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Building Green and Resilient Cities in Africa: Analyzing the role of Urban Green Spaces, Urban Agriculture, and the Water-Energy-Food Nexus in the Transition to a Green Economy

Présentée par: **Adama KANE**

Devant le Jury :

Président du Jury **Mr. Birahim Bouna NIANG,** Professeur Titulaire, Faculté des Sciences Economiques et de Gestion, FASEG/UCAD

Rapporteurs

Mr. Mr. Yao Grégoire Aklesso EGBENDEWE, Professeur Titulaire, Faculté des Sciences Economiques et de Gestion, FASEG/ Université de Lomé

Mr. Assane BEYE, Professeur Agrégé, Faculté des Sciences Economiques et de Gestion, FASEG/WASCAL-UCAD

Mr. Ndéné KA, Professeur Agregé, Faculté des Sciences Economiques et de Gestion, Université Alioune Diop de BAMBEY

Directeur de Thèse Mr. Ndiack FALL, Professeur Titulaire, *Laboratoire d'Analyse des Politiques Economiques et Sociales (LAPES)*

Co-directrice : **Mme Awa NIANG FALL**, Professeur Titulaire Faculté des lettres et sciences humaines, Université Cheikh Anta DIOP de Dakar

Co-Directrice: Professor Dr. **Mme Sandra VENGHAUS**, School of Economics and Business, RWTH-AACHEN University

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DEDICATION

"This PhD dissertation is **first** and foremost dedicated to my beloved father, Seydou Kaya KANE, whose wisdom, love, and sacrifices have shaped my path. I also dedicate it to my wonderful mother, Marietou KANE, whose unwavering support and encouragement have been my constant source of strength, to my cherished son, Elhadj Madani SY, for being my motivation and the joy in my life and to my entire family for their love and support".

"**Secondly**, I dedicate this work to all the teachers and professors who have guided and inspired me throughout my academic journey, from Thierno Marsassoum Primary School in Ziguinchor, to Franco-Arabe Cheikh Mouhamadou Fadillou Mbacké High School, the Faculty of Economics and Management at Cheikh Anta Diop University (UCAD), the NPTCI Program, and the WASCAL Program. Your knowledge, guidance, and support have been invaluable".

"**Finally,** I dedicate this dissertation to all those who believe in the transformative power of education and a green, resilient future for Africa."

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ABSTRACT:

This study analyzes how African cities particularly in Senegal can strengthen climate resilience and promote sustainable urban development towards green economy transition through three key drivers: urban green spaces, urban agriculture, and the integrated Water-Energy-Food (WEF) Nexus approach. To achieve this, a mixed-methods research design was employed, combining both qualitative and quantitative data. Surveys, interviews, and field observations were conducted with urban households, urban farmers, and municipal stakeholders across six Senegalese cities in October 2023. Additionally, an econometric analysis was performed using regional data from thirteen Sub-Saharan African countries (2000–2022), applying Principal Component Analysis (PCA), the Environmental Kuznets Curve (EKC) framework, and dynamic panel data modeling (GMM). The findings show that knowledge and satisfaction with urban green spaces are influenced by socioeconomic factors such as education, income, and environmental awareness. These factors also determine the willingness to pay for green space improvements. Urban agriculture significantly contributes to food security and climate resilience by providing fresh local produce and promoting sustainable practices like crop diversification and efficient irrigation. Municipal governments play a critical role in facilitating urban agriculture through land-use policies and resource allocation. At the regional level, the econometric results confirm that adopting a WEF Nexus approach improves food security, reduces environmental degradation, and supports the transition to a green economy. The research advocates comprehensive policies that integrate the Water-Energy-Food (WEF) Nexus with green economy principles to address resource challenges and foster long-term urban resilience. Effective implementation of policies promoting renewable energy, sustainable agriculture, water conservation, and environmental regulations is crucial for ensuring urban sustainability and resilience in the face of climate change. Based on these findings, the dissertation recommends integrating green spaces and urban agriculture into urban planning, enhancing public-private partnerships, improving access to productive resources, and adopting multisectoral policies grounded in the WEF Nexus framework. These actions are essential for building long-term climate resilience and achieving sustainable development across African cities.

Keywords: Resilient cities, Green spaces, Urban agriculture, Climate resilience, Food security, Urban sustainability, Water-Energy-Food (WEF) Nexus, Green economy, Renewable energy, Sustainable agriculture, Water conservation, Urban resilience, Senegal, Climate change adaptation.

RESUME :

