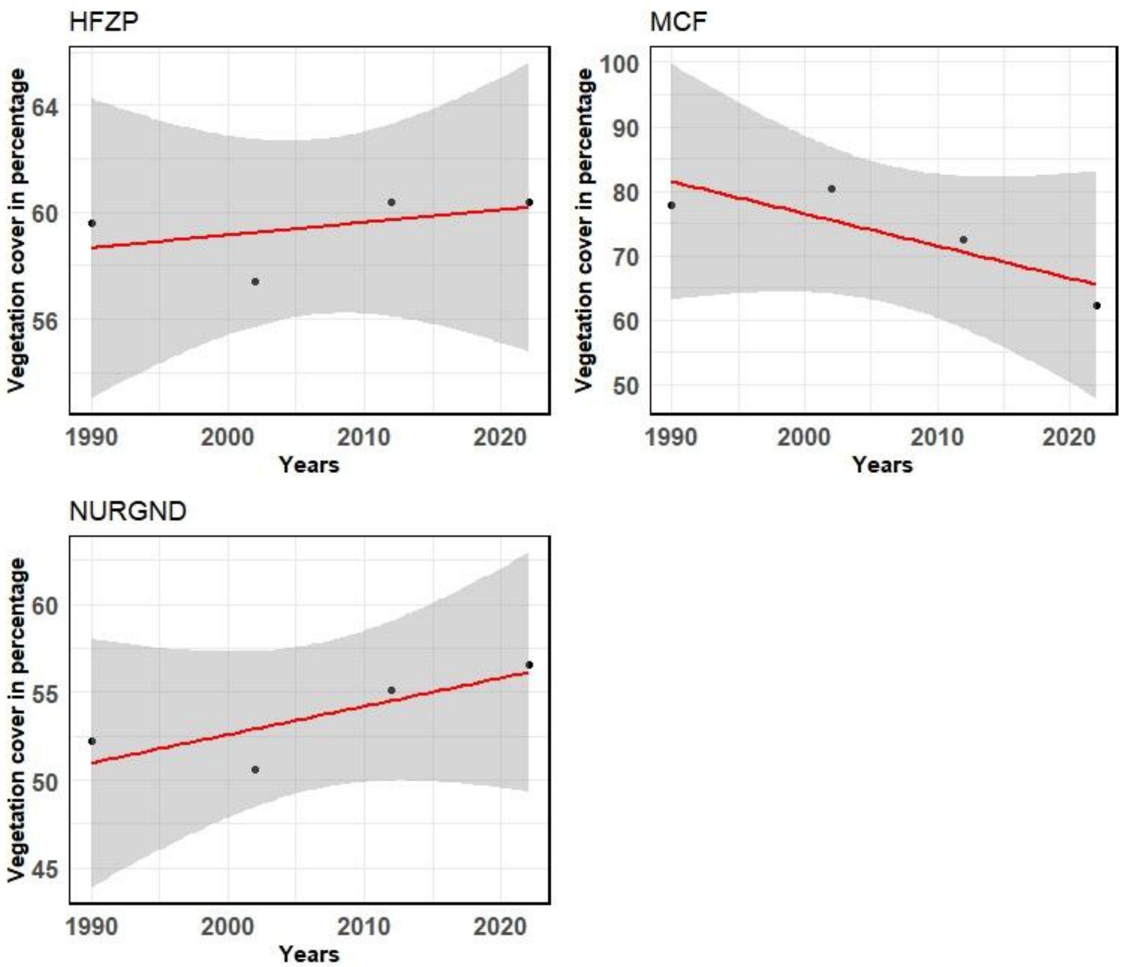

Figure 4.15: Linear regression of the vegetation cover of the three major green spaces in the Dakar region from 1990 to 2022

Furthermore, major changes in vegetation cover are revealed by land use classification, with gains and huge losses (Figure 4.16). Between 1990 and 2002, gains in vegetation cover were higher, equivalent to 14.22 %, than the losses, estimated at 11.79 %. The decade between 2002 and 2012 is characterised by a greater decline in vegetation cover than growth. The increase in vegetation area is 47.96 % of their space, the largest rise in vegetation for these three green spaces between 1990 and 2022. On the other hand, these areas registered a reduction of 49.1 % in their vegetated area, which is rather a huge loss. Contrary to the 2002-2012 decade, the 2012-2022 period is marked by an increase in vegetation in these three large green spaces rather than a decrease. Vegetation cover has risen by 17.29 %, compared with a loss of 9.58 %. Despite the high fragmentation that the three green areas have experienced, it was found that between 1990 and 2022, the increase in vegetation cover of 55.5 % was greater than the reduction of 46.43 %.

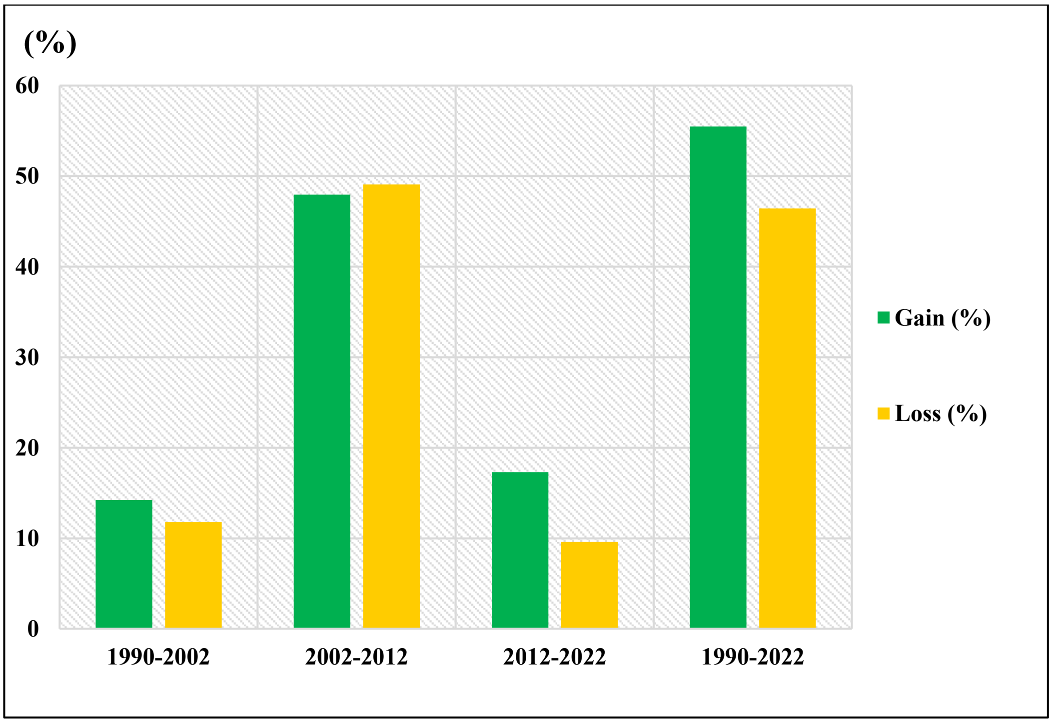

Figure 4.16: Vegetation gains and losses in Dakar's three major green lungs in percentage

Among the three green spaces, the area that has known the greatest change in vegetation cover between 1990 and 2022 is the Natural Urban Reserve of the Great Niayes and Dependence, which has lost 25.23 % of its vegetation, followed by the Mbao Classified Forest with 14.3 %. Hann Forest and Zoological Park recorded the smallest loss with 6.9 %. The variability of vegetation cover in these three large green spaces is due to the significant changes in these areas, as illustrated by the matrix table, which showed both increases and decreases in vegetation in favour of other types of land use.

In the case of Hann Forest and Zoological Park, a gradual decline in vegetation in favour of the built-up area was observed, with an overall conversion of 1.76 % of plant cover to buildings between 1990 and 2022. From 2012 to 2022, a large regression in forest cover was recorded, with a loss of 3.65 % of vegetation cover for buildings. This can be explained by the fact that the park comprises many infrastructures and facilities for its various functions. Besides these losses, the vegetation cover also benefited from a tiny percentage of the other classes.

This negative evolution of vegetation cover constated in the park is also found in the Mbao Classified Forest, which has seen its plant cover gradually disappear. Globally, the vegetation of the forest, which occupied 77.89 % of the surface area in 1990, has diminished to 63.25 % in 2022, a reduction of more than 10 %, giving way to built-up areas, which have progressively become established in the forest, as well as bare land. It has been revealed that over the years, the reduction in the vegetation cover is due to the progressive development of agriculture, built-up areas and bare soil. The increase in bare land has contributed strongly to the decline in the area of vegetation between 2002 and 2012, with 10.26 % of vegetation transformed into bare soil. On the other hand, agriculture has also gradually expanded, leading to a depletion of 2.43 % between 1990 and 2002 and 1.92 % between 2002 and 2012. Like agriculture, the built-up area has also played an important role in this downward trend in the vegetation of the Mbao forest. The results show that the greatest increase in the built-up area occurred during the period 2002 to 2012, with 2.01 % of vegetation converted.

The case of the Natural Urban Reserve of Great Niaye and Dependence, the most important wetland of Dakar, seems to be like the park, with a slight global increase in plant cover between 1990 and 2022, from a total of 52.22 % to 56.58 %. Furthermore, the area occupied by vegetation did not reach 50 % of the total area of the reserve during the period between 1990 and 2002 and drastically diminished between 2002 and 2012. This decline in vegetation is explained by the transformation of 18.77 % of vegetation into bare land, in addition to the 2.85 % that became built-up. The increase during this period is mainly because 14.86 % of the water surface is occupied by vegetation. At the same time, the built-up area has increased by 6.45 % agriculture has also expanded. However, between 2012 and 2022, there has been a marked increase in surface area of 22.38 %. This is the same period in which the water area of the reserve has expanded by 28.22 %, in contrast to previous periods.

4.1.2.2 Drivers of degradation of public green spaces in the Dakar region

Data obtained from surveys enabled the identification of the factors contributing to the degradation of public green spaces in the Dakar region (Figure 4.17). The results show that more than 60 % of responses have mentioned anthropogenic factors as the main causes of the degradation of green spaces. Nevertheless, natural causes are cited too but at low frequencies with 5.31 % of responses. Furthermore, the non-responses correspond to neighbourhoods where respondents confirm that there are no public green spaces. In addition, Figure 4.18 highlights the contribution of the kinds of human activity that cause degradation. It reveals that urban expansion is considered to be the main cause of the depletion of public green space, accounting for 58.41 % of responses, followed by industrial activities with 3 % and agriculture needs with 1 %. The remainder represents areas without public green spaces.

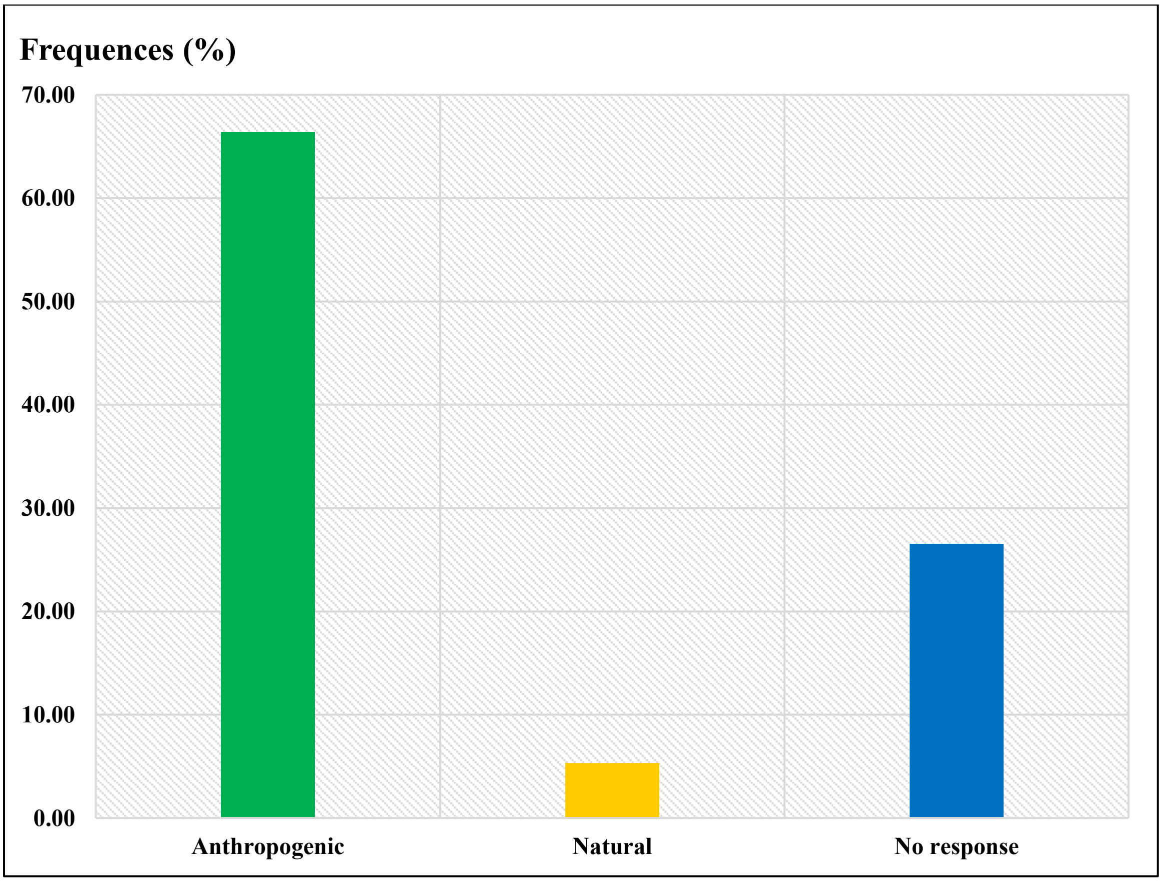

Figure 4.17: Causes of the degradation of public green spaces in the Dakar region

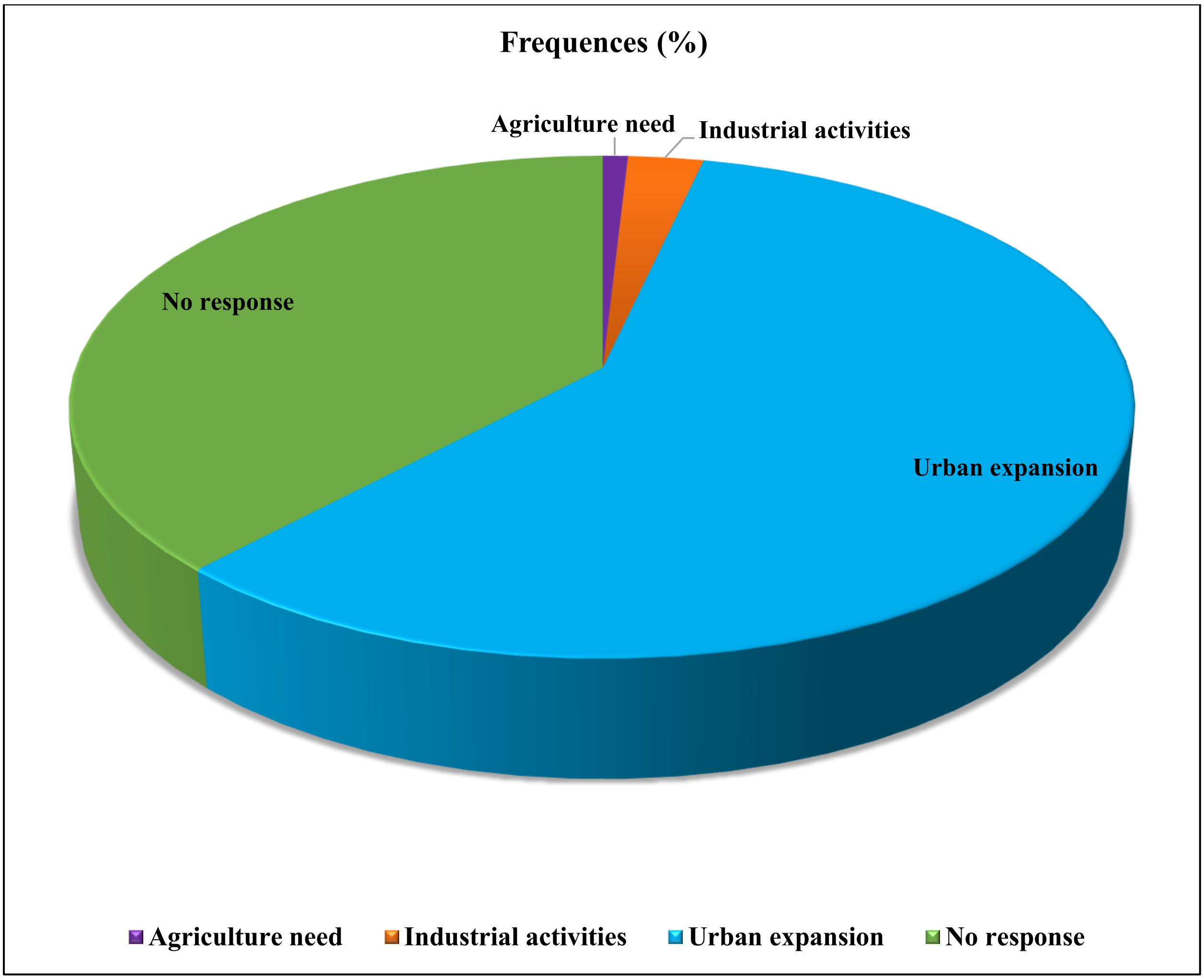

Figure 4.18: Nature of public green space degradation causes

This evidence from the surveys is supported by the interviews as highlighted in the word cloud (Figure 4.19). For the three major green spaces, urban development is cited as the main cause of the reduction in plant cover. This is done by declassifying certain parts, as they are protected by law by presidential decree, for the benefit of the buildings. In addition, the development of infrastructures such as roads, administrative buildings, and housing are the main infrastructure found in these green spaces. For example, the Mbao Classified Forest is crossed by two major road infrastructures, the highway and the express regional train. The same situation applies to the Natural Urban Reserve of Great Niayes and Dependence, where the highway has split into two parts (Plates XI, XII, XIII, XIV, XV, XVI). It should be noted, however, that the word water was frequently used in the interviews. This is because flooding is cited as a cause of deterioration of the plant cover of the park and the forest, because of the quantities of water that flow into these areas.