Cette étude analyse comment les villes africaines, en particulier celles du Sénégal, peuvent renforcer leur résilience face au changement climatique et promouvoir un développement urbain durable dans le cadre de la transition vers une économie verte. Trois leviers principaux sont explorés : les espaces verts urbains, l'agriculture urbaine et l'approche intégrée Nexus Eau-Énergie-Alimentation (WEF). Pour atteindre cet objectif, une méthodologie mixte a été adoptée, combinant des données qualitatives et quantitatives. Des enquêtes, des entretiens et des observations de terrain ont été menés auprès des ménages urbains, des agriculteurs urbains et des acteurs municipaux dans six villes sénégalaises en octobre 2023. Par ailleurs, une analyse économétrique a été réalisée à partir de données régionales de treize pays d'Afrique subsaharienne couvrant la période 2000–2022, en mobilisant l'Analyse en Composantes Principales (ACP), le cadre de la courbe de Kuznets environnementale (EKC), et des modèles dynamiques de données de panel (GMM). Les résultats montrent que la connaissance et la satisfaction liées aux espaces verts urbains sont influencées par des facteurs socio-économiques tels que le niveau d'éducation, le revenu et la sensibilisation environnementale. Ces mêmes facteurs déterminent également la volonté de payer pour l'amélioration des espaces verts. L'agriculture urbaine contribue significativement à la sécurité alimentaire et à la résilience climatique en fournissant des produits frais locaux et en favorisant des pratiques durables comme la diversification des cultures et l'irrigation efficiente. Les municipalités jouent un rôle clé en facilitant cette dynamique via les politiques d'aménagement du territoire et l'allocation de ressources. À l'échelle régionale, les résultats économétriques confirment qu'une approche intégrée Nexus Eau-Énergie-Alimentation permet d'améliorer la sécurité alimentaire, de réduire la dégradation de l'environnement et de soutenir la transition vers une économie verte. L'étude plaide pour l'adoption de politiques intégrées associant le cadre du Nexus WEF aux principes de l'économie verte afin de répondre aux défis liés à la gestion des ressources et de favoriser la résilience urbaine à long terme. Une mise en œuvre efficace des politiques en matière d'énergies renouvelables, d'agriculture durable, de gestion de l'eau et de réglementation environnementale est essentielle pour assurer la durabilité urbaine face aux effets du changement climatique. Sur la base de ces résultats, cette étude recommande d'intégrer les espaces verts et l'agriculture urbaine dans la planification urbaine, de renforcer les partenariats public-privé, d'améliorer l'accès aux ressources productives et de promouvoir des politiques multisectorielles fondées sur le cadre du Nexus Eau-Énergie-Alimentation. Ces actions sont indispensables pour bâtir une résilience climatique durable et atteindre les objectifs de développement durable dans les villes africaines dans la transition vers une économie verte.

Mots-clés : Villes résilientes, Espaces verts, Agriculture urbaine, Résilience climatique, Sécurité alimentaire, Durabilité urbaine, Nexus Eau-Énergie-Alimentation (WEF), Économie verte, Énergie renouvelable, Agriculture durable, Conservation de l'eau, Réglementation environnementale, Adaptation au changement climatique, Sénégal.

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SUMMARY

General Introduction

A) Background of the study

Today, over half of the global population, approximately 4.4 billion people, resides in urban areas (World Bank, 2024). This urban shift is accelerating and is expected to continue, with nearly 70% of the global population projected to live in cities by 2050, an increase of about 2.5 billion people (W.C. Report, 2024). Nearly 90% of global urban growth will occur in Asia and Africa. According to the United Nations Department of Economic and Social Affairs (2018), Africa's urban population is expected to triple to 1.3 billion by 2050. This projection is reinforced by the ECA and AfDB (2022), who estimate that the continent's urban population will reach 1.4 billion by mid-century. From 2000 to 2020, Africa's urban population grew by 469 million people, adding 58,000 urban dwellers daily (Africapolis database, OECD/SWAC, 2024). Africa is rapidly transforming into a predominantly urban continent, with 54% of its population living in urban areas and 90 cities with over 1 million inhabitants. This rapid urbanization presents both challenges and opportunities, especially regarding climate change, resource constraints, and social inequalities. The global community is addressing complex issues such as poverty, climate crisis, food insecurity, and access to essential resources like clean air, energy, and water (A. Report, 2024). In Africa, these challenges are compounded by rising temperatures and increasing demands for water, energy, and food. As Africa's urban population grows, building climate-resilient cities has become crucial for sustainable development and improving urban living conditions (United Nations, UN-Habitat, World Bank). By 2050, two-thirds of Africans are expected to live in urban areas, making it essential to proactively plan for urban growth that promotes sustainability, inclusiveness, and resilience (United Nations Department of Economic and Social Affairs, 2018).

The world is confronting a set of intertwined challenges such as poverty, the climate crisis, debt, food insecurity, pandemics, and fragility along with the urgent need to accelerate access to clean air, energy, and water(A. Report, 2024). Added to these challenges is the rapid urbanization taking place in Africa, occurring in a context of rising temperatures, environmental degradation, and increasing demand for water, energy, and food.

These overlapping pressures threaten the sustainability and resilience of African cities, especially in regions already vulnerable to climate change impacts.

As highlighted by institutions such as the **United Nations**, **UN-Habitat**, and the **World Bank**, building climate-resilient cities is now a strategic imperative for advancing sustainable development and improving the quality of life for urban populations. Africa's urban population is expected to triple toward 2050 to reach 1.3 billion even though it is mostly rural (United Nations Department of Economic and Soical Affairs, 2018). That's why the United Nations in 2015, through the eleven (11) Sustainable Development Goal (SDG) particularly at the seventh target (11.7), decide to build the sustainable communities and cities by 2030 *by providing universal access to safe, inclusive and accessible, green and public spaces, in particular for women and children, older persons and persons with disabilities (*(Rigg, 2024). According to the Förster & Ammann, (2018), Africa currently evolves at a pace of urbanization greater than that of all other continents with the diversity of cities which is difficult to conceptualize.

In sub-Saharan Africa, cities are well known to be coping with severe pressures with diverse challenges notably rapid population change, extreme poverty and seemingly chaotic urban development processes (Lindley & al., 2018). Some studies addressing cities' problems have showed that the rapid urbanization resulted from rapid population growth leads to the anarchic dwelling of the people living in the slums without improved water, sanitation, security of tenure, access to food, green spaces (Smit et al., 2017).

Indeed, the number of people around the world who live in cities is steadily increasing. For the first time in history, the percentage of the population living in cities exceeded the 50% mark. These cities are rapidly becoming the main spaces for planning and implementing strategies to eradicate hunger and poverty. Many cities cannot cope with rapid population growth and face enormous challenges in creating enough jobs; in the provision of basic services; and in the planning and management of urban waste and wastewater.

In many cities, unstable economic and political situations or natural hazards aggravate this condition of vulnerability, for example increasing water scarcity, rapidly rising food prices and climate change.

To this rapid population growth, Lindley & al. (2018) added the high levels of poverty and the pace of development as threats of the existence of the productive urban green spaces upon which the livelihoods and wellbeing of the urban poor communities largely depend.

For example, according to Douglas, (2018), in West Africa, Niamey has the highest proportions on urban dwellings living in slums (with 81.9%) while Dakar has the lowest proportions in the region (with 38.1%).

It is admitted that the change that occurred with the transformation of the landscape to accommodate housing contributes to the losses of the high quality of agricultural land and threatens the livelihoods and well-being of the residents in different cities (Damour & al., 2017). In respond, the theory of spatial capital has to be highlighted. According to this theory, the value of land enhanced by investments in fixed capital, such as infrastructure, buildings and roads and by the way the spatial form of land is designed in the urban areas creating locations with specific socio-economic and ecological potentials.

Climate change has emerged as one of the most critical cross-border challenges of our time, with serious impacts on urban communities in sub-Saharan Africa, including floods, recurring droughts, and changes in water systems. Like many Asian cities, African cities have yet to fully adopt resilient urban planning practices that address the growing challenges posed by climate change, which has become central in global discussions (Chirisa et al., 2021). Each year, West and Central Africa experience floods of varying intensity between June and September, during the rainy season that sweeps across the Sahelian belt along the southern edge of the Sahara Desert (Reuters, 2022). According to United Nations climate experts, rising temperatures caused by climate change are increasing the intensity and frequency of rainfall across Africa. River siltation and land degradation have further worsened the impacts, quickly overloading water systems with disastrous consequences. Flooding is particularly recurrent in African cities, especially in Senegal. Furthermore, cities depend on increasing amounts of resources such as water, energy, and food even as these resources become increasingly scarce (Vogt et al., 2014).

To deal with these different urban challenges, the urban professionals and city leaders adopt increasingly the framing concept of **"resilience"** which, however, poses the problem of precision and operationalization (Ahern, 2011).

Resilient cities are cities that can operate efficiently and provide services in distressed conditions. Resilient cities can better absorb the type of shocks and stresses identified.

Rather than focusing on vulnerability, focusing on resilience means emphasizing what can be done by a city or community itself, building on natural, social, political, human capital, existing financial and physical resources, while strengthening its capacities.

According to the Figueiredo(2018) , The Resilience is increasingly understood as a fundamentally dynamic property of complex socio-technical systems: "the capacity of individuals, communities, institutions, businesses, and systems within a city to survive, adapt, and grow, no matter what kinds of chronic stresses and acute shocks they experience". From the viewpoint of economics, resilience provides a systematic approach to reduce vulnerability and economic loss and improve the situation of the people in distress climatic (Bastaminia & al., 2017). These losses and damages resulting from the loss of urban green spaces lead to a decrease in insurance values linked to resilience, increasing the vulnerability of cities to shocks such as heat waves, floods, storms, landslides and even food crises (Wangai and al., 2016). The insight from Lwasa et al. (2014) highlights the importance of assessing urban green spaces and urban agriculture not only for their direct contributions to food security but also for their broader co-benefits, such as improving resource efficiency and enhancing urban resilience. This perspective is particularly relevant for African cities, where urban agriculture remains underdeveloped but presents significant potential for boosting climate resilience. The WEF Nexus approach, which emphasizes the interconnectedness of water, energy, and food systems, can offer solutions to urban challenges like water scarcity, energy access, and food insecurity.

In this way, urban agriculture and green spaces not only help mitigate climate change impacts but also contribute to the sustainable development of cities by creating synergies between these key resources. Studying how urban agriculture and green spaces can complement each other in the context of the WEF Nexus can offer innovative solutions for strengthening resilience to climate change. Furthermore, this approach supports the transition toward a green economy by promoting sustainable urban development that aligns with climate adaptation and the broader goals of environmental sustainability.

In this context, the integration of **urban green spaces**, **urban agriculture**, and the **Water-Energy-Food (WEF) Nexus** offers promising pathways to strengthen urban climate resilience and facilitate the transition to a **green economy**.

These strategies not only improve environmental sustainability and food security but also enhance social inclusion, economic opportunities, and the health of urban ecosystems.

Theoretically grounded in systems thinking, ecological economics, and resilience theory and supported by practical frameworks like the SDGs, Agenda 2063 of the African Union, and WEF Nexus policies this thesis investigates how cities in Senegal, and more broadly across Africa, can leverage these tools to become more climate-resilient and sustainable in a rapidly urbanizing world. This study is structured around three core components that reflect the interlinked strategies necessary for building climate-resilient and sustainable African cities. Each chapter explores a critical dimension: urban green spaces, urban agriculture, and the Water–Energy–Food (WEF) Nexus, with an overarching focus on their roles in enhancing resilience and supporting the transition to a green economy.

B) Problem statement

Cities in West Africa experience a substantial depletion of green spaces, which already occupy a tiny percent of the total land due predominantly to the high rate of urbanization (Mensah, 2014). This alarming trend exacerbates climate change impacts (Nero et al., 2019), disrupting ecosystem services, increasing vulnerability to shocks such as heatwaves, floods, droughts, and food crises, and weakening climate resilience (Geest et al., 2019). The growing evidence of climate and natural hazards underlines the urgent need for improved city planning and design to build resilience (du Toit et al., 2018). To this end, West African cities must develop climate-resilient infrastructure, reform institutional and policy frameworks, and share knowledge and resources to scale up effective adaptation practices (Lwasa et al., 2014). For example, some municipalities are adopting urban plans promoting rainwater storage systems to reduce flood risks (Douglas, 2018).

According to Cilliers and al., (2013), the development of urban green spaces is limited by the lack of financial capacity of African states to manage urban green spaces, the lack of priority to urban green spaces in the development agenda, and the weak involvement of local communities as well as their poor awareness of the benefits of urban green spaces, the influence of poverty, corruption, uncooperative attitudes of local communities and political instability.

In addition to provisioning services, urban green spaces provide vital regulating, cultural, and supporting services that local communities increasingly depend on (Cilliers et al., 2013). Yet, their benefits depend heavily on accessibility and effective management (Anderson & Patiño Quinchia, 2022b).