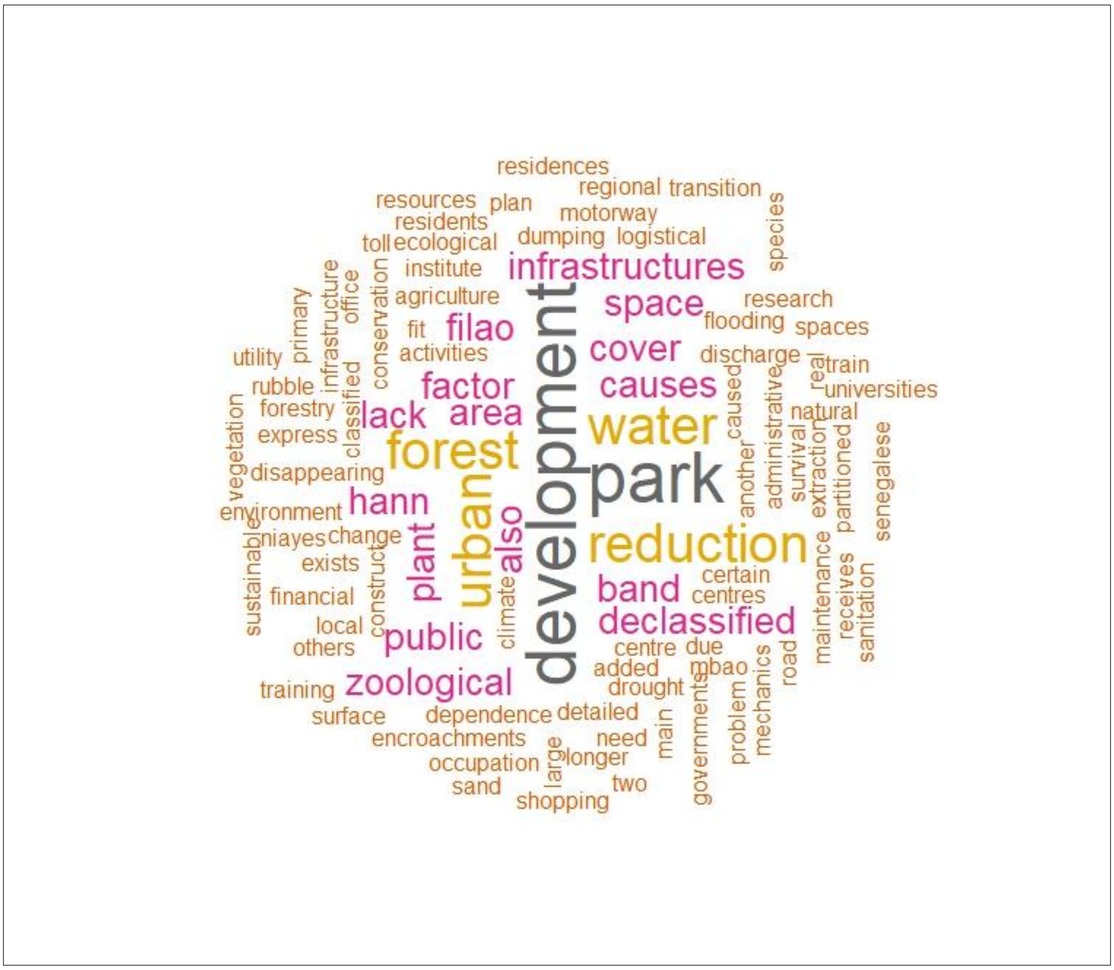

Figure 4.19: Word cloud on the causes of degradation of public green spaces in the Dakar region

Plate XI: Highway crossing the Mbao Classified Forest

Plate XII: Flooded area of the Mbao Classified Forest

Plate XIII: Flooded area of the Hann Forest and Zoological Park

Plate XIV: Buildings within the Hann Forest and Zoological Park

Plate XV: Buildings encroachment in the NURGND

Plate XVI: Fragmentation of the NURGND by the highway and housing

4.1.3 Impacts of green space's dynamics on urban ecosystem services in the Dakar region

This section of the study consists of assessing the implications that changes in green spaces have on ecosystem services, particularly regulating services. To do this, we first analyse the evolution of ecosystem services from 1990 to 2022 to assess the changes. After that, a correlation is made between green spaces and the services. However, only green spaces with an ecological function are taken into account in this study. Among them are the Hann Forest and Zoological Park (HFZP), the Mbao Classified Forest (MCF), and the Natural Urban Reserve of Great Niaye and Dependence (NURGND).

4.1.3.1. Changes in ecosystem services of green spaces

The regulating services considered in this study are carbon storage and sequestration, the cooling capacity of green spaces and their role in flood mitigation.

(a) Carbon sequestration and storage of green spaces

InVEST provides results in raster format, which must be visualised using GIS software such as Qgis. The spatial distribution of the carbon stocks across the Dakar administrative region shows higher quantities in areas with vegetation, such as the three green spaces selected in this study, demonstrating the role played by urban green spaces in reducing atmospheric carbon dioxide (Figure 4.20).

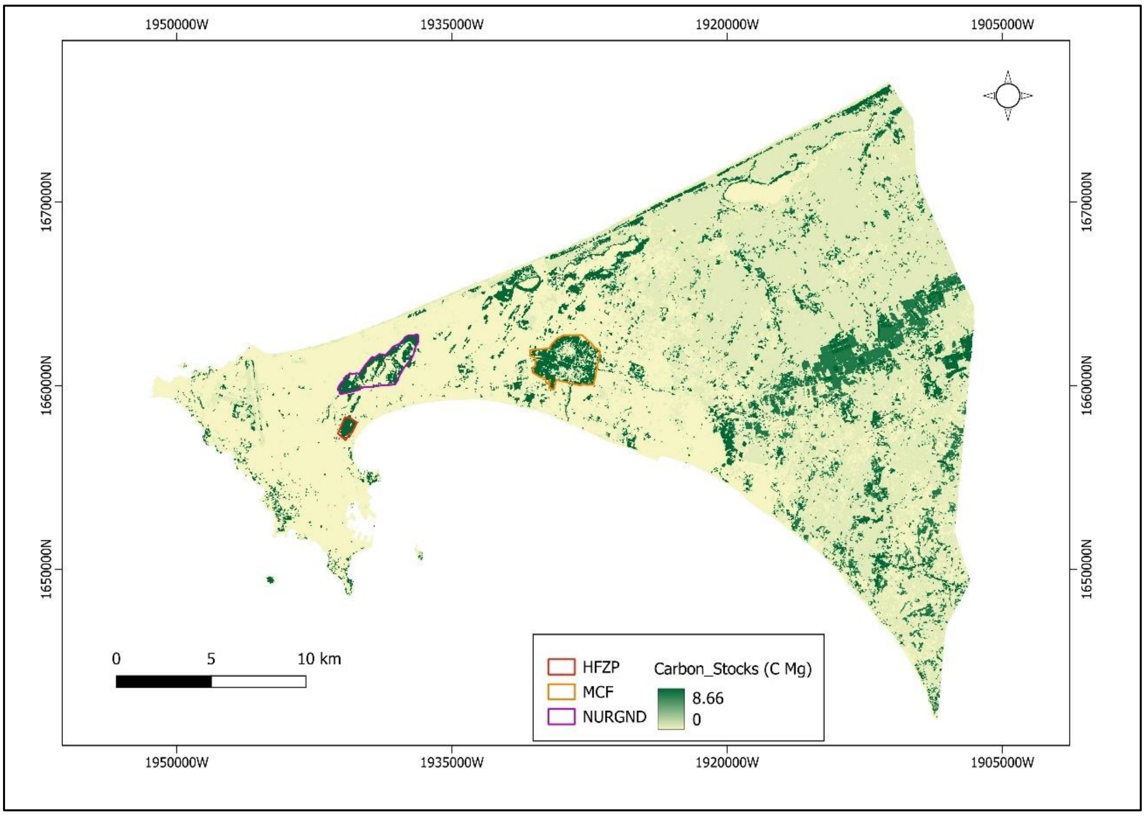

Figure 4.20: Spatial pattern of carbon stocks in Dakar in 2022

An analysis of changes in overall carbon stocks across the three selected green spaces in the Dakar administrative region reveals a significant dynamic in the amount of carbon stored between 1990 and 2022. Figure 4.21 presents the linear regression model, with years as the independent variable and carbon stocks as the dependent variable. The analysis indicates a clear negative trend, showing a statistically significant reduction in carbon stocks (p-value = 0.025) across the HFZP, the MCF, and the NURGND. The model also shows a high explanatory power, with an R^2 value of 0.95, suggesting a strong correlation between time and the decrease in carbon storage.

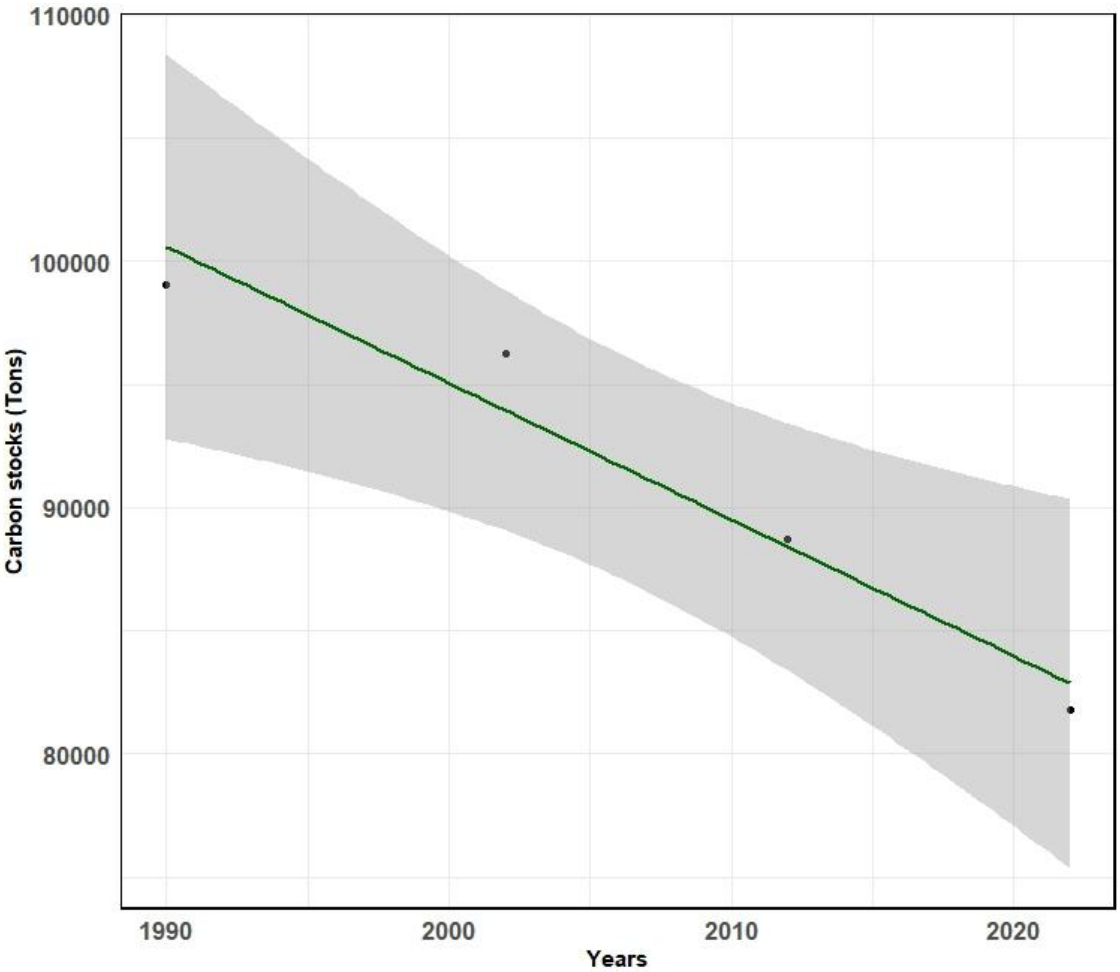

Figure 4.21: Linear regression of carbon stocks in the three major public green spaces in the Dakar region from 1990 to 2022

More specifically, the linear regression analysis conducted to assess the evolution of carbon stocks (in tons), in the park, forest, and wetland areas of the Dakar region revealed a downward trend from 1990 to 2022 (Figure 4.22), with varying levels of strength and statistically significance across the different green spaces.

In the Hann Forest and Zoological Park (HFZP), carbon stocks decreased gradually over time, with an R^2 value of 0.87 and a marginal level of significance (p-value = 0.065). the annual reduction is estimated at 8.72 tons of carbon. A similar situation was observed in the Mbao Classified Forest (MCF), where the R^2 was slightly higher at 0.88, and the p-value was 0.064, also marginally significant. The decrease here was estimated at 447.4

tons of carbon per year, making it the most substantial reduction among the three green spaces. Finally, in the Natural Urban Reserve of Great Niaye and Dependence, the trend was also negative, though with a slightly lower R^2 of 0.86 and a p-value of 0.075. Carbon losses corresponded to 98.3 tons of carbon per year.

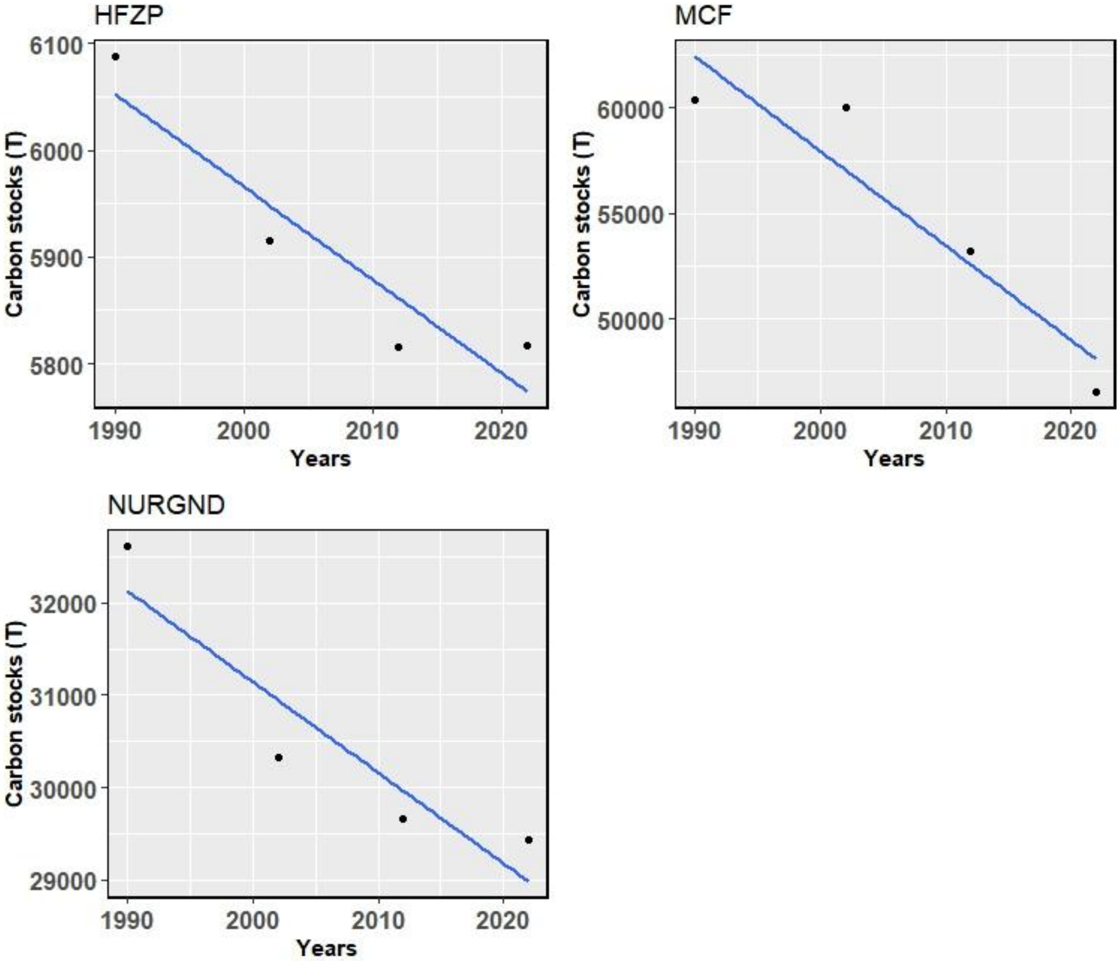

Figure 4.22: Trend evolution of the carbon stocks of each green space

Figure 4.23 illustrates the spatial distribution of carbon stocks within the three green spaces, highlighting the degradation observed over time. Table 4.7 gives the corresponding carbon quantities, which support the findings of the regression models. Indeed, the Mbao Classified Forest, which holds the largest stocks, experienced the most substantial loss from 60 360.63 tC in 1990 to 46 548.47 tC in 2022. Similarly, the Hann Forest and Zoological Park has lost from 6 087.45 tC in 1990 to 5 816.97 tC in 2022, although this reduction is less pronounced than in the forest. In the Natural Urban Reserve of Great Niaye and Dependence, the reduction was also notable from 32 610.04 tC in 1990 to 29 424.33 tC in 2022. Consequently, among the three, the park appears to be the most stable green space, showing smaller changes in carbon stocks over the observed period.

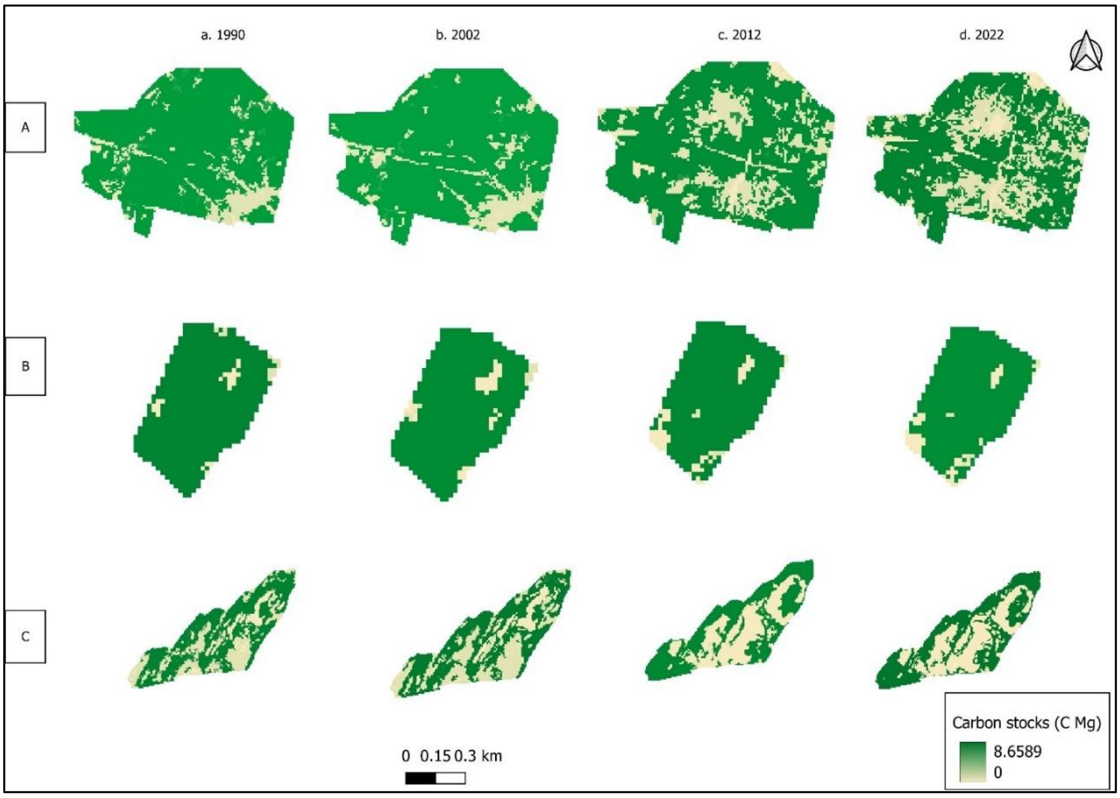

Figure 4.23: Spatial distribution of carbon stocks of MCF (A), HFZP (B), and NURGND (C) in 1990, 2002, 2012, and 2022

Table 4.7: Carbon stocks of the three major green spaces of the Dakar region from 1990 to 2022 (tC)

Green spaces	1990	2002	2012	2022
MCF	60 360.63	60 027.61	53 218.41	46 548.47
HFZP	6 087.45	5 914.96	5 816.29	5 816.97
NURGND	32 610.04	30 324.36	29 657.71	29 424.33

The results show that between 2002 and 2012 is the decade in which the most significant losses in carbon are recorded, with -7 574.53 tC lost. The period 1990 and 2002 follows with losses estimated at -6 902.64 tC, and finally, the period 2012 and 2022 in which the lowest losses are noted, with -2 791.18 tC (Figure 4.24). Figure 4.25 illustrates the losses in red and the sequestered carbon in green for the three green spaces over these years. It is noted that the Mbao Classified Forest and the Natural Urban Reserve of Great Niaye and Dependence have recorded more carbon losses than the Hann Forest and Zoological Park, particularly during the 2002 and 2012 decades, when huge quantities of carbon were released. In addition, the greatest quantities of carbon sequestered over the years were between 2002 and 2012, and the forest and the reserve sequestered more than the park, showing the few efforts made to restore these areas.