Urban green space management faces major obstacles, including weak enforcement of planning regulations and socioeconomic and political constraints (Mensah & Roji, 2021), leading to reduced availability and quality of these spaces, and sometimes resulting in ecosystem disservices (Nero et al., 2019; Mngumi, 2020; Mensah & Roji, 2021). Most empirical studies on West African cities focus on green space management problems, with little attention paid to the accessibility of green spaces or the drivers of their management practices and contributions to urban climate resilience. While international literature (notably in Europe, the US, and Asia) demonstrates the potential of urban green spaces to support climate resilience, this nexus remains largely unexplored in cities like Niamey(Moussa, 2024), including the role of urban agriculture and its linkages to the water-energy-food (WEF) needs of growing urban populations.

However, major limitations hinder the contribution of urban green spaces, urban agriculture, and the Water-Energy-Food (WEF) Nexus to urban climate resilience in West Africa. First, **urban green spaces** are often poorly managed due to insufficient enforcement of urban planning regulations, financial constraints, land competition, and weak institutional coordination are often poorly managed due to insufficient enforcement of urban planning regulations, financial constraints, land competition, and weak institutional coordination (Mensah & Roji, 2021). These challenges result in reduced availability, inequitable access, and declining quality of green spaces, ultimately limiting their capacity to deliver essential ecosystem services and increasing the risk of ecosystem disservices (Nero et al., 2019; Mngumi, 2020). Second, **urban agriculture** in African cities remains underdeveloped and faces significant challenges, including limited access to land, insecure tenure, poor integration in urban planning, and growing pressure on water, energy, and food systems. These constraints are compounded by weak governance and institutional fragmentation, limiting its contribution to food security and resilience.

Third, the **WEF Nexus**, which is critical for sustainable urban development, is rarely operationalized in city planning. Water scarcity, energy insecurity, and weak food systems are treated in silos, which prevents integrated responses to urban resilience.

Urban farmers often lack access to reliable water for irrigation, face high energy costs for pumping or processing, and operate in food markets that are poorly regulated and inefficient.

These interdependencies, when not properly managed, create systemic vulnerabilities that intensify under climate stress. Moreover, the urban agriculture sector is heavily dependent on the interlinked water-energy-food (WEF) systems, which are themselves strained by rapid urban growth and climate variability. Poor access to water for irrigation, high energy costs, and food system inefficiencies reduce the productivity and sustainability of urban agriculture, limiting its potential to meet the needs of growing urban populations. Despite the growing global literature recognizing the importance of green infrastructure and the WEF Nexus for resilience particularly in Europe, North America, and Asia few studies in West African contexts like Senegal have holistically analyzed the **accessibility and governance of green spaces**, the **constraints of urban agriculture**, or the **institutional mechanisms needed to integrate the WEF Nexus**. Bridging this knowledge gap is essential for designing inclusive, sustainable, and climate-resilient urban strategies in the region.

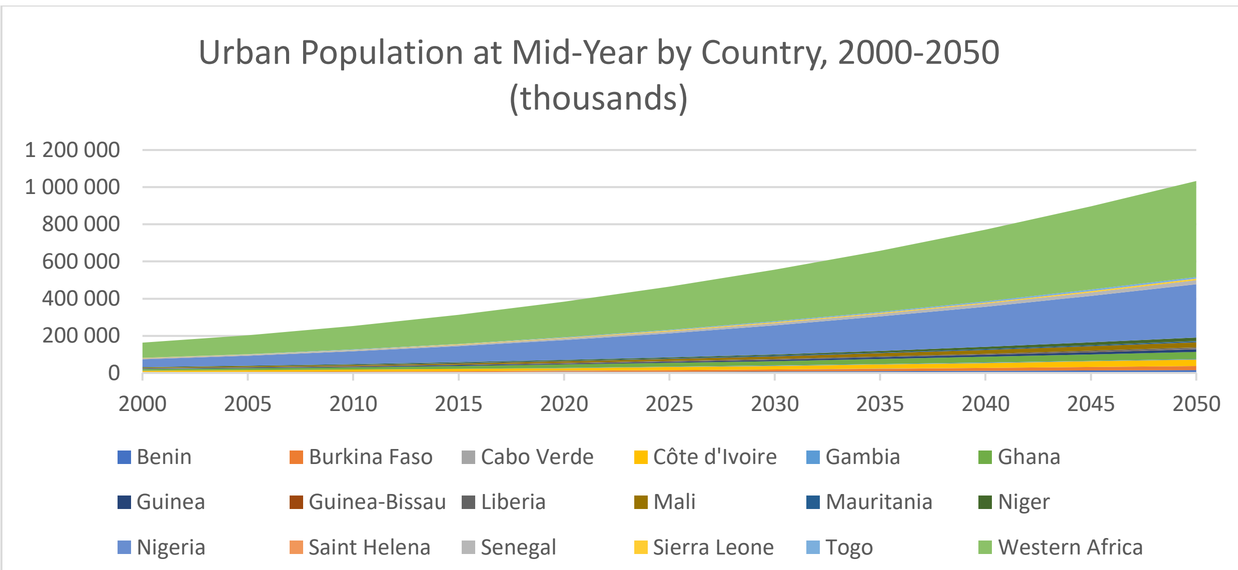
C) Rationale of the study

Urbanization in Africa is taking place at an unprecedented scale and speed, unmatched even by the extremely rapid urbanization in East Asia in the late 20th and early 21st centuries(ECA/AfDB, 2022). In many African countries, such as Senegal, we are witnessing poorly controlled urbanization with the proliferation of so-called “spontaneous” neighborhoods(Cisse, 2022). The Dakar region is marked by this reality through the inadequacies of its current urban planning system, which leads to a lack of control of urban space, a deterioration of the living environment and the social vulnerability of many segments of the population(Cisse, 2022). According to the Africa’s Urbanization Dynamics 2025, the level of urbanization in Africa continues to rise steadily. As of 2025, 57% of the continent's population lives in urban areas, and this proportion is expected to increase to 58% by 2030, 60% by 2035, 62% by 2040, 63% by 2045, and 65% by 2050 (ECA/AfDB, 2022).

This sustained growth reflects the rapid urban transformation underway, which will have significant implications for infrastructure, resource management, and climate resilience.

In Senegal, urbanization is following a similar upward trend. The urban population accounts for 55% in 2025 and is projected to grow to 57% by 2030, 59% by 2035, 60% by 2040, 62% by 2045, and 64% by 2050.

These figures highlight the critical need to anticipate and address the challenges of urban development through integrated planning, investment in basic services, and sustainable management of land, water, energy, and food systems(ECA/AfDB, 2022). The following graph, the UN-Habitat report (2018), illustrates the evolution of the urban population at the midpoint of the year by country, between 2000 and 2050 (in thousands). It highlights a rapid growth of the urban population, particularly marked in developing countries, thus underscoring the growing challenges related to urbanization, resource management, and climate resilience in African cities.



Graph 1: Urban Population at Mid-Year by Country, 2000-2050 (thousands), UN-Habitat, 2018

D) Research question, Objectives and Hypothesis

In order to structure this research and respond rigorously to the issues raised, this study is based on precise research questions, clearly defined general and specific objectives, as well as testable hypotheses presented below.

1. **Research Question**

How do the dynamics between urban agriculture, urban green spaces, and the Water-Energy-Food (WEF) nexus influence food security, climate resilience, and the transition to a green economy in Senegalese cities and West-Africa?

2. **General objective of the thesis**

To analyze how, urban green spaces, urban agriculture and the integration of the Water-Energy-Food nexus can strengthen climate resilience and support the transition to a green economy in African cities, with a particular focus on the Senegalese context.

3. **Specific Objectives**

a) To investigate the role of urban households' knowledge of green cities, satisfaction with the management of green spaces, and willingness to pay in enhancing the effectiveness of urban green spaces in promoting climate resilience in Senegalese cities.

b) To analyze the contribution of urban agriculture to improving food security and enhancing climate resilience in Senegalese cities.

c) To enhance climate resilience in West African by leveraging the Water-Energy-Food (WEF) nexus to facilitate the transition to a green economy.

4. **Research Hypothesis**

a) Socioeconomic characteristics significantly influence citizens' knowledge, satisfaction and willingness to pay for urban green spaces, which are essential elements for strengthening climate resilience.

b) Urban agriculture significantly contributes to food security and climate resilience among urban households in Senegal by strengthening their adaptive capacity through favorable socio-economic factors (such as income, remittances, and education), improved access to productive resources, and the adoption of sustainable practices in the face of climate shocks.

c) Strengthening human capital and promoting sustainable management of natural resources are critical for improving the productivity of water, energy, and food systems, which in turn supports economic growth, mitigates environmental degradation, and drives the transition to a green economy in West Africa.

E) Significance of study

The significance of this study, *"Green Cities and Building Climate Resilient Cities in Africa: Analyzing the Role of Urban Green Spaces, Urban Agriculture, and the Water-Energy-Food Nexus in Advancing the Green Economy Transition,"* lies in its timely relevance lies in its timely relevance to Africa's sustainable development. With rapid urbanization placing growing pressure on infrastructure and natural resources, the research explores how green cities—through urban green spaces and agriculture—can support climate adaptation and mitigate impacts such as floods, heatwaves, and food insecurity. Green spaces offer environmental and health benefits, while urban agriculture promotes food security, local livelihoods, and ecological sustainability.

The study presents an integrated framework for advancing a green economy based on resource efficiency, reduced waste, and resilient livelihoods by linking these strategies with the Water-Energy-Food (WEF) Nexus. The findings provide practical guidance for policymakers, urban planners, and development actors, emphasizing the importance of investing in green infrastructure and climate-smart agriculture. Beyond environmental benefits, the study also addresses social and economic dimensions, highlighting how sustainable urban development can combat poverty, improve quality of life, and support equitable growth. In doing so, it makes a meaningful contribution to literature and practice on climate resilience and sustainable urban transitions in Africa.

F. Research Methodology

In Chapter 1, the study analyzes the role of urban green spaces in climate resilience, focusing on public knowledge, satisfaction, and willingness to pay (WTP). A mixed-methods approach is employed, using both qualitative and quantitative models: To analyze the integration of urban green spaces into climate resilience strategies, this study employs a combination of econometric models.

The Multivariate Probit (MVProbit) model captures the interdependence of knowledge factors across households, farmers, and municipal agents, while a subsequent Probit model assesses the likelihood of varying knowledge levels among these groups, accounting for socioeconomic and environmental variables.

For satisfaction with urban green space management, the study applies the Ordered Logistic model, complemented by the Generalized Ordered Logit (Gologit) model to evaluate the influence of factors such as income, education, and infrastructure.

Lastly, the Logit model estimates residents' willingness to pay (WTP) for improved green space management, considering individual characteristics, environmental values, and perceived benefits. Together, these models provide a comprehensive framework for understanding the roles of knowledge, satisfaction, and WTP in shaping effective and inclusive green space policies across diverse urban contexts.

In the second chapter, the analysis focuses on the interconnections between urban agriculture, food security, and resilience to climate change. A multi-method approach is used: Logistic regression models evaluate the impact of urban agriculture on urban household food security, identifying key socioeconomic and environmental drivers. Decision tree models analyze the adaptive behaviors of urban farmers in response to climate challenges, focusing on decision-making processes around crop choices, resource management, and technology adoption. Normalized Difference Vegetation Index (NDVI) , derived from satellite imagery, is employed to assess the vegetation cover and ecological health of urban agricultural areas as a proxy for climate resilience. This triangulation of methods allows for a nuanced understanding of how urban agriculture can enhance food security and adaptive capacity in urban environments.