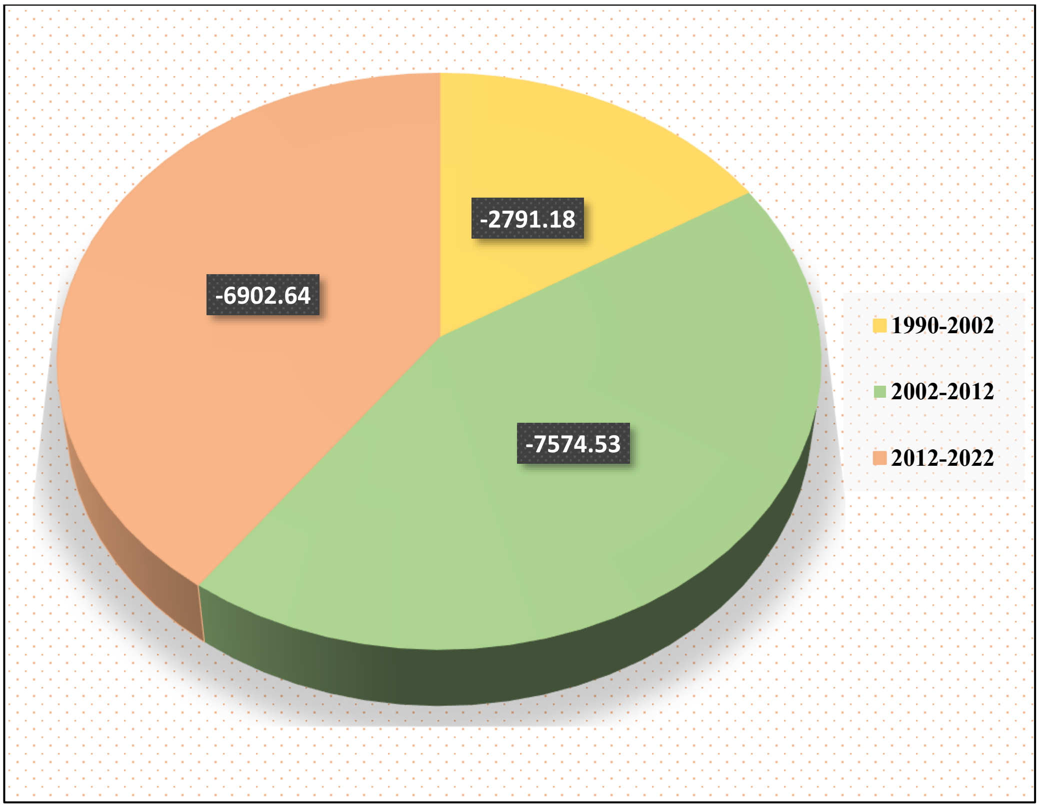

Figure 4.24: Losses in carbon stocks from 1990 to 2022 (tC)

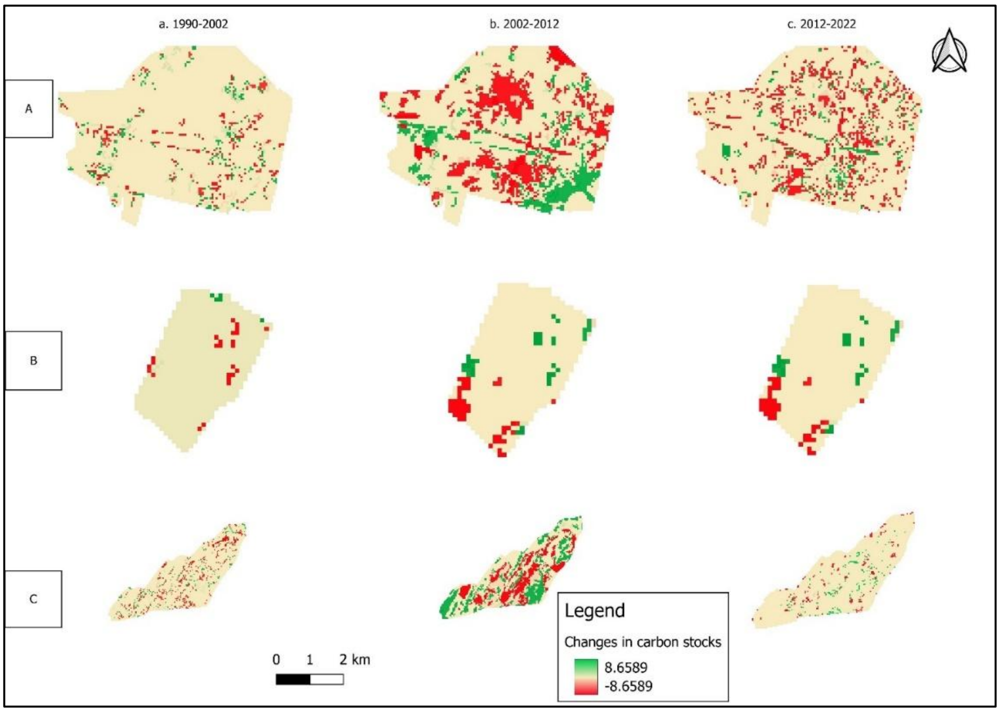

Figure 4.25: Changes in carbon stocks of MCF (A), HFZP (B), and NURGND (C) from 1990 to 2022

(b) Urban cooling capacity of green spaces

Based on shading, evapotranspiration and albedo, the InVEST urban cooling model assessed the heat mitigation capacity of the three major green spaces in the Dakar region from 1990 to 2022 over a cooling distance of 2000 m.

Overall, the results show that vegetated areas such as the Hann Forest and Zoological Park, the Mbao Classified Forest, and the Natural Urban Reserve of Great Niaye and Dependence play a crucial role in reducing heat in the Dakar region, demonstrating a relatively moderate cooling capacity of 0.39 (Figure 4.26). Additionally, air temperatures were found to be lower near and inside these green spaces, reaching 31°C compared to 33°C in areas without vegetation (Figure 4.27).

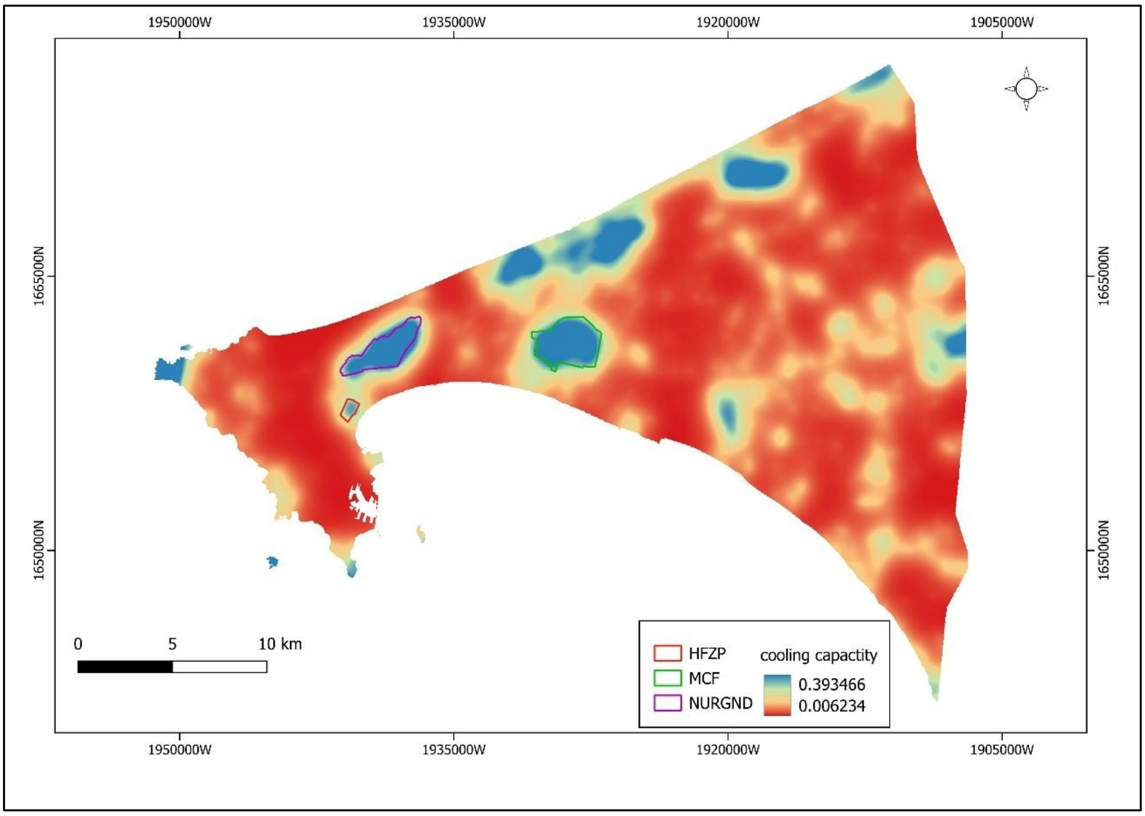

Figure 4.26: Spatial pattern of the cooling capacity in Dakar in 2022

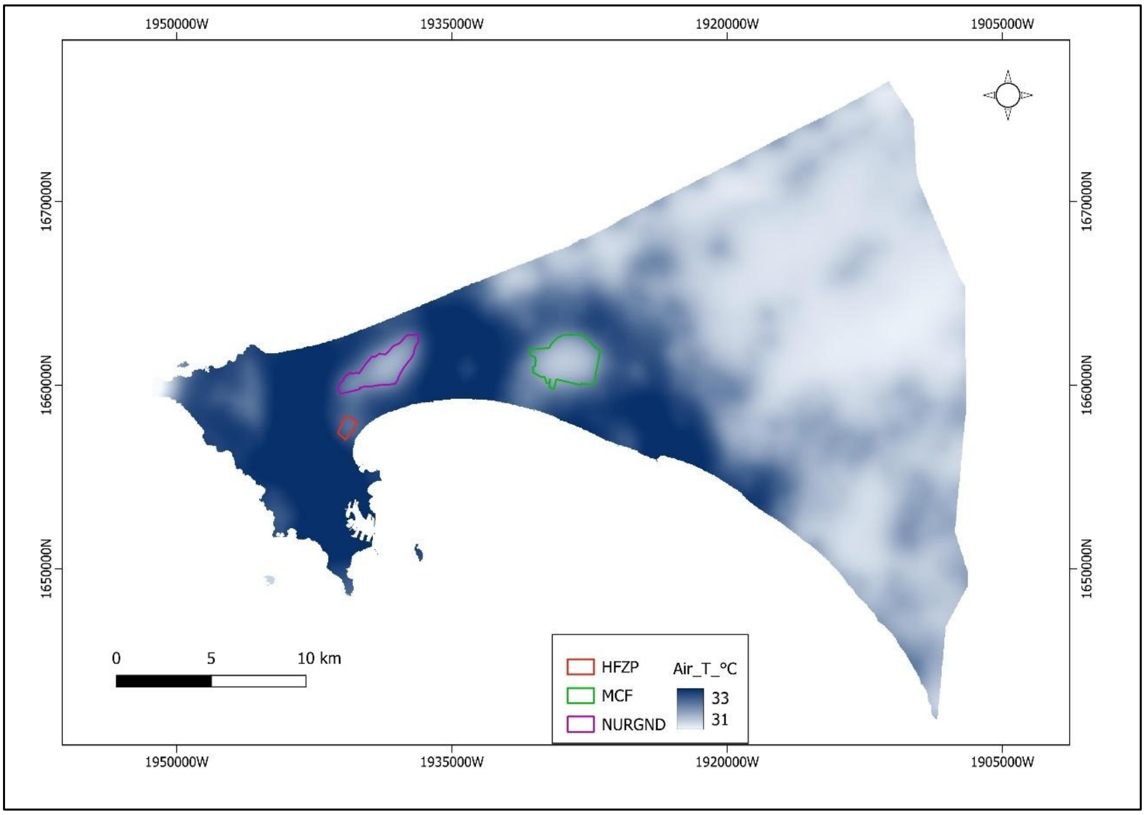

Figure 4.27: Spatial distribution of the air temperature in Dakar in 2022

Furthermore, the results show a relatively high heat mitigation index (HMI) varying from one green space to another depending on their surface area. Globally, the average heat mitigation index (HMI) ranges from 0.61 to 0.77 between 1990 and 2022. The findings indicate that the Mbao Classified Forest (MCF) has the highest HMI due to its larger surface area of 724 ha. However, the vegetation density plays a key role in this index, as in the case of the Hann Forest and Zoological Park (HFZP), which has a higher index than the Natural Urban Reserve of Great Niaye and Dependence (NURGND) despite its larger surface area of 535.38 ha.

However, linear regression models of the heat mitigation index in the three green spaces show a decreasing trend between 1990 and 2022 (Figure 4.28). Indeed, only HFZP exhibits a strong, significant, and consistent decline in the HMI, with an R^2 value of 0.99 and a statistically significant p-value of 0.001. This suggests a real loss of cooling capacity in this park. In contrast, the MCF and the NURGND both show negative trends, but with low R^2 values of 0.30 and 0.22, respectively, and high p-values of 0.449 and 0.527. This indicates that these two green spaces experience smaller reductions in cooling capacity compared to the park.

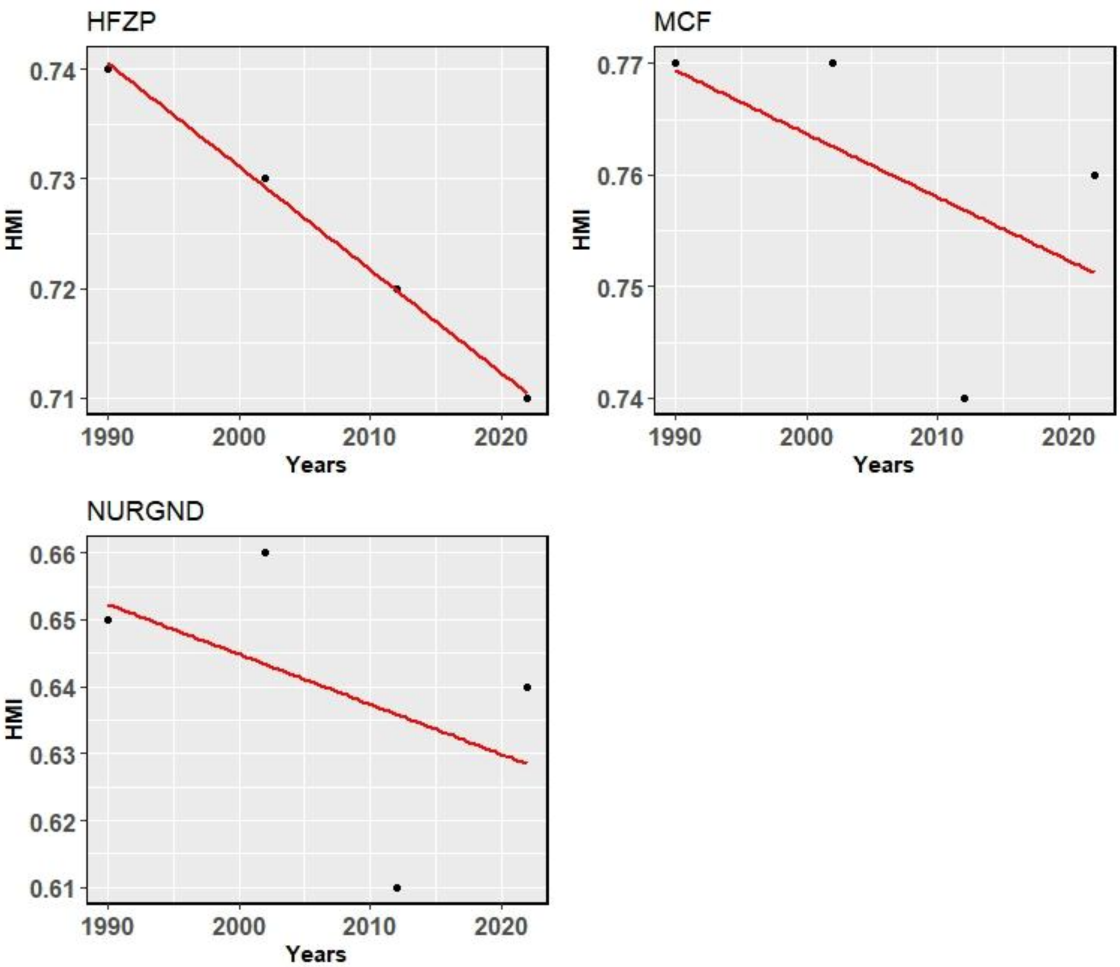

Figure 4.28: Trend evolution of the heat mitigation index of the three green spaces from 1990 to 2022

Changes are more illustrated in figures 4.29, 4.30 and 4.31, where the maximum cooling capacity of each green space, which varies between 0.81 and 0.83, is represented by the blue colour and the minimum capacity, which is between 0.22 and 0.52, represented by the red colour. The observation made is that the maximum heat mitigation index depends on the density of the vegetation. The results show that the denser the vegetation, the higher the heat mitigation index, and the more intense the blue colour. The yellow colour indicates that the vegetation is less dense, showing a decrease in the heat mitigation index. Where the vegetation is poorer or non-existent, the orange colour is intense, indicating that the heat mitigation index is very low. These are the areas where the vegetation has been destroyed for buildings or bare soil. However, contrary to what the models suggest, the spatial pattern of the park's cooling capacity showed a slight increase between 2012 and 2022. In contrast, the forest and the reserve exhibited more noticeable changes in the index, while the park appeared more stable.

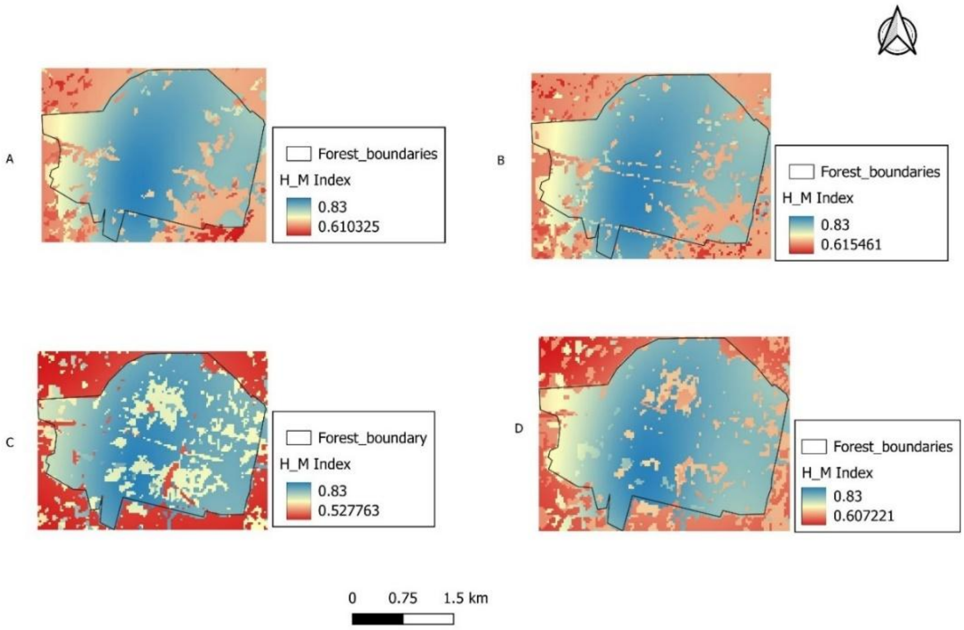

Figure 4.29: Cooling capacity of the Mbao Classified Forest of 1990 (A), 2002 (B), 2012 (C), and 2022 (D)

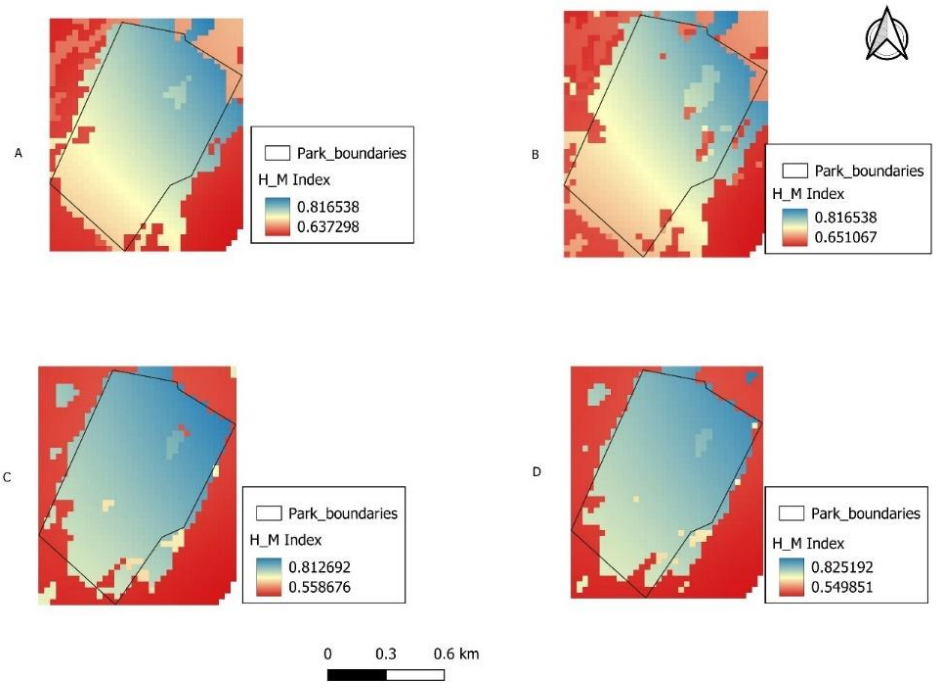

Figure 4.30: Cooling capacity of the Hann Forest and Zoological Park of 1990 (A), 2002 (B), 2012 (C), and 2022 (D)

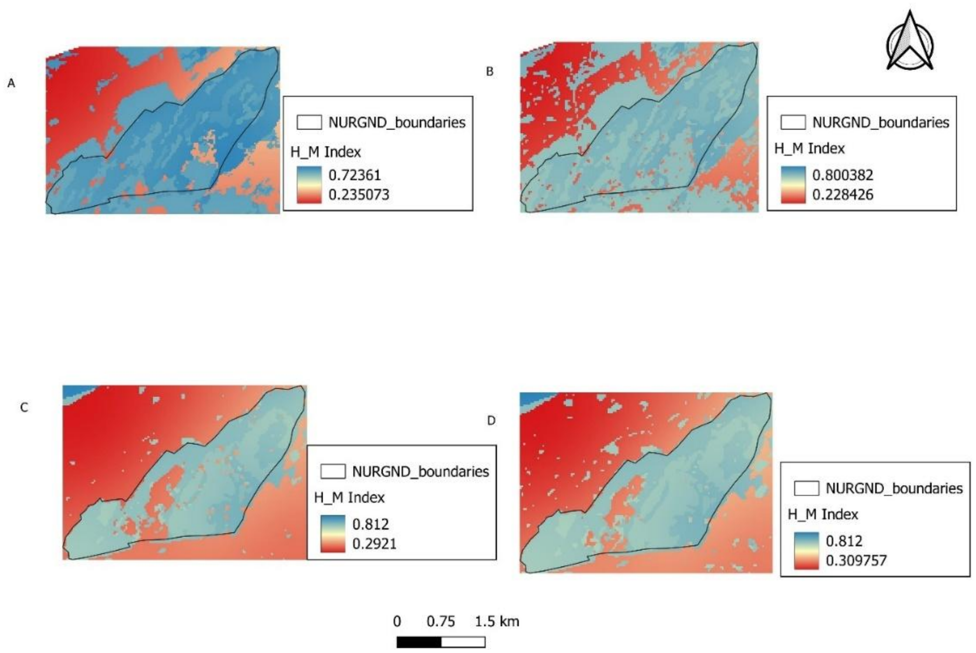

Figure 4.31: Cooling capacity of the Natural Urban Reserve of Great Niaye and Dependence of 1990 (A), 2002 (B), 2012 (C), and 2022 (D)

(c) Flood risk mitigation capacity of green spaces

The InVEST urban flood risk mitigation model was used to analyse the runoff retention capacity of the three major green spaces of Dakar to assess their contribution to flood reduction in this region between 1990 and 2022. Generally, the results indicate that green spaces significantly mitigate flooding, with a high average runoff retention capacity (Ri). Notably, the Hann Forest and Zoological Park, the Mbao Classified Forest, and the Natural Urban Reserve of Great Niaye and Dependence demonstrated strong retention performance, with a maximum Ri value of 0.98 (Figure 4.32).

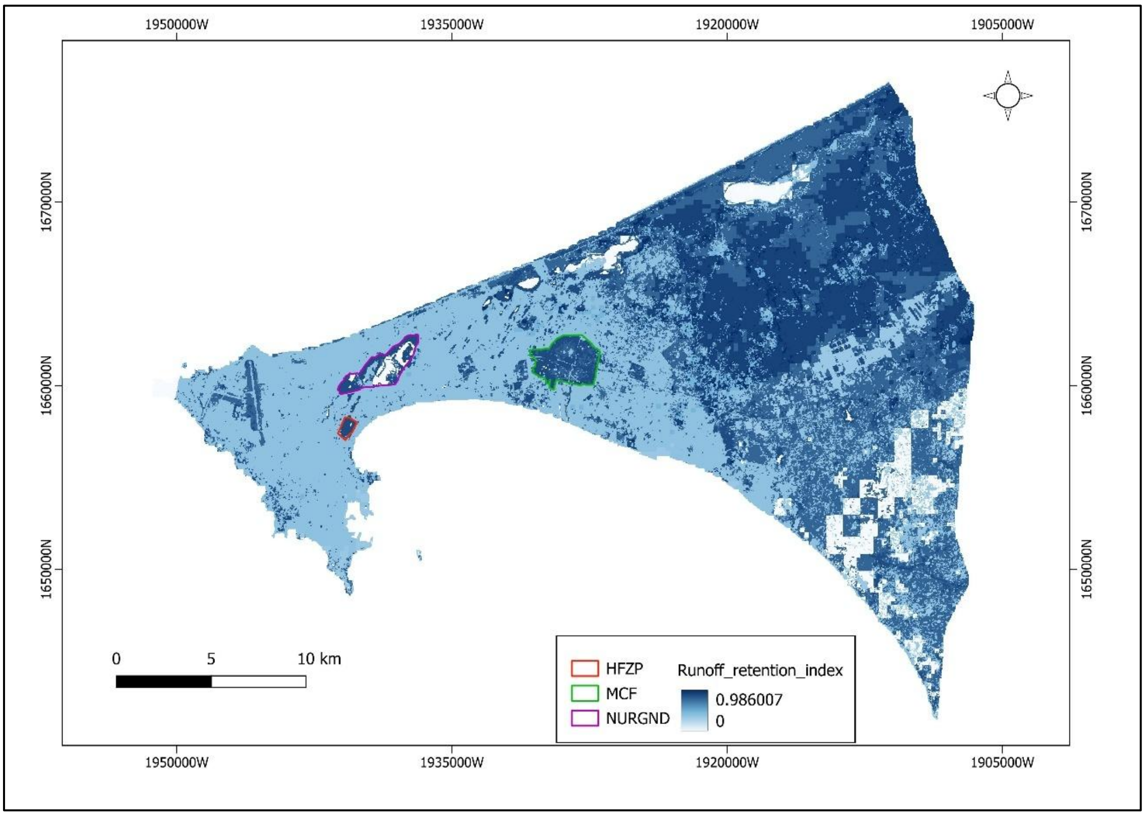

Figure 4.32: Spatial pattern of the runoff retention in Dakar in 2022

Moreover, the Ri index seems to have changed over the years in all three green spaces (Figure 4.33). The analysis of runoff retention over time across the Hann Forest and Zoological Park, the Mbao Classified Forest, and the Natural Urban Reserve of Great Niaye and Dependence reveals a general decline trend from 1990 to 2022. In the park, the model suggests a slight decrease in runoff retention, but with a weak fit ($R^2 = 0.43$) and a non-significant p-value (0.344), indicating no strong evidence of change. In the forest, a more noticeable decrease in retention is observed, with a strong model fit ($R^2 = 0.86$) and a marginally significant p-value (0.072), suggesting some decline in runoff retention, although the trend is not fully conclusive. Similarly, the reserve, which is the largest wetland, shows a notable decline with an R^2 of 0.80, but the trend is not statistically significant (p-value = 0.105), likely due to the small sample size. Overall, while all models suggest a decrease in runoff retention, the forest and the wetland show stronger trends.

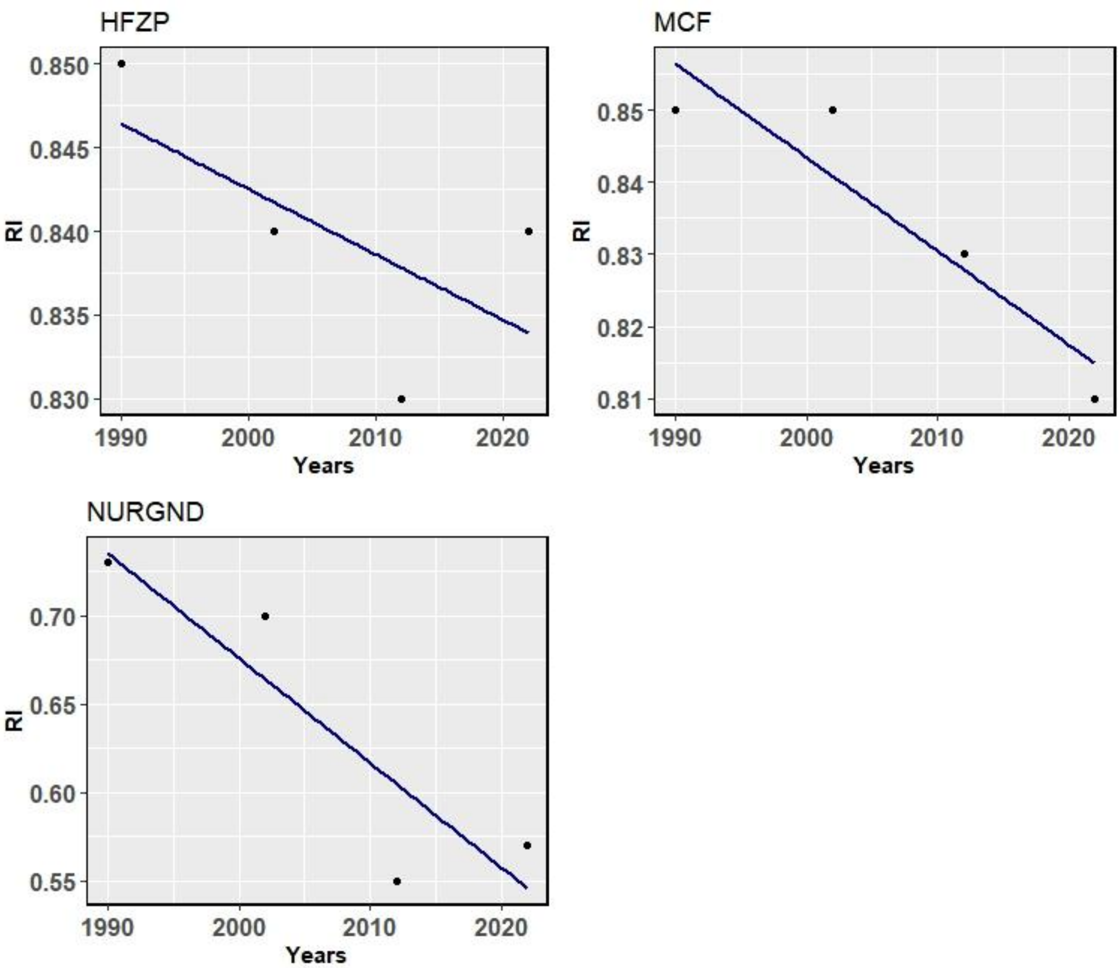

Figure 4.33: Evolution of the average runoff retention values (Ri) of the three green spaces

Figures 4.34, 4.35 and 4.36 show the volumes of water retained by these green spaces. The results reveal that the surface area of the green space plays a key role. The larger the surface area, the higher the volumes retained. This is why the Mbao Classified Forest, which has the largest surface area (724 ha), retains more water, with 618 457.19 m^3 of rainwater received in 1990 and 619 075.38 m^3 in 2002. Thus, in 2012, a reduction of the volumes retained was observed, with 601 233.13 in 2012 to 585 947.75 m^3 in 2022, still demonstrating the degrading state of the forest over the years. The NURGND is the second largest green space, with 537.38 ha, and is the second rainwater collector after the forest. In 1990, the reserve received a quantity of 391 075.88 m^3 of rainwater. Like in the forest, the volumes retained in the reserve also reduced between 2002 and 2012, with 375 695.19 and 295 939.38 m^3 respectively. Furthermore, a slight increase was noted in 2022, with 301 99.91 m^3 of water collected. The HFZP, despite its smaller surface area (66.71 ha), receives important quantities of rainwater due to its geographic location. Indeed, the park is located on a swamp, which means that huge volumes of water flow into this green space with 56 752.07 in 1990, 56 383.49 in 2002, 55 747.70 in 2012, and 55 783.59 m^3 in 2022. Like in the forest and the reserve, a downward trend is also noted in the park.