The third chapter investigates the integration of the WEF Nexus within green economy transition frameworks in West Africa. It utilizes panel data from the World Bank covering several West African countries. A Principal Component Analysis (PCA) is conducted to construct a composite Food Security Index reflecting multiple dimensions of food availability, access, and stability. A Generalized Method of Moments (GMM) model is then employed to examine the dynamic interactions among water, energy, and food variables, while also capturing the effects of green economy policies on sustainable development and resilience outcomes. This chapter provides empirical evidence on the interdependencies of WEF sectors and their potential to drive inclusive, climate-resilient development.

G. Sources of Data

In chapter 1, Primary data was collected through surveys targeting urban households, farmers, and municipal agents in various Senegalese cities. This data focuses on public knowledge, satisfaction, and willingness to pay for urban green spaces. Secondary data includes census reports and municipal records.

In chapter 2, Primary data was gathered from surveys of urban farmers, households, and municipal agents in selected urban areas in Senegal. Additionally, the Normalized Difference Vegetation Index (NDVI) data was used to assess the resilience of urban agriculture to climate change.

In **Chapter 3**, panel data from the World Bank for West African countries is utilized. Principal Component Analysis (PCA) is applied to construct a food security index, while the Generalized Method of Moments (GMM) model is used to assess the relationships between water, energy, and food systems, and their alignment with green economy policies.

H. Organization of the Study

The initial chapter is oriented towards an examination of the notion of green cities and urban green spaces, with a particular focus on the Senegalese context. It undertakes an analysis of the role of urban green spaces in enhancing climate resilience and improving the quality of urban life.

Furthermore, it assesses the knowledge, satisfaction levels of residents with regard to the management of these green spaces and explores their willingness to pay for the effective management and maintenance of urban green spaces. This analysis highlights the significance of effective urban green space management in fostering climate adaptation and urban resilience, offering insights into public perception and financial support for green infrastructure initiatives.

The second chapter explores the role of urban agriculture in enhancing food security and promoting climate resilience in Senegalese cities. It examines how urban agriculture can contribute to sustainable livelihoods, food access, and resilience to climate shocks in urban areas. The chapter also investigates the challenges and opportunities for integrating urban agriculture into city planning, with a focus on its potential to improve local food systems, mitigate climate change impacts, and foster sustainable urban development.

The third chapter analyzes the interaction between the Water-Energy-Food (WEF) Nexus and its alignment with green economy transition policies in Africa. It explores how the interconnections between water, energy, and food systems can be leveraged to advance sustainable development goals and contribute to climate resilience in West African countries. The chapter also assesses the effectiveness of current green economy policies in addressing these nexus challenges, with particular emphasis on how they can be integrated into national and local strategies to support the transition towards a green economy in the African context.

CHAPTER 1: BUILDING CLIMATE RESILIENT CITY THROUGH URBAN GREEN SPACES: CASE STUDY IN SENEGAL

Abstract: This dissertation explores the role of urban green spaces in enhancing climate resilience and promoting sustainable urban development in Senegal. The main objective of the study is to assess the public's knowledge of green cities and green spaces, satisfaction with their management, and the willingness to pay (WTP) for their improvement. The research employs a mixed-methods approach, combining both qualitative and quantitative data collected from urban households, farmers, and municipal stakeholders in six Senegalese cities. Surveys, interviews, and observational studies were conducted to gather insights into the public's perceptions and attitudes towards urban green spaces and their role in urban resilience. The key findings reveal that knowledge of green cities and green spaces is shaped by socio-economic factors such as education, income, and access to environmental information. Higher levels of education and awareness campaigns positively influence individuals' understanding of urban resilience. Satisfaction with the management of urban green spaces varies, with some respondents expressing satisfaction, while others report challenges such as poor maintenance, accessibility issues, and insufficient integration into urban planning. Furthermore, the analysis of WTP indicates that individuals with higher awareness and satisfaction are more willing to financially support improvements to green spaces. Socioeconomic status, environmental awareness, and the perceived benefits of green spaces were found to be significant determinants of WTP. The dissertation recommends policies that promote public-private partnerships, incentive mechanisms, and effective community engagement to enhance the management, accessibility, and quality of urban green spaces. Additionally, the integration of green spaces into urban planning and the implementation of awareness campaigns are critical for fostering urban resilience and improving the long-term adaptability of cities. These findings provide a foundation for policy recommendations aimed at advancing green cities in Senegal, contributing to long-term urban resilience in the face of climate change.

Keywords: Green cities, Urban green spaces, Climate resilience, Urban resilience, Sustainable development, Knowledge of green cities and green spaces, satisfaction, Willingness to pay, Public awareness, Senegal.

INTRODUCTION

A-Background of the study

In recent decades, rapid urbanization has had a considerable impact on global demographic trends, particularly in Africa, where the urban population is projected to increase threefold by 2050 (UN-habitat, 2010). This unparalleled expansion has contributed to elevated greenhouse gas emissions and the consumption of urban green spaces, particularly in economically disadvantaged cities where green space per capita falls below global standards (White et al., 2017).Consequently, the decrease of urban green spaces has the effect of reducing cities' capacity to mitigate the impacts of climate change. These include extreme heat, flooding, and poor air quality (Anderson et al., 2022) (Lindley et al., 2018).

In response to these challenges, international frameworks such as the Paris Agreement, the Sustainable Development Goals (SDGs), and the New Urban Agenda emphasize the need for sustainable urban planning (WC Report, 2024). However, the frequency and economic cost of climate-related disasters have continued to rise, rendering urban areas increasingly vulnerable to sea-level rise and extreme weather events (I.A. Report, 2020). Without intervention, climate change could reduce global GDP by up to 18% by 2050, with serious implications for the built environment. Urban land transformation for housing exacerbates land scarcity and restricts access to essential urban services, posing a threat to sustainable development (D'Amour et al., 2017; Du & Zhang, 2020).