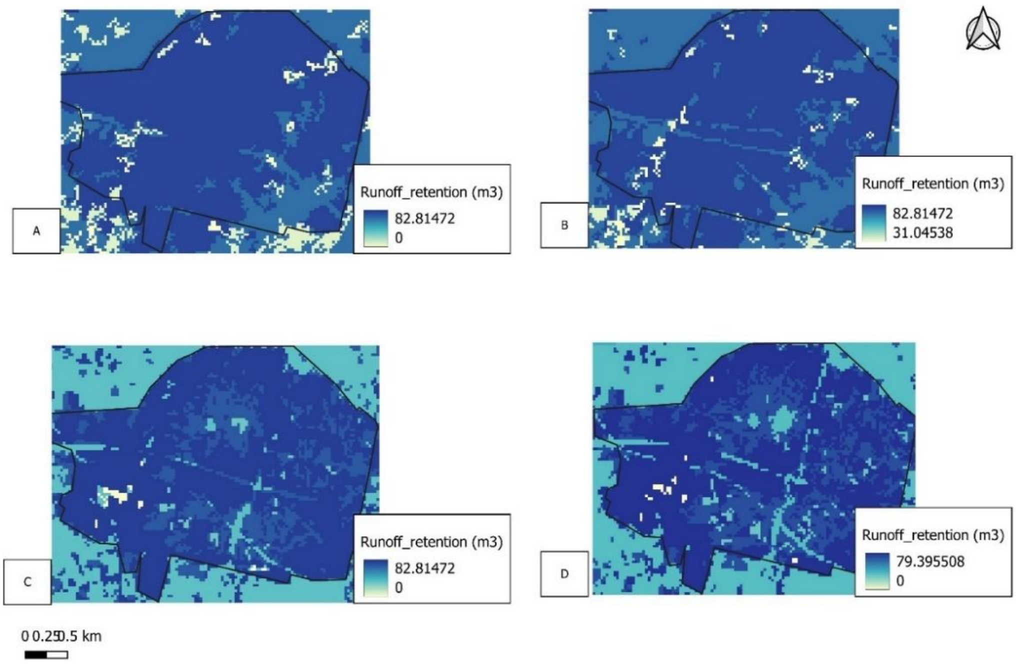

Figure 4.34: Runoff retention of the Mbao Classified Forest of 1990 (A), 2002 (B), 2012 (C) and 2022 (D)

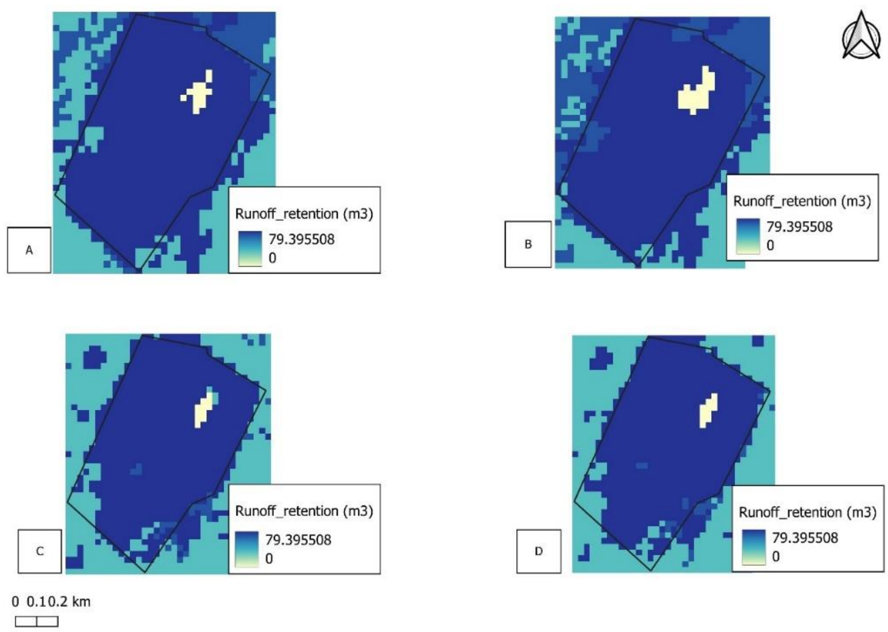

Figure 4.35: Runoff retention of the Hann Forest and Zoological Park of 1990 (A), 2002 (B), 2012 (C) and 2022 (D)

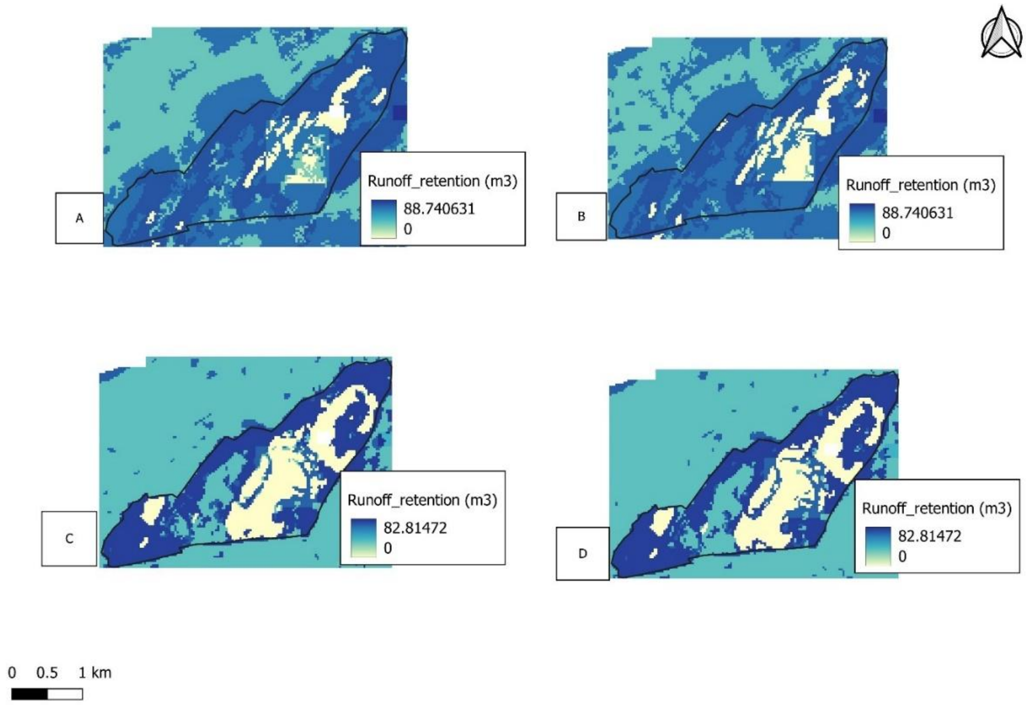

Figure 4.36: Runoff retention of the Natural Urban Reserve of Great Niaye and Dependence of 1990 (A), 2002 (B), 2012 (C) and 2022 (D)

4.1.3.2 Relationship between the vegetation cover of the three green spaces and ecosystem services

The impact of decreased vegetation cover on the provision of ecosystem services such as carbon sequestration, urban heat mitigation and flood risk mitigation was assessed in Dakar's three major green spaces using Spearman's rank correlation. This method has been used to analyse the relationships between vegetation cover and ecosystem services to determine whether vegetation is increasing or decreasing, the carbon stocks, heat mitigation, and flood mitigation are also changing. In the MCF, the results revealed a strong relationship between vegetation cover ecosystem services provision with Spearman's rho equal to 0.8, 0.73 and 0.94 for carbon stocks, heat mitigation index and flood risk mitigation, respectively (Figure 4.37). Specifically, a reduction in vegetation cover was associated with a decline in forest carbon stocks, a decrease in the heat mitigation index and a reduction in runoff retention capacity. Moreover, for ecosystem services such as carbon sequestration and heat mitigation, the relationship with the reduction in vegetation cover is not statistically significant, with p-values of 0.33 and 0.26, which are greater than 0.05. In contrast, the relationship with the reduction in flood risk has a p-value of 0.05, which is equal to 0.05. This suggests that other factors, aside from the reduction in vegetation cover, contribute to the decline in ecosystem services in the forest.

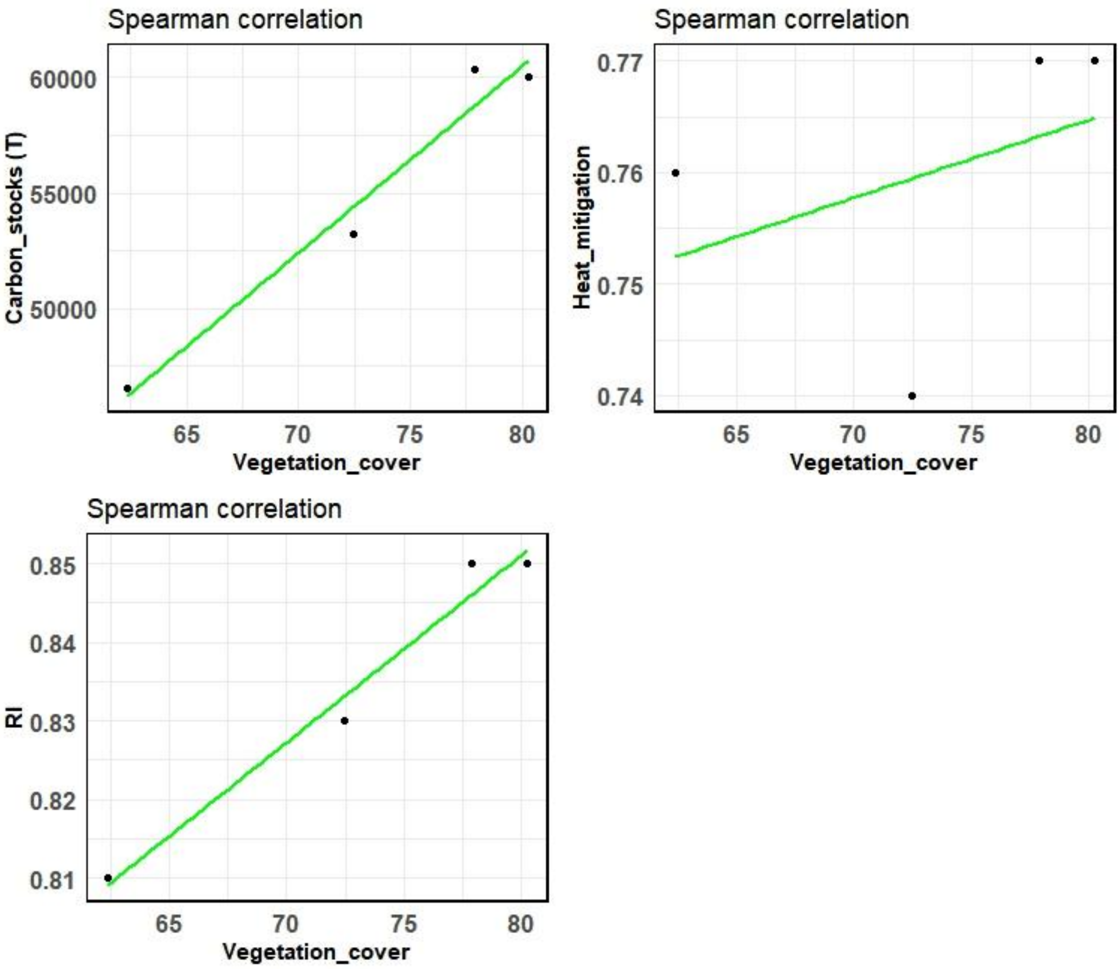

Figure 4.37: Relationship between vegetation cover and ecosystem services in the MCF

In contrast, in the HFZP, a negative correlation was observed with Spearman's rho values of -0.74 for carbon sequestration and heat mitigation, and -0.5 for flood mitigation services (Figure 4.38). This means that as the vegetation cover increases in the park, the three ecosystem services continue to decrease. Furthermore, for all three ecosystem services, the p-values are greater than 0.05, with 0.26 for carbon sequestration and heat mitigation and 0.5 for flood risk reduction. Additionally, the Spearman curves show a slight downward trend, indicating that the relationships are not strongly negative. In other words, the observed changes in vegetation cover in this park over time appear to have a limited influence on the reduction in ecosystem services, as evidenced more clearly by the park's capacity to retain runoff.

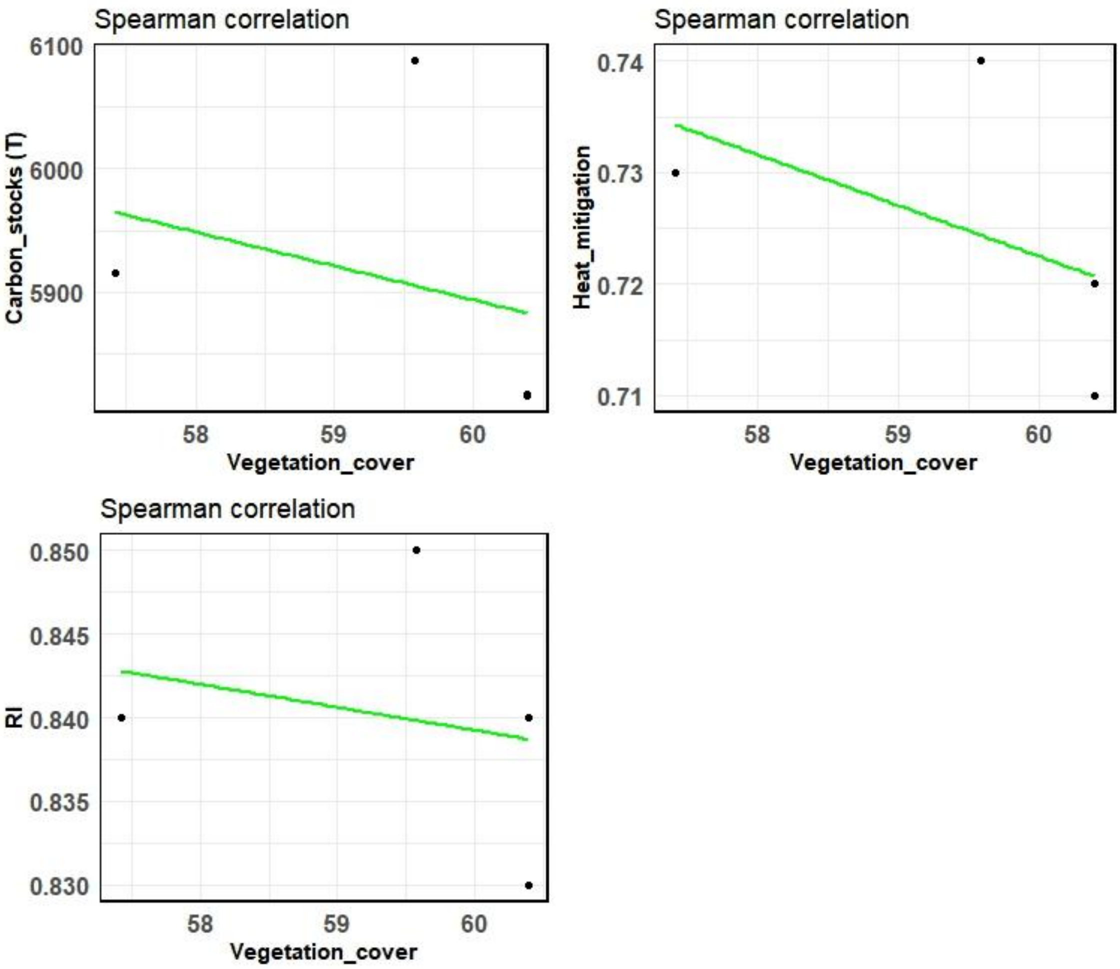

Figure 4.38: Relationship between vegetation cover and ecosystem services in the HFZP

The same negative correlation was observed in the NURGND, with Spearman's rho values of -0.8 for carbon sequestration and heat mitigation index, and -0.6 for flood risk mitigation (Figure 4.39), accompanied by a statistically insignificant relationship with p-values of 0.33 and 0.42, respectively. The Spearman curves for the carbon and flood reduction index appear to be more pronounced, showing a sharper decline compared to the heat mitigation index, which shows a slight negative trend. This indicates that an increase in vegetation cover in the wetland does not significantly influence the decrease in carbon stocks and flood reduction, but it does seem to have a slight impact on heat reduction.

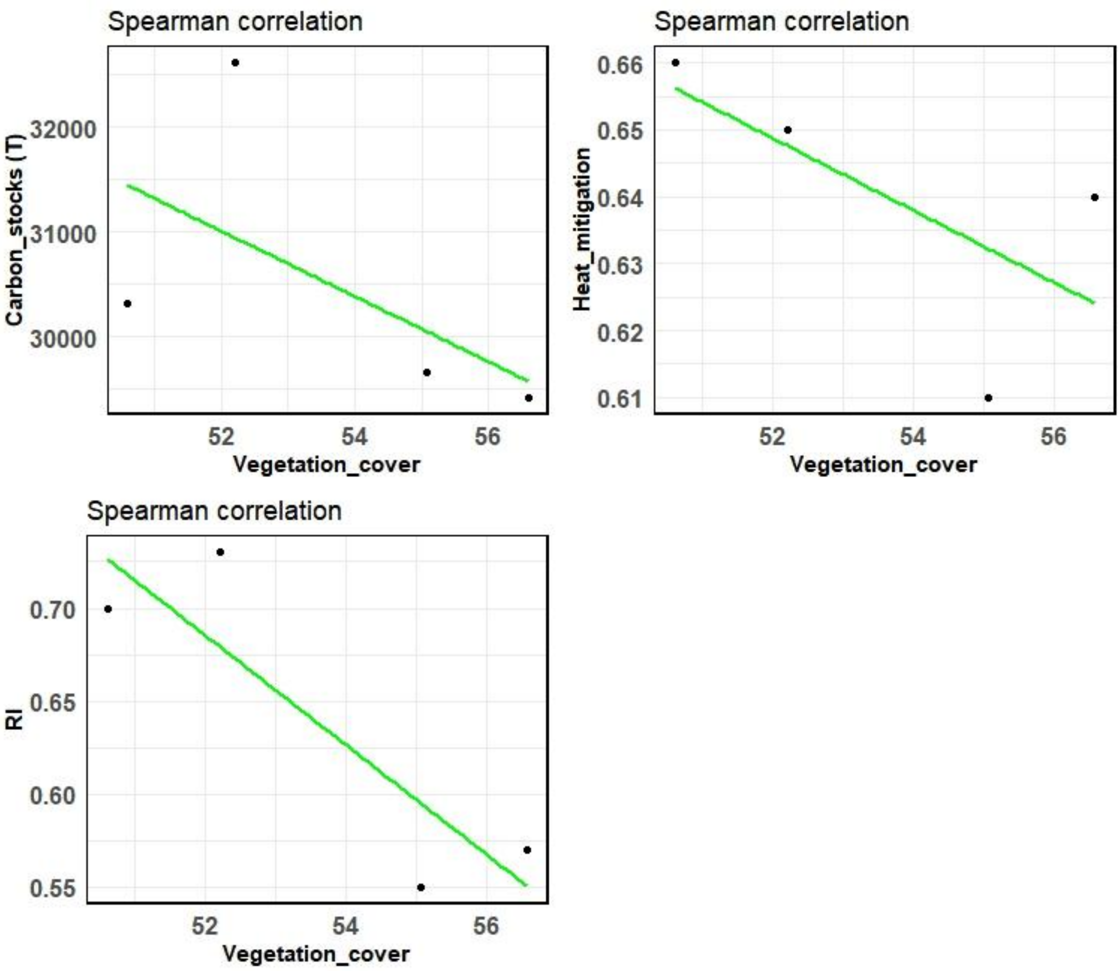

Figure 4.39: Relationship between vegetation cover and ecosystem services in the NURGND

4.1.4 Land suitability analysis for future public green space development in the Dakar region

4.1.4.1 Suitability analysis of the criteria

(a) Suitability of land use and land cover

Land use and land cover are composed of five classes such as green space, water, agricultural land, bare land, and built-up area. 45.28 % of the area of Dakar is classified as highly suitable (S1) and consists of bare land. The built-up area is classified as moderately suitable (S2) and represents 39.32 % of the total area. Green space is less suitable (S3) with 9.54 %, and water and agricultural land are classified as not suitable (N1) (Figure 4.40 and Table 4.8). The department of Rufisque has a wider high suitability land than the others, which means that there is more land available in this area for green spaces.