Theoretical perspectives such as spatial capital (Von Thünen, 1826) and compact city planning advocate for efficient land use to enhance socio-economic and ecological resilience capital (Hillier et al., 2010) ;Ahern, 2011). Urban resilience, defined as the ability to maintain or rapidly restore essential functions after disturbances (Meerow & Newell, 2019), can be strengthened through urban green infrastructure. Green spaces contribute to climate resilience by mitigating flooding, reducing heat islands, improving air quality, and conserving biodiversity (Saleh & Weinstein, 2016). However, challenges such as inadequate design, maintenance issues, and potential health risks must also be addressed (Braubach et al., 2017; Byrne, 2014).

The global response to the threat of climate change has been marked by the adoption of several significant agreements, including the Paris Agreement on Climate Change, the Sendai Framework for Disaster Risk Reduction, the Sustainable Development Goals (SDGs) and the New Urban Agenda (NUA).

In the same context, the United Nations Framework Convention on Climate Change (UNFCCC) has convened the Conference of the Parties to assess progress in addressing climate change(W. C. Report, 2024). In response, the United Nations established Sustainable Development Goal (SDG) 11.7 in 2015, aimed at creating inclusive, safe, resilient, and sustainable cities by 2030. This goal emphasizes universal access to safe, inclusive, accessible, green, and public spaces, with a particular focus on enhancing the quality of life for women, children, the elderly, and persons with disabilities(Ramani & Hettiarachchi, 2022).

Studies show that unregulated urbanization, often driven by rapid population growth, results in poor living conditions for slum dwellers who lack access to basic services like water, sanitation, secure tenure, food, and green spaces (Smit et al., 2017). As more than half of the global population now lives in urban areas, cities have become critical arenas for implementing strategies to combat hunger and poverty.

Many urban centers are struggling to cope with rapid population growth, including the challenges of generating employment, delivering essential services, and managing waste and wastewater. The vulnerability of cities is exacerbated by factors such as economic and political instability and natural disasters. This is demonstrated by growing water scarcity, rising food prices, and the effects of climate change. The combination of rapid population growth, economic disadvantage, and mounting development pressures poses a significant threat to the viability of productive urban green spaces, which are crucial for the well-being and livelihoods of low-income urban communities (Lindley et al., 2018).

For instance, (Douglas, 2018) found that Niamey, West Africa, has the highest proportions of urban dwellers living in slums (81.9%), while Dakar, West Africa, has the lowest proportions in the region (38.1%). The transformation of the landscape to accommodate housing has been identified as a contributing factor to the loss of high-quality agricultural land, which in turn poses a threat to the livelihoods and well-being of residents in various cities(D'Amour et al., 2017).

In response to these challenges, the theory of spatial capital has emerged as a crucial framework for understanding and addressing these issues. This theory posits that the value of land is enhanced by investments in fixed capital, such as infrastructure, buildings, and roads, as well as by the manner in which the spatial form of land is designed in urban areas, thereby creating locations with specific socio-economic and ecological potentials. The aim of this study is to assess the willingness of urban households to pay for the management of urban green spaces.

To effectively evaluate their willingness to pay, it is essential to first understand the concept of green cities and green spaces. This involves examining the level of knowledge urban residents have about green cities and green spaces, as well as their satisfaction with the current management of urban green spaces. By assessing these factors, we can better evaluate the public's willingness to financially support the improvement and maintenance of these spaces. This approach allows for a comprehensive understanding of the factors influencing urban residents' willingness to invest in the sustainability and resilience of green spaces within their cities.

This study seeks to investigate the impact of various factors on the effectiveness of urban green spaces in building climate resilience in Senegalese cities. More specifically, it explores the relationship between urban households' knowledge of green cities & green spaces satisfaction with green space management, and willingness to pay.

B-Research question and objectives

The central research question: How do urban households' knowledge of green cities, satisfaction with green space management, and willingness to pay influence the effectiveness of urban green spaces in building climate resilience in Senegalese cities?

The general objective of this study is to investigate the role of urban households' knowledge of green cities, satisfaction with the management of green spaces, and willingness to pay in enhancing the effectiveness of urban green spaces in promoting climate resilience in Senegalese cities.

Specific Objectives:

1) To assess the level of knowledge of urban households about green cities and green spaces.
2) To evaluate satisfaction with the management and accessibility of urban green spaces.
3) To estimate urban households' willingness to pay for the improvement of green spaces.

To achieve these specific objectives, we propose the following research hypotheses, which aim to explore the relationships between urban households' knowledge, satisfaction, and willingness to pay for urban green space management, in the context of enhancing climate resilience in Senegalese cities.

H1: Higher levels of education, employment in the service sector, and exposure to climate change positively influence knowledge of green cities and green spaces, while larger household size is associated with lower awareness, highlighting socio-economic disparities in environmental knowledge essential for guiding a transition to a green and resilient economy

H2: Gender and education level significantly influence satisfaction with green spaces, with women and individuals with higher education exhibiting lower satisfaction levels, while the impact of other socio-demographic factors varies across different levels of satisfaction.

H3: Socioeconomic characteristics particularly income and education—significantly influence knowledge levels, satisfaction, and willingness to pay for the improvement and management of urban green spaces.

This chapter's main contribution lies in demonstrating how urban green spaces can enhance climate resilience in Senegalese cities. It assesses the current state of urban resilience, highlights the dual role of green spaces in climate mitigation and adaptation, and offers policy recommendations for integrating them into urban planning.

Based on empirical data, the study emphasizes the importance of community engagement and provides a local perspective that enriches the limited literature on green cities in Africa, especially in the context of rapid urbanization and climate challenges in Senegal.