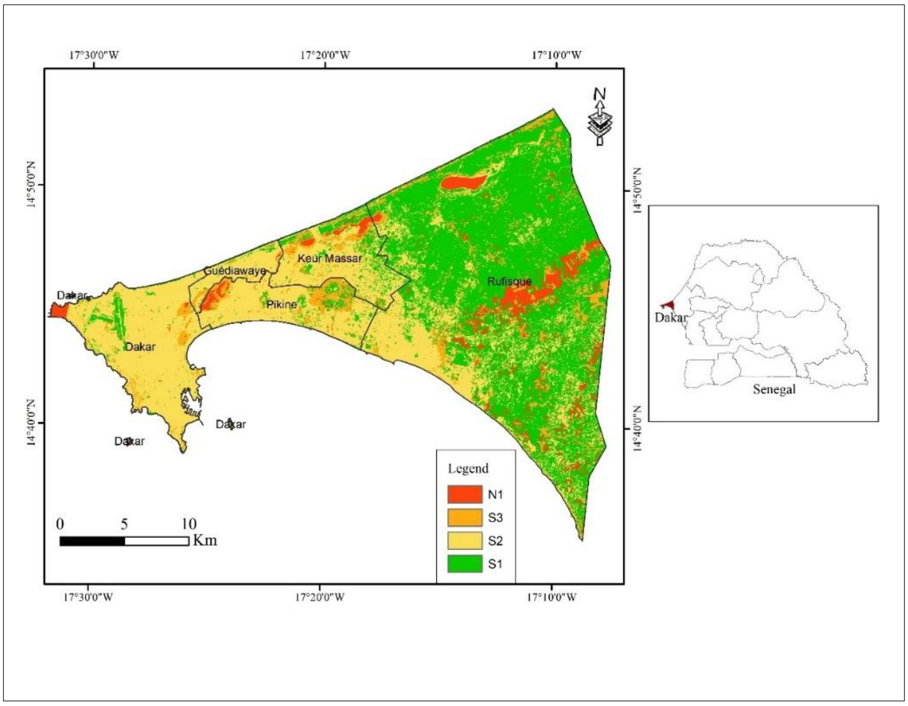

Figure 4.40: Reclassified land use and land cover

Table 4.8: Reclassified LULC and area coverage of suitability level

LULC types	Level of suitability	Value	Area (km^2)	Percentage (%)
Bare land	S1	5	245.42	45.28
Built-up	S2	4	213.11	39.32
Green space	S3	3	51.71	9.54
Water/Agriculture land	N1	2	31.78	5.86

(b) Suitability of soil types

The Dakar region is divided into four soil types such as sandy loam, sandy clay loam, clay loam, and sandy clay. Sandy loam is considered highly suitable (S1) for green spaces in 31.41 % of the area, due to its capacity to retain water and allow plants to grow, and is present in the five departments, with more in the department of Rufisque. Sandy clay, which is the most widespread soil type, is classified as moderately suitable (S2) with 66.29 %. Clay loam and sandy clay are classified as less suitable (S3) and not suitable (N1), respectively. They are the least represented in the Dakar region (Figure 4.41 and Table 4.9).

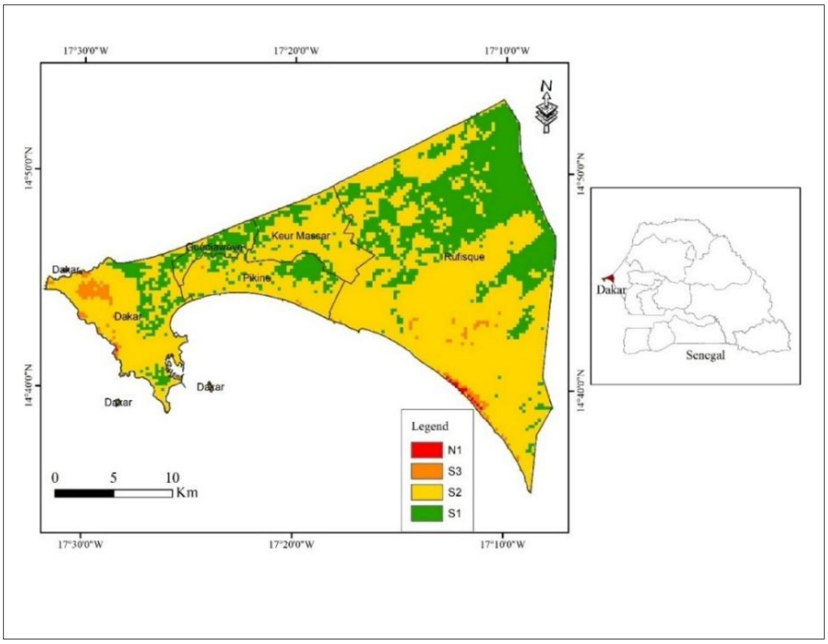

Figure 4.41: Reclassified soil types

Table 4.9: Reclassified soil types and area coverage of suitability level

Soil types	Level of suitability	Value	Area (km^2)	Percentage (%)
Sandy loam	S1	5	170.19	31.41
Sandy clay loam	S2	4	359.24	66.29
Clay loam	S3	3	11.66	2.15
Sandy clay	N1	2	0.82	0.15

(c) Suitability of slope

The Dakar region is essentially a flat area with little elevation. The lower the slope, the more suitable the area. A site with a slope of less than 5 % is considered highly suitable (S1) and represents 96.84 % of the total area of Dakar. With a slope between 5 and 10 %, it is a moderately suitable site (S2) with 2.77 %. Between 10 and 15 % and greater than 15 % are classified as less suitable (S3) and not suitable (N1) respectively (Figure 4.42 and Table 4.10).

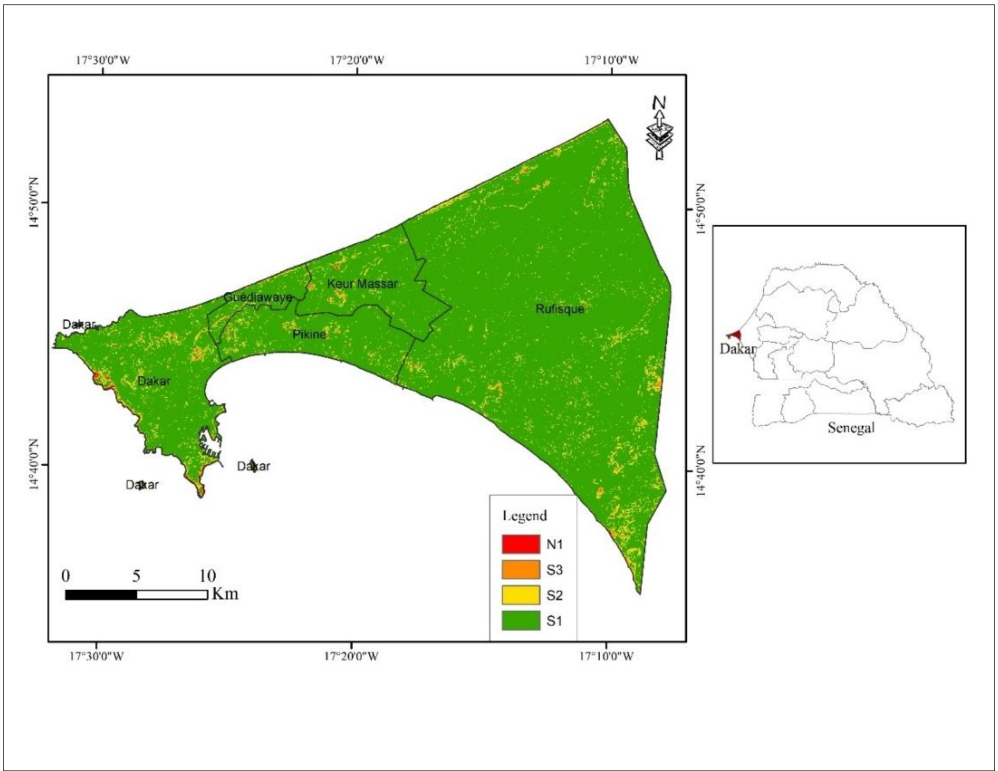

Figure 4.42: Reclassified slope

Table 4.10: Reclassified slope and area coverage of suitability level

Slope (%)	Level of suitability	Value	Area (km^2)	Percentage (%)
< 5	S1	5	524.87	96.84
5 - 10	S2	4	15.01	2.77
10 - 15	S3	3	1.54	0.28
>15	N1	2	0.57	0.1

(d) Suitability of population density

The density of the population is an important criterion in the design of public green spaces. An area with a higher population density with more than 2000 inhabitants per square kilometre is classified as highly suitable (S1) with 44.12 % of the area. The highly suitable areas cover the entire departments of Dakar, Guediawaye, Pikine, and Keur Massar, as well as a small portion of Rufisque. The density between 1000 and 2000 is considered medium and classified as moderately suitable (S3) with 22 % of the area. Low density areas between 100 and 1000 are less suitable. These two latter classes are only found in the department of Rufisque (Figure 4.43 and Table 4.11).

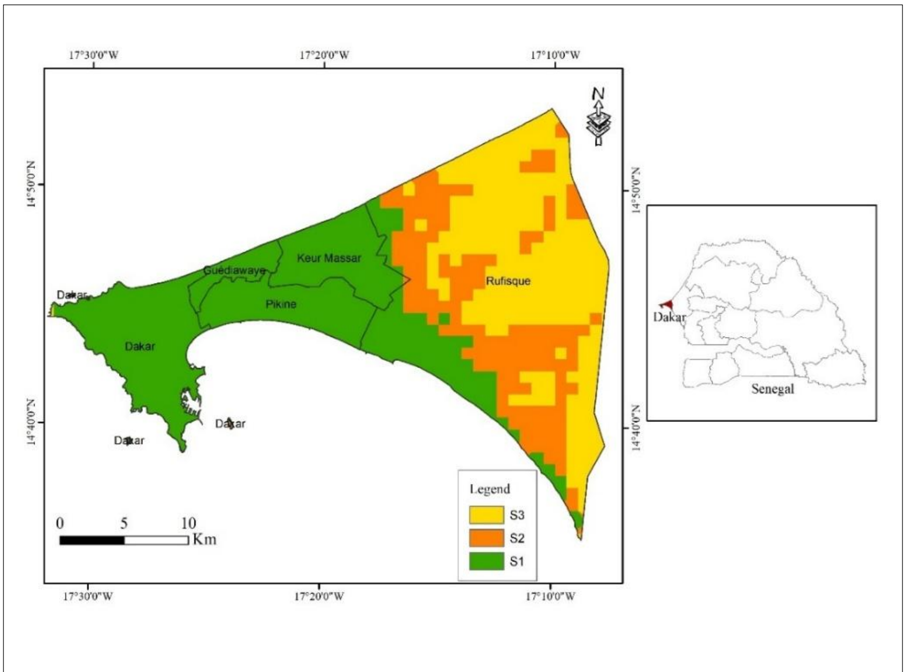

Figure 4.43: Reclassified density of population

Table 4.11: Reclassified density of population and area coverage of suitability level

Density of population	Level of suitability	Value	Area (km^2)	Percentage (%)
High	S1	5	237.82	44.12
Medium	S2	4	121.46	22.53
Low	S3	3	179.71	33.34

(e) Distance from the existing public green spaces

The proximity of existing green spaces is also considered an important parameter for future developments. In this sense, a distance greater than 6 km is classified as highly suitable (S1) and constitutes 36.81 % of the surface area. Between 4 and 6 km and 2 and 4 km are moderately suitable (S2) with 13.70 % and less suitable (S3) with 18.16 % of the area. A distance of less than 2 km is considered not suitable (N1) and represents the largest proportion with 31.33 % of the area. Only the department of Rufisque has highly and moderately suitable areas, whereas the other departments are almost entirely not suitable. This demonstrates the absence of green spaces in Rufisque (Figure 4.44 and Table 4.12).

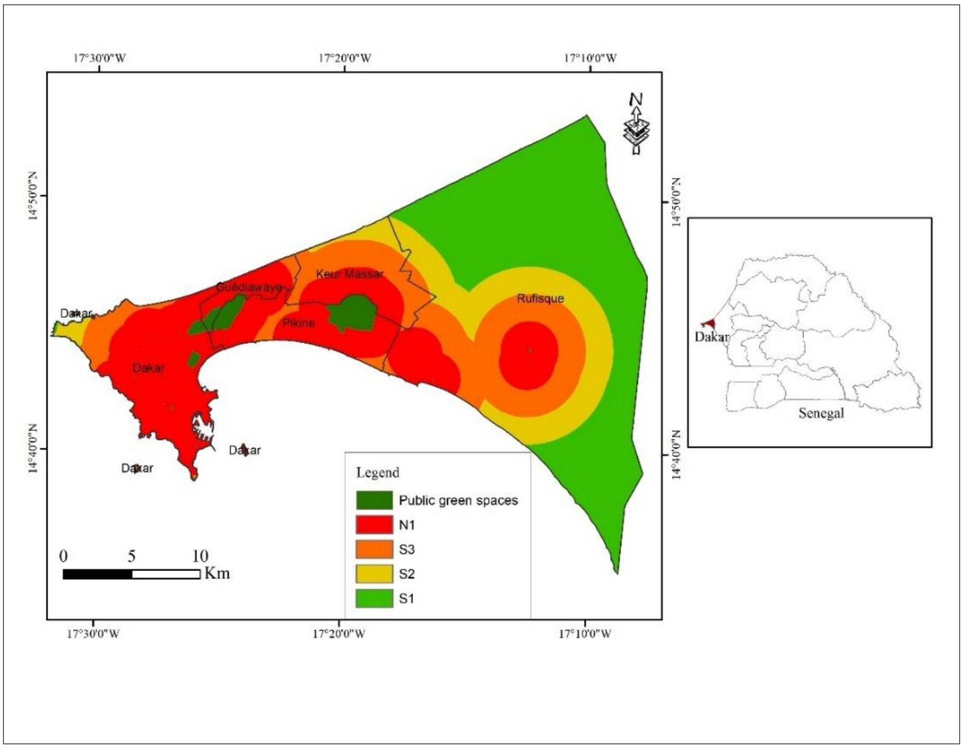

Figure 4.44: Reclassified distance from the existing public green spaces

Table 4.12: Reclassified distance from green spaces and area coverage of suitability level

Distance (km)	Level of suitability	Value	Area (km^2)	Percentage (%)
> 6	S1	5	199.49	36.81
4 - 6	S2	4	74.28	13.7
2 - 4	S3	3	98.45	18.16
< 2	N1	2	169.79	31.33

(f) Distance from the main roads

The accessibility of green spaces assessed through the proximity of roads is also important for future developments. The closer the green spaces are to the roads, the more suitable the location. A distance of less than 1 km is classified as highly suitable (S1) with 41.41 % of the area. From 1 km, the site is moderately suitable (S2) with 22.55 %. Distances of 2 km and greater than 2 km are considered less suitable (S3) and not suitable (N1) respectively (Figure 4.45 and Table 4.13). Due to the higher density of roads in the departments of Dakar, Pikine, and Guediawaye, these three departments have the largest areas of suitable sites.

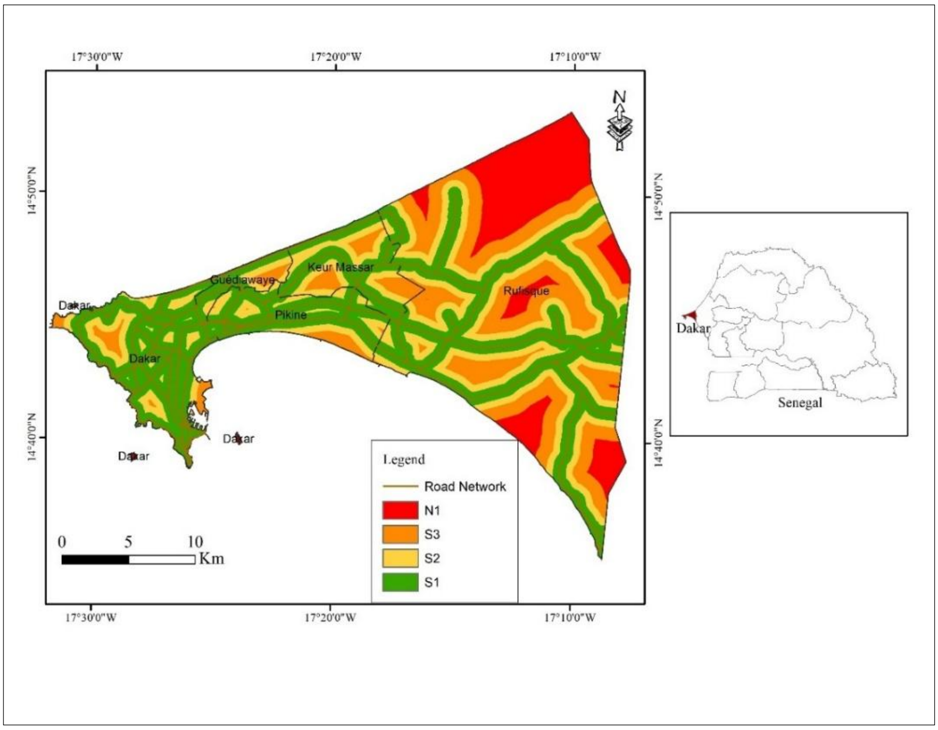

Figure 4.45: Reclassified distance from roads

Table 4.13: Reclassified distance from roads and area coverage of suitability level

Distance (km)	Classes	Value	Area (km^2)	Percentage (%)
< 1	S1	5	224.45	41.41
1	S2	4	122.22	22.55
2	S3	3	116.26	21.45
> 2	N1	2	79.08	14.59

4.1.4.2 Weight of the criteria

Table 4.14 presents the weights of the different criteria obtained after normalising the pairwise comparison matrix (Appendix D). Land use and land cover have the highest weight with 0.36 (36 %), followed by the proximity to the existing green spaces with 0.25 (25 %), the density of population with 0.19 (19 %), and the proximity to roads with 0.09 (9 %). Soil types and slope record the smaller weights with 0.05 and 0.06 respectively.

To validate the AHP analysis, the consistency ratio (CR) was calculated, which equals 0.09, less than 0.1, indicating that the process can proceed.

Table 4.14: Computation of the weight of the criteria

Criteria	LULC	PD	PGS	ST	Sl	PR	Weight	λ	CI	RI	CR
LULC	0.43	0.48	0.44	0.25	0.29	0.29	0.36	6.39	0.11	1.24	0.09
PD	0.14	0.24	0.3	0.25	0.29	0.29	0.19	6.54			
PGS	0.14	0.12	0.15	0.2	0.23	0.29	0.25	6.49			
ST	0.09	0.05	0.04	0.05	0.03	0.02	0.05	6.04			
Sl	0.09	0.05	0.04	0.1	0.06	0.04	0.06	6.04			
PR	0.11	0.06	0.04	0.15	0.11	0.07	0.09	6.09			

LULC= land use and land cover; PD= population density; PGS= proximity to green spaces; ST= soil types; Sl=slope; PR= proximity to roads; CI= consistency index; RI= random inconsistency; CR= consistency ratio

4.1.4.3 Overall suitability areas

The criteria, along with their respective weights, were overlaid to generate the final suitability map for green spaces in the Dakar region. The results of the multicriteria analysis reveal four main categories such as highly suitable (S1), moderately suitable (S2), less suitable (S3), and not suitable (N1) areas (Figure 4.46). The analysis shows that more than 90 % of the region is suitable for green spaces. The moderately suitable category is the most widespread, covering 76.08 % (407.70 km^2) of the total area, indicating that a large portion of the Dakar region is moderately favourable for the development of green spaces (Table 4.15). Additionally, the western part of the region, along the centre to the eastern parts, including the departments of Dakar, Guediawaye, and Pikine, is predominantly moderately suitable. The highly suitable category accounts for 14.75 % (79.06 km^2) and is primarily located in the northern, eastern, and southern parts, covering the departments of Rufisque and Keur Massar. The less suitable and not suitable categories cover only 9.16 and 0.02 % of space, respectively. The not suitable areas are relatively scattered across the Dakar region and are more commonly found in areas with existing green spaces, water, or agricultural land. Conversely, the not suitable category is virtually absent across the region.

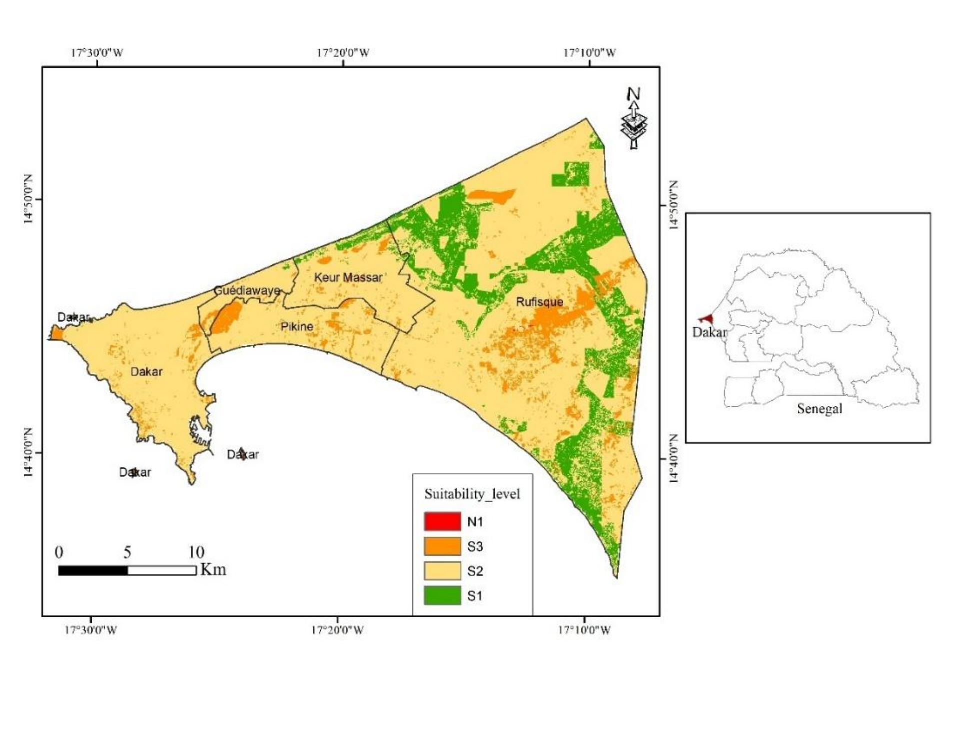

Figure 4.46: Final suitability map of the Dakar region

Table 4.15: Area of suitable sites for green spaces

Suitability level	value	Area (km^2)	Percentage (%)
Highly suitable	5	79.06	14.75
Moderately suitable	4	407.7	76.08
Less suitable	3	49.07	9.16
Not suitable	2	0.08	0.02

4.2 Discussion

4.2.1 Typology and characteristics of public green spaces

The analysis partially confirms the initial hypothesis. While a relatively large number of Public Green Spaces (PGS) exist in the Dakar region, their high level of diversity was not confirmed by the results. However, the hypothesis regarding the unequal distribution of PGS and low density and coverage across the city is supported. In addition, the low green space to inhabitant ratio was confirmed, and the overall quality of these spaces was found to be poor.

The diversity indices suggest a low level of PGS types diversity, with over 10 types identified in the region. This is particularly noteworthy for a dynamic city like Dakar. Moreover, the Pielou index indicates a dominance of certain green spaces over others, with approximately five types predominating. For instance, accompanying green spaces and informal green spaces are more present than parks and public gardens. These green spaces not only serve ecological functions but also significantly contribute to improving the quality of life for city dwellers, considering that Dakar houses over 20 % of Senegal's total population. This result differs from that found by Tine *et al.* (2021) in the same area, which did not include public gardens and parks in their identification. The findings of this study align with those discovered in Benin, exhibiting relatively similar types of PGS with a smaller number (Amontcha *et al.*, 2017). Moreover, Dakar, Senegal, has a higher number of PGS types than Kumasi, Ghana, which has eight PGS types (Nero, 2017).

The uneven distribution of public green spaces in the Dakar region is evident from the relatively high Gini coefficient and the Lorenz curve that deviates significantly from the equality curve. This coefficient indicates that green spaces in Dakar are moderately distributed, with a significant concentration in certain departments compared to others. This situation is not unique to Dakar but is similar to many other cities, such as South

Africa, where green spaces are often unevenly distributed (Matthew McConnachie and Shackleton, 2010). Similarly, in Warsaw, the capital of Poland, the majority of green spaces are located in the centre of the city, despite their high coverage level for 25 % of the city's landmass (Bielecka *et al.*, 2018).

In the case of Dakar, the unequal distribution of public green spaces can be attributed to the fact that most public institutions, including schools, the main university of Dakar, and government ministries, are situated in the department of Dakar. Moreover, the efforts made by Dakar City Hall and the Direction of Urban Landscape and Public Spaces have played a crucial role in this regard. Additionally, the department of Dakar, comprising predominantly attractive districts such as Plateau, Fann Residence, Sacre-Coeur, and Mermoz (which is often considered the centre of Dakar), is better served by green spaces compared to other areas located in the periphery, commonly referred to as the Dakar suburbs. This coincides with a study conducted in Shanghai by Shen *et al.* (2017), which highlights other reasons, such as the greater accessibility of PGS in neighbourhoods inhabited by high-income individuals compared to middle-class individuals. Additionally, it notes that unemployed individuals have lower access to green spaces. Elsewhere in the Netherlands, Vries *et al.* (2020) have also confirmed that green spaces are more common in neighbourhoods inhabited by wealthy individuals, while poorer communities have limited access to these recreational areas.

Despite the numerous benefits that green spaces provide to urban residents, unequal access to these areas in the Dakar region raises concerns about environmental justice, similar to patterns observed in China, due to historical urban development, high residential density, and rapid urbanisation rates (Wolch *et al.*, 2014).

The study revealed a low density of PGS (2 green spaces per square kilometre) in the Dakar region, coupled with a low coverage of these spaces (3.6%). Consequently, due to the high demand for housing and infrastructure development, the existing natural spaces have completely vanished (Dieng and Keita, 2017). This same situation is found in Cairo, Egypt, where Aly and Dimitrijevic (2022) state that the city has a limited number of green spaces, with a significant loss over the years due to development projects. Among the departments in the Dakar region, the Dakar department boasts the highest population density, while others, such as Rufisque, have low or zero densities. In contrast to the coverage rate of PGS, the Pikine department takes the top spot with the highest due to the presence of a forest and a significant portion of the wetland commonly called "Technopole". This stands in stark contrast to the Dakar department, which features small green spaces, rarely exceeding five hectares in size.

The green space ratio calculated in this study reveals that the Dakar region falls significantly short in terms of public green spaces, with an average of 4.69 square meters per inhabitant, justifying the low priority given to public green spaces in living environment policies and the inadequate conservation and preservation of these spaces. This finding is significantly lower than the one discovered by Nero, (2017) in Kumasi, Ghana, where the green space ratio per individual is 25 m^2. Thus, the low ratio can be attributed to the limited coverage of PGS. In fact, there's a strong correlation between the ratio and the coverage rate (p-value of 0.025). The lower the coverage rate, the lower the ratio. This is corroborated by the results, with the Pikine department having the highest ratio because of its high PGS coverage. Conversely, the Dakar department, with its low PGS coverage rate and large population size, has the lowest ratio of PGS.

The NDVI index has been used to assess the quality of public green spaces. Generally, NDVI values range from -1 to 1. Values between -1 and 0 indicate the absence of vegetation, while values above 0 suggest the presence of vegetation (Zaitunah *et al.*, 2022). The NDVI values obtained in this study contradict the initial hypothesis, which suggested that low NDVI values would be associated with PGS. In fact, the NDVI values do not vary significantly from one type of PGS to another, except for a few exceptions. Small PGS have the lowest NDVI values because they have a low density of woody species, lawns or ornamental plants, and a mix with mineral materials, which is the case with squares, public gardens, and cemeteries. On the other hand, large PGS have the highest NDVI values. It is worth noting that not all of their areas are considered. For instance, in the Hann Forest, Zoological Park, Mbao Classified Forest, Natural Urban Reserve of Great Niayes, and Dependency, as well as several other wetlands, the NDVI is high because of the presence of a significant number of woody species with high density compared to the first group. However, low values are also observed in these areas due to low woody density or other types of land use, such as bare land or buildings. According to the classification provided by Nawar *et al.* (2022), an NDVI between 0 and 0.2 indicates unhealthy plants, while an NDVI between 0.2 and 0.5 corresponds to moderately healthy plants. Conversely, an NDVI above 0.5 and 1 indicates healthy plants. Therefore, based on this classification, it can be concluded that the majority of PGS in the Dakar region are of low quality. These results align with the statement made by Zaitunah *et al.* (2022) that vegetation density is intrinsically linked to the NDVI value; the higher the density, the higher the NDVI. This study corroborates the findings of Zambrano-Monserrate *et al.* (2021) in Guayaquil City, South America, where they discovered that small parks had lower NDVI values compared to larger parks.

4.2.2 Spatio-temporal dynamics of green spaces in the Dakar region

4.2.2.1 Land use and land cover of the region of Dakar from 1990 to 2022

The analysis of land use in the Dakar region reveals a period marked by significant spatial dynamics. This manifested in profound changes across all land cover types. The built-up area remains the most dominant, exhibiting substantial growth in surface area between

1990 and 2022. However, this expansion has not been uniform across space. Three dense urban blocks emerged in the departments of Dakar, Guediawaye, and Pikine between 1990 and 2002. Notably, from 2012 onwards, urban expansion accelerated significantly, moving from west to east across the region. This unprecedented absorption of space by built-up areas has become a recurring trend in cities, particularly those in developing countries. In fact, this trend has been observed in several cities, including Dakar itself. For instance, in Zimbabwe, Matsa *et al.* (2021) have shown that the built-up area increased considerably in less than 20 years.

Green spaces are the third most dominant type of land cover after bare soil. In parallel to the growth of the built fabric, this study also revealed a decline in the vegetal cover of the Dakar region, as is the case in many other countries. In South Africa and Ethiopia, for example, a loss of green spaces has also been noted by Munyati and Drummond (2020) and by Assaye *et al.* (2017) with green spaces becoming residences and schools, or other types of land cover.

4.2.2.2 Land cover change in the Dakar region from 1990 to 2022

The outputs of this study confirmed the initial hypothesis that green spaces in the Dakar administrative region have gradually decreased, while built-up areas have consistently increased between 1990 and 2022.

Changes in land cover are influenced by several specific factors and also depend on socio-economic and environmental contexts (Sambou, 2017). From this perspective, the space of Dakar has undergone many changes over the years. Indeed, all classes have undergone significant changes during the study period. Except for built-up areas, all classes, including green spaces, water bodies, agricultural land, and bare land, have shown a declining trend between 1990 and 2022. As a result of the conversion of certain vegetated areas, the spatial coverage of green spaces has significantly decreased over the years. The most substantial loss occurred between 1990 and 2002, when 3.07% of vegetation was converted into agricultural land. Furthermore, between 2002 and 2012, an alarming 4.75% of vegetation was completely denuded, leaving bare soil. These losses are primarily attributed to strong human activities.

In contrast, the Dakar region's built-up area has grown rapidly. This is driven by the high demand for housing and other infrastructure to meet the population's needs. The rapid demographic growth, exacerbated by migratory flows, has led to a concentration of people, increasing in built-up areas. This rise in the proportion of built-up areas has consequences for other areas. In reality, the changes observed in green spaces are more significant in unprotected green spaces on the periphery, which have gradually disappeared and become built-up or bare soil. Urban green spaces are disappearing everywhere, as observed in various cities. For instance, in Kumasi (Ghana), Africa, green spaces are vanishing and are frequently replaced by buildings and bare soil (Nero, 2017). According to Biazen Molla *et al.* (2018), in Ethiopia, a similar situation has emerged, with the transformation of green spaces into vacant or open areas devoid of vegetation. In 1992, the spatial coverage of green spaces reached 612 hectares (24%), but this figure has been declining since 1985 due to the expansion of towns and the development of new areas. In other Asian countries, the disappearance of green spaces is a prevalent phenomenon, primarily attributed to the rapid pace of urbanisation. For instance, a spatiotemporal study of green spaces in Mumbai, India, from 1988 to 2018 revealed substantial changes (Rahaman *et al.*, 2021). These changes are attributed to the expansion of urban areas, the increase in built-up areas, and significant migratory flows (Matsa *et al.*, 2021).

The changes in vegetation have also been noticed in the three largest green spaces, including the Hann Forest and Zoological Park, the Mbao Classified Forest, and the

Natural Urban Reserve of Great Niayes and Dependence, even though these areas are protected by presidential decrees. Between 1990 and 2022, there has been a steady decline in vegetation cover, particularly in the forest, where the trend is clearly negative. Furthermore, despite the positive trend observed in the park and the reserve, they also experienced losses in vegetation cover. These variations are attributed to the numerous declassifications of these spaces in favour of infrastructure development. For example, according to the manager of the Mbao Classified Forest, 35 hectares were declassified in 2010 in favour of the National Agency for the Promotion of Investment and Major Works for the construction of the Dakar to Diamniadio highway. A similar situation is observed in the park, with approximately 30 hectares allocated to the actual Ministry of Environment and Ecological Transition and state technical services such as the Senegalese Institute for Agricultural Research and the Centre of Forestry Training, as mentioned by the deputy managing director of the park.

4.2.2.3 Drivers of degradation of public green spaces in the Dakar region

The findings of this study revealed that the primary cause behind the destruction of green spaces in the Dakar administrative region is anthropogenic factors, resulting from human actions. One such factor is the rapid expansion of urban space, which has led to the proliferation of built-up areas. This phenomenon has been observed in Shanghai, where rapid urbanisation has resulted in a significant decline in urban green spaces (Liu *et al.*, 2021). Urban green spaces in Dhaka, Bangladesh, are also facing the same issue. In fact, according to Byomkesh *et al.* (2012), with the population growing by several hundred thousand people annually, including migrants, green spaces are being encroached upon and transformed into buildings and other infrastructures, thereby expanding urban land.

In the case of Dakar, the surveys revealed that buildings, roads, and bare soil often replace green spaces. Informal services like trading and car washing are also set up in public green spaces, and sometimes, these spaces even become dumping grounds for waste. Another human-caused factor is the abandonment and lack of maintenance of green spaces. Due to financial and material constraints, it can be challenging to manage these areas effectively, leading to their abandonment and the subsequent death of plant species until they become bare soil. Natural causes are not ignored, with flooding being the primary natural factor contributing to the disappearance of green spaces, particularly in the park and the forest. For instance, as mentioned in the interview with the person from the Hann Forest and Zoological Park, flooding leads to the demise of certain plants that are unable to survive underwater. This aligns with the observation made by Cissé (2021), who reported numerous dead plants submerged in this park.

4.2.3 Impacts of green space's dynamics on urban ecosystem services in the Dakar region

The findings of this study reveal that urban green spaces in the Dakar region offer crucial ecosystem services, such as high carbon stocks, urban heat reduction, and flood risk mitigation. Notably, the Mbao Classified Forest, the Hann Forest and Zoological Park, and the Natural Urban Reserve of Great Niaye and Dependence stand out as particularly important areas. The forest, with its larger surface area, holds the highest carbon reserves. In essence, forests and trees absorb and store carbon dioxide through a biological process called photosynthesis, converting it into carbon in their biomass (Sambou, 2017). This forest serves as a significant carbon reservoir, underscoring its crucial role in mitigating climate change by sequestering carbon dioxide in the atmosphere. Moreover, it holds the highest capacity for cooling and flood reduction index. As the largest wetland and the second-largest green space in terms of surface area, the reserve contributes substantially to providing ecosystem services. Despite its relatively smaller surface area, the park makes a significant impact on the provision of these benefits. These findings emphasise the significance and importance of urban green spaces in combating climate change and adapting to its impacts.

The study confirmed the initial hypothesis that the dynamics of green spaces have substantial implications for ecosystem services. The spatiotemporal analysis of ecosystem services from 1990 to 2022 revealed a declining trend in three services selected for this study provided by the three major public green spaces in Dakar. This decline corresponds to an analysis of changes in vegetation cover within these areas. Specifically, carbon stocks have been steadily decreasing over the years, with substantial losses recorded, especially in 2012. A similar pattern was observed regarding the capacity of urban areas to cool down and mitigate flood risks. These findings underscore the instability of the ecosystem in the Dakar region, resulting in significant fluctuations in ecosystem services. This clearly illustrates the profound impact of land use and land cover changes on ecosystems, particularly green spaces, which, in turn, influence the services they provide, as numerous studies have demonstrated (Peng *et al.*, 2022; Xiao *et al.*, 2022).

The effects of reduced vegetation cover on ecosystem services are more noticeable in forests compared to other green spaces. A positive correlation exists between the three services and vegetation cover, indicating that when vegetation is depleted, the services are also reduced. In this green space, trees play a central role in providing ecosystem services. This is particularly evident between 2012 and 2022, a period during which the forest experienced substantial vegetation loss, coinciding with significant declines in all three services. The results of the present study align with those of Essel (2017) and Okikiola and Akintunde-Alo, (2020) in Kumasi (Ghana) and Nigeria, who discovered that the rise in surface temperature is positively correlated with the decrease in green spaces.

Unlike the forest, there is a negative correlation between the three services and vegetation cover in the park and the reserve. This implies that changes in vegetation cover do not significantly impact ecosystem services. In other words, the observed increase in vegetation cover in these green spaces does not affect ecosystem services, which have continued to evolve. This negative correlation suggests that other factors, like the spatial configuration and components of the area, influence ecosystem services like urban cooling and flood control. These findings do not corroborate with other studies conducted in this regard, in which an increase in vegetation cover leads to a positive change in services, as found by Hoque *et al.* (2021) in Bangladesh, where carbon stocks have increased over the years in line with the growth of vegetation in forests.

4.2.4 Suitability sites for green spaces

The findings support the initial hypothesis that the Dakar administrative region still contains areas suitable for the development of public green spaces.

Green spaces are increasingly being planned and developed based on site suitability analysis, with criteria selected based on their importance and influence. In this study of the Dakar region, a total of six criteria or factors were chosen.

Land use and land cover, a crucial factor, played a significant role in determining the availability of land in the region. Bare land, being unoccupied and devoid of potential conflicts, is highly suitable for establishing green spaces. Moreover, it enables the distinction between areas with vegetation and those without, ensuring that existing green spaces are taken into account when planning the distribution of future green spaces. Soil types are also considered a criterion, although to a lesser extent than land use, for example. This does not mean it is not important, as the soil, with its various properties, plays a crucial role in selecting the tree species to be planted in green spaces. Another criterion is the slope, which is also highly favoured in the literature for selecting sites for green spaces. Indeed, the slope helps choose areas with easy access, meaning areas with little or no elevation. This also allows for more cost-effective development. The Dakar region is generally flat with minimal elevation. Population density is another crucial factor in selecting locations for green spaces. Given the pressing need to establish recreational and leisure areas and bring nature closer to residents, it is vital to identify and categorise the population. The demand is particularly acute in densely populated areas compared to low-density ones. Additionally, when planning new green spaces, it is essential to take into account the existing green spaces in the region. This approach helps rectify the uneven spatial distribution of green spaces. Accessibility is a crucial factor in choosing the locations of green spaces. Generally, green spaces should be accessible to the local population, and the closer the site is to the road network, the more suitable it is. These factors were also considered in two similar studies conducted in Ethiopia. Additionally, the authors took into account other criteria such as proximity to water sources, visibility, and proximity to industrial areas (Abebe and Megento, 2017; Gelan, 2021).

Using the Analytical Hierarchy Process (AHP), the weights of the criteria were determined. The results revealed that land use and land cover, distance to existing green spaces, and population density are the most influential factors. The final results of assessing the suitability of sites in the Dakar region for green space development reveal that a substantial portion of the region is suitable for green spaces. Notably, moderately suitable areas dominate the landscape, followed by highly suitable sites. These findings underscore a substantial opportunity to develop green spaces, which can significantly enhance urban biodiversity, ecosystem services, and the overall quality of life in the region.

Moderately suitable areas indicate the presence of certain obstacles that can hinder the development of green spaces. In fact, there are areas where the population is predominantly concentrated in built-up areas, while in others, there are already some green spaces. To address this issue, the selection of green space types is paramount, with a strong emphasis on small parks and street trees. In contrast, areas with high suitability for green space development face virtually no significant constraints. Given their availability on the outskirts of the region, green spaces like forests or large parks could be established there to provide greater ecological benefits. This would help diversify the types of green spaces, which would offer a range of ecosystem services.

These results do not corroborate those found in Ethiopia, in the city of Addis Ababa, where less suitable sites dominate, followed by moderately suitable spaces, with very few highly suitable sites (Abebe and Megento, 2017). Similarly, in Pakistan, a study on the suitability of sites for public parks reveals a dominance of unsuitable areas at 98 %, with only a small portion of moderately and highly suitable areas (Chandio *et al.*, 2011). Likewise, in India, in the city of Noida, less suitable and unsuitable locations dominate for green spaces development (Sharma *et al.*, 2022)

4.3 Summary of Findings

i. The identification, classification, and characterisation of public green spaces in the capital of Senegal reveal the presence of various types of green spaces in the city, albeit in limited numbers. While there is a low diversity of public green space types, their spatial distribution is uneven, resulting in low density and coverage rates. Moreover, the ratio of green spaces per inhabitant is very low, and the NDVI values are weak.

ii. The spatial and temporal analysis of green spaces in Dakar revealed a general downward trend. Green spaces decreased from 13.36% in 1990 to 9.53% in 2022. Meanwhile, built-up areas expanded, reaching 39.33% in 2022 compared to 19.24% in 1990. Notably, the analysis focused on the three major green spaces in Dakar, where gradual changes in vegetation cover were observed over the study period. Anthropogenic factors, particularly urban expansion, were identified as the primary drivers influencing the dynamics of green spaces

iii. This study also observed a downward trend in ecosystem services like carbon sequestration, urban cooling, and flood risk mitigation within the three major green spaces of the Dakar region. The Mbao Classified Forest and the Natural Urban Reserve of Great Niaye and Dependence exhibited more significant changes in service provision compared to the Hann Forest and Zoological Park, which has remained relatively stable. The correlation between vegetation cover and ecosystem services revealed positive relationships within the forest, indicating that as vegetation decreases, the services provided also decline. Conversely, negative relationships were observed in the park and the reserve, suggesting that vegetation reduction alone does not directly impact the services.

iv. This study emphasises the significance of expanding the number of green spaces in the Dakar region by strategically selecting suitable locations for their development. The land suitability analysis revealed that over 90% of the area is suitable for green spaces, with the moderately suitable category being prevalent across the region.

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This study investigated public green spaces in the Dakar region, the capital of Senegal. The primary objective was to assess the impacts of public green space dynamics on the ecosystem services they provide from 1990 to 2022, focusing mainly on their regulating functions. First, a typology and classification of public green spaces were conducted to identify the types of green spaces that exist, their various functions, and their characteristics.

The analysis has shown several types of green spaces identified in the Dakar region, including public gardens, parks and forests, squares, and accompanying green spaces. These spaces provide ecological, cultural, and productive benefits. The research revealed that these green spaces are characterised by a moderate diversity of PGS, with relatively low density for a region as crowded and densely populated as Dakar, primarily due to their limited spatial coverage. Furthermore, these green spaces are unevenly distributed across the region, with a significant concentration in the department of Dakar. The study also highlighted a low per capita green space ratio, which falls below international standards. Similarly, their quality was found to be generally low, as indicated by relatively low NDVI values for the majority.

The analysis of land use and land cover changes in Dakar reveals intense landscape dynamics between 1990 and 2022. This spatiotemporal transformation has significantly impacted the existence of green spaces. The findings indicate a decline in green spaces over the years, accompanied by an increase in other types of land cover such as bare land and built-up areas. A more detailed examination was conducted on the three major public green spaces in Dakar, which are legally protected. Unfortunately, despite this protection, these spaces have experienced dynamic changes, including significant losses in their vegetation cover. Generally, human activities are highlighted as the main factors contributing to the degradation of green spaces due to urban expansion.

The changes in vegetation cover have significant consequences on the ecosystem services provided by green spaces, such as carbon sequestration, urban cooling, and flood risk mitigation. The spatiotemporal analysis of these three services in the green spaces of Hann Forest and Zoological Park, the Mbao Classified Forest, and the Natural Urban Reserve of Great Niaye and Dependence indicates a decline in carbon stocks, particularly between 2002 and 2012. During this period, these green spaces experienced significant negative changes in their vegetation cover. It was noted that the forest and the reserve went through greater losses in carbon stocks, as they underwent more substantial modifications compared to the park. Similarly, the heat mitigation service showed a downward trend during this period. Due to the numerous changes in these spaces, the heat mitigation index fluctuated over the years, with more pronounced variations in the reserve. Notably, like carbon stocks, the heat mitigation index experienced a steeper decline between 2002 and 2012. A similar observation was made with the flood risk mitigation. The forest and the reserve decreased over the years, while the park maintained a relatively stable index. Moreover, only the carbon stocks are directly affected by the reduction in vegetation cover in the forest. In contrast, for the park and the reserve, where an increase in vegetation cover was observed, the three ecosystem services assessed show a continual decrease.

This analysis highlights that, despite the changes they have undergone, these green spaces continue to provide essential functions. The findings underscore the importance of increasing the quantity of public green spaces in the region by developing new ones in suitable locations to sustain urban ecosystem services and more accessibility to the population. The suitable site analysis for green spaces in the Dakar region based on various criteria, reveals that significant areas were favourable to green spaces. The larger dominant areas are moderately suitable followed by highly suitable land.

5.2 Recommendations

Based on the findings of this study, several recommendations can be made to public decision-makers. These recommendations are divided into four parts:

(a) Policy improvement

This study has shown that public green spaces are significantly affected by the development of Dakar. As a result, vegetation in the city has almost disappeared, leaving only fragmented spaces. Even protected areas have not been spared. It has also been demonstrated that the current status of green spaces in the city of Dakar is far from being quantitatively and qualitatively adequate. Therefore, it is important to review urban planning policies, emphasising the integration of green spaces as an integral part of the urban fabric through spatial zoning. To achieve this, the country needs to establish a national green space ratio that all urban policies will respect. This includes considering new green space developments throughout cities and ensuring there is an appropriate management system for their proper conservation. Furthermore, it is crucial that the various concerned parties, such as the Ministry of Environment and Ecological Transition, the Ministry of Urbanism, Territorial Communities, and Territorial Planning, along with the respective subdivisions, work in perfect synergy to improve the urban environment and achieve the SDGs, particularly SDG 11, through a solid urban policy document. In this regard, it is important to focus on new ecological approaches such as nature-based solutions for the restoration of urban vegetation. New developments should be based on the selection of sites according to physical and socio-economic criteria, as exemplified in this study.

(b) Performance improvement

The study highlighted the various benefits derived from urban green spaces, particularly in the context of climate change. In this regard, it would be important to revise or develop management plans, that include ecosystem services, such as carbon sequestration for the three major green spaces of Dakar. Furthermore, in response to changes in ecosystem services based on vegetation cover dynamics, as emphasised by this study, the managers of the protected green spaces should focus more on reforestation efforts to renew vegetation cover and enhance ecosystem services. When planning new green spaces, the Direction of Urban Landscape and Public Spaces should consider specialising green space types based on ecosystem services, also known as ecosystem-based planning. For example, alignment trees can improve air quality and regulate temperatures, while larger green spaces like forests or parks can contribute to mitigating carbon dioxide. It would also be important to make informed choices regarding the species to be planted, based on their capacity to provide services, such as species with high potential for carbon storage, and shading, and those that are adapted to flood-prone areas. In a city with such a density of population, small parks, known as "pocket parks", should be considered to increase the number of green spaces in neighbourhoods.

(c) Body of knowledge

Through this study, it is demonstrated that the use of geographic information systems (GIS) incorporating remote sensing techniques can be utilised for spatiotemporal analysis using satellite imagery. Given the limitations of some commercially available software, it is important to consider these in other studies, especially in Africa, where resources may be limited. Additionally, for a large-scale ecosystem service assessment, it is useful to employ models such as InVEST, which have been developed for this purpose.

5.3 Contribution to Knowledge

The study identified 13 types of public green spaces (PGS) in Dakar, including forests, parks, public gardens, and accompanying green areas. Green spaces were low in density (2 PGS/km^2), spatial coverage (3.5%), and per capita (4.69 m^2). Qualitatively, they scored low, with limited diversity (Shannon index = 1.44; Pielou's Evenness = 0.56), spatial inequality (Gini coefficient = 0.59), and weak vegetation health (NDVI: 0.18–0.61). Green space coverage has declined over time, from 13.4% in 1990 to 9.5% in 2022, with a slight increase in 2012 (12.5%). Similar trends were observed in three major PGS, where vegetation cover declined (p-values: 0.14, 0.53, 0.18 for the forest, park, and wetland, respectively). This degradation is largely anthropogenic, with 58.41% of survey responses citing urban expansion, followed by industrial (3%) and agricultural activities (1%). As a result, critical ecosystem services have been reduced. In the Mbao Classified Forest, decreased vegetation cover correlated positively with reduced carbon sequestration ($p = 0.33$), urban cooling ($p = 0.26$), and flood mitigation ($p = 0.05$). In the Hann Park and Great Niaye Wetland, the relationships were negative. To guide green space expansion, a land suitability analysis showed 76.08% of Dakar's land is moderately suitable, 14.75% highly suitable, 9.16% less suitable, and 0.02% not suitable.

This study highlighted that green spaces in Dakar are not only dynamic but also weakly spatially distributed, with negative impacts on ecosystem services and globally on climate change. It also demonstrated that there are still possibilities to expand green spaces across the region.

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APPENDICES

Appendix A: Questionnaire for neighbourhood delegates

Purpose: This questionnaire is part of a doctoral thesis conducted at the WASCAL Climate Change and Human Habitat research centre at the Federal University of Technology in Minna, Nigeria. The objective is to gather information on the significance and advantages of public green spaces, as well as their spatial and temporal variations. The collected data will solely be used for academic research purposes.

I. Identification

1. What is the name of the neighbourhood?

2. Gender of the respondent.

Female

Male

3. In which municipality are you residing?

- Plateau
- Fann/Point E/Amitié
- Grand Dakar
- Hann/Bel Air
- Mermoz/Sacré-cœur
- Golf Sud
- Pikine Ouest
- Keur Massar
- Mbao
- Rufisque Est

4. How old are you?

30-39 years

40-49 years

50-59 years

60 years and over

5. What is the status of your education?

Educated

Not educated

6. If you are educated, please specify your educational level.

Primary

Secondary

High school

Arabic school

II. In this section, we will explore the perception and benefits of public green spaces.

7. What kinds of green spaces are there in your neighbourhood?

Urban forest

Urban park

Public garden

Trees street

Square

Vegetable garden

Natural green space

Spread trees

Other to be specified

8. Are they naturally occurring or man-made?

Natural

Man-made

9. If these were man-made, who designed them?

Town Hall

Neighbourhood delegate

Direction of Urban Landscapes and Public Spaces

I do not know

Other to be specified

10. Who selects the locations for development?

Town Hall

Neighbourhood delegate

Direction of Urban Landscapes and Public Spaces

I do not know

Other to be specified

11. Do you believe green spaces are beneficial?

Yes

No

12. If you agree, what advantages do green spaces offer you?

Fresh air

Recreation

Well-being

Stress reduction

Socialising

Education

Sports facilities

Firewood/energy

Food

Other to be specified

13. If not, what are the adverse consequences?

Noise

Allergy

Waste

Presence of mosquitoes or insects

Insecurity

Other to be specified

14. Are green spaces:

Accessible

Less accessible

Not accessible

15. Are green spaces attractive?

Yes

No

16. Why are they not attractive?

Lack of many trees

Lack of water

Other to be specified

17. Do you believe their location is ideal?

Yes

No

18. If you agree, please explain your reasoning.

Close to residential areas

A little close to residential areas

Very close to residential areas

Other to be specified

19. Why not, if not perfect?

Away from residential areas

A little away from residential areas

Very far from residential areas

Other to be specified

20. Is the distribution of green spaces in the neighbourhood fair and equitable?

Very fair

Just fair

Not fair

Undecided

21. Are the green spaces provided in the neighbourhood sufficient?

Very sufficient

Just sufficient

Neutral

Insufficient

Very insufficient

22. How frequently do people engage in activities within green spaces?

Very often

Often

Sometimes

Rarely

Never

23. If not frequently used, why is that?

Lack of knowledge of these areas

Not used to it

Lack of time

Other to be specified

24. When do people visit green spaces the most, if they do?

Hot period

Cold season

During the holidays

During the school year

Other to be specified

25. How frequently do they visit?

Daily

Weekly

Once a day

Once a week

Once a month

III. III. The spatial and temporal dynamics of public green spaces

26. Have green spaces always been present in the same locations?

Yes

No

27. In your own words, describe the current state of the green spaces.

Excellent

Good

Average

Fair Poor

28. If poor, are these changes to the green spaces recent?

One year ago

5 years ago

More than 5 years

Other to be specified

29. How rapidly are these changes unfolding?

Very quickly

Quickly

Moderately quickly

Slowly

Very slowly

30. Have any green spaces completely vanished in recent years?

Yes

No

31. If you agree, could you please provide a list of them?

32. Why have they disappeared?

Lack of maintenance

Abandon

Drought

Flooding

Other to be specified

33. Do you miss these green spaces?

Yes

No

34. What are the causes of the decline of green spaces?

Anthropogenic

Natural

35. If anthropogenic, could you please identify the primary reasons behind their disappearance?

Urban expansion

Agriculture needs

Industrial activities

Other to be specified

36. What most frequently replaces these green spaces?

Building

Road

Bare land

Services

Other to be specified

37. With these changes, is this green space effectively fulfilling its intended functions?

Yes

No

IV. IV. Maintaining public green spaces

38. Who is responsible for maintaining the green spaces?

Town hall

State services

Communities

Non-Governmental Organisation

Other to be specified

39. Are there any maintenance staff?

Yes

No

40. If you agree, please specify the employer.

Town hall

State services

Local population

Non-Governmental Organisation

Other to be specified

41. How are the maintenance tasks organised?

Every day

Once a week

Weekly

Every fortnight

Once a month

42. What are the responsibilities involved in maintaining green spaces?

Watering

Cleaning

Pruning trees

Don't know

Other to be specified

43. How would you rate the maintenance of the green spaces?

Very satisfactory

Satisfactory

Neutral

Unsatisfactory

Very unsatisfactory

44. Is the local community actively involved in maintaining and preserving green spaces?

Yes

No

45. If yes, on what do they participate?

Watering

Cleaning

Reforestation

Payment of maintenance staff

46. Do you believe that the sole responsibility for maintenance should lie with the local authority?

Yes

No

47. If you agree, please explain your reasons.

It is its responsibility

It has the necessary resources

Other to be specified

48. If not, who should be involved in the process?

Young people from the neighbourhood/commune

Local associations

Economic Interest Grouping (EIG)

Other to be specified

Appendix B: Interview guide for the Direction of Urban Landscape and Public Spaces

Purpose of the interview: To gather information on the various green spaces in the Dakar region, including their types, location, functions, transformations, and maintenance practices, to write a doctoral thesis.

Identifying the interviewee

Surname/First name:

Profession:

I. Typology of public green spaces

1. What kinds of public green spaces are you developing in the Dakar region?

2. Are there any differences in terms of size, composition, and function among these types of public green spaces?

3. How do you design various types of public green spaces?

4. Are there any specific criteria that are used to determine the suitability of locations for development?

5. Are there any specific challenges you are facing in their development?

6. Do you consider natural areas in your calculations?

II. Ecosystem services of public green spaces

7. What are the various purposes of public green spaces?

8. Do you consider their diverse benefits when you are planning them?

III. Spatial and temporal dynamics of public green spaces

9. Is there a national average of green spaces per person?

10. Does this ratio vary over time?

11. Has there been a decline in the quantity and quality of public green spaces over the past few years?

12. Can you pinpoint the factors that are causing these changes?

IV. Maintenance of public green spaces

13. How are public green spaces managed in Dakar?

14. Are there any challenges you face in keeping them in good condition?

15. Do you involve the local community in maintenance activities?

16. What are your thoughts on the significance of green spaces in addressing climate change, and how can they be effectively managed to mitigate its impacts?

Appendix C: Interview guide for the three major public green spaces: the Mbao Classified Forest, Hann Forest, and Zoological Park; the Natural Urban Reserve of Great Niaye and Dependence; and the Filao Band of Guediawaye.

Purpose of the interview: To conduct research on the significance, evolution, factors contributing to degradation, and management strategies of public green spaces in the Dakar region, with the aim of writing a doctoral thesis.

1. Identification of the interviewee

2. Could you please provide us with information about the green space and its primary functions?

3. How vibrant and dynamic is this area?

4. What are the various factors that contribute to the deterioration of this green space?

5. How the management of this green space is carried out?

6. Given the significance of this area within the city of Dakar, what measures should be taken to ensure the development of green spaces?

Appendix D: Pair-wise comparison of the criteria

Criteria	LULC	PD	PGS	ST	Sl	PR
LULC	1	2	2	5	5	5
PD	1/2	1	1/3	3	3	3
PGS	1/2	3	1	5	5	4
ST	1/5	1/	0.2	1	1/2	1/3
Sl	1/5	1/3	1/5	2	1	1/2
PR	0.2	1/3	1/4	3	2	1

LULC= land use and land cover; PD= population density; PGS= proximity to green spaces; ST= soil types; Sl=slope; PR= proximity to roads