This chapter will analyze these objectives by first establishing the theoretical and empirical approaches, followed by an explanation of the data and methodology used. Finally, the key findings will be presented, providing a comprehensive understanding of the factors influencing urban households' willingness to pay for the management of urban green spaces.

SECTION 1: Theoretical Framework and Empirical Review

This section lays the foundational theories and concepts essential for understanding the research framework. It explores key urban planning theories related to the sustainable and efficient use of land, specifically through the lens of spatial capital theory. According to this theory, land is considered a form of capital that should enhance urban life, ensuring both ecological and socio-economic benefits for all urban residents. This concept aligns with principles found in economic infrastructure resources theory and environmental justice theory, emphasizing the need for equitable access to resources, including green spaces, for all segments of society.

A crucial element in this framework is the self-green governance approach, which serves as a governance model explaining how individuals and communities engage with and manage urban green spaces. This model reflects how collective action in urban green space management contributes to sustainable urban development and climate resilience. By understanding these theories and governance models, we can explore how urban green spaces contribute to building more resilient and sustainable cities.

In addition to the theoretical foundations, this section also introduces key concepts and prior research that provide the empirical basis for the study of urban green spaces, green cities, and climate resilience. The following theories inform the research:

Urban Green Spaces Theory: This theory discusses how urban green spaces are conceptualized within urban planning. Green spaces are recognized not only for their aesthetic and recreational value but also for their critical role in sustainability and climate resilience. They help mitigate urban heat islands, improve air quality, manage stormwater, and promote biodiversity, all of which contribute to a city's ability to adapt to and mitigate climate change impacts.

Green Cities Framework: The concept of green cities refers to urban environments that integrate green spaces into their infrastructure and urban planning. A green city is characterized by the efficient use of land to promote ecological sustainability, social resilience, and economic well-being. Urban green spaces, as a key component of this framework, contribute to the city's environmental health by reducing pollution, enhancing public health, and supporting community well-being.

Willingness to Pay (WTP) Theory: This theory provides insights into how individuals value environmental goods and services, such as urban green spaces. Willingness to Pay (WTP) refers to the amount individuals are willing to pay for improvements in their environment.

In the context of urban green spaces, WTP is used to assess the perceived value that urban residents place on green spaces and their willingness to financially support the enhancement or preservation of these spaces.

1.1. Theoretical framework: Urban green spaces theory

1.1.1. Urban Planning Theories

Urban sprawl, defined by a high-density population, extensive land use, and high pollution levels, poses a significant challenge to the development of resilient and sustainable cities by altering urban landscapes in substantial ways(Dieleman & Wegener, 2004). In response to this challenge, the theory of spaces, based on fundamental, relational, and relativity space theories, provides a novel perspective for integrating green spaces into urban design(van Nes, 2014).

This approach aims to restore urban ecosystem balance by bridging the gap between built environments and open green spaces. This approach entails the expansion of natural green spaces in both horizontal and vertical dimensions, manifested in building components such as floors, walls, and roofs, or through multi-level structures(van Nes, 2014).

Similarly, the compact city theory advocates for the intensive and innovative utilization of urban space, encompassing vertical urban growth, thereby facilitating the integration of green spaces. This approach has been shown to have significant positive impacts on urban life, including the reduction of anxiety and noise levels, as well as enhanced safety and cleanliness(Mouratidis, 2019). In contrast, the garden city theory addresses issues related to uncontrolled urban expansion and weak connections between cities and their surrounding areas. The objective of this theory is to mitigate rising urban social costs(Gatarić et al., 2019).The original concept of the garden city theory envisioned a central city surrounded by satellite towns, each with a limited number of inhabitants, where green spaces serve both agricultural and recreational or hygienic purposes. According to this principle, cities should include a green belt of approximately 300 meters, occupying more than half of the city's landmass and following the waterways to create sports and recreation zones(Pipit Muliyah, Dyah Aminatun, Sukma Septian Nasution, Tommy Hastomo, Setiana Sri Wahyuni Sitepu, 2020).

Recent advancements have resulted in a novel synthesis of compact city and garden city theories, thereby forming a modern compact city model.

This approach advocates for sustainable urban design, emphasizing ecosystem services and integrating green elements such as green roofs, facades, railway corridors, street trees, and greenways in areas where large green spaces are impractical (Russo & Cirella, 2018). This approach is in alignment with the principles of smart growth theory, which advocates for compact, livable, and well-designed urban neighborhoods, emphasizing environmental, ecological, economic, and social benefits(Allah & Khalil, 2017). These theories, which delineate strategies for creating livable cities, are also in alignment with religious perspectives. Bagader et al. (2006), cited by Mensah et al. (2015), emphasize that major world religions, especially Islam and Christianity, encourage the conservation of green spaces. The Quran urges Muslims to protect natural vegetation as a virtuous act, while the Bible's Genesis 2:8-15 commands humanity to cultivate and protect the Garden of Eden.

1.1.2. Spatial Capital Theory

Spatial capital theory examines how urban form influences various aspects of urban life. It provides a valuable perspective on urban form through the lenses of density, diversity, and accessibility, which influence proximity and distance to urban areas. This theory also provides a means to evaluate the impact of urban form on land value, considering both exchange value and use value in relation to social, cultural, environmental, and economic capital.

According to spatial capital theory, the true value of land is derived not only from investments in fixed capital, such as infrastructure (buildings, roads), but also from the way in which the spatial form of the land is designed to integrate socio-economic and environmental potential. In classical economic theory, land was treated as one of the three main factors of production, along with labor and capital. However, with the degradation of land, neoclassical economic theory reduced the factors of production to labor and capital, considering land as merely another form of capital. This perspective was later reconsidered by the spatial economic theory of von Thunen (1826), which considered land as a spatial extension location. Thus, spatial capital theory focuses on urban form, examining how green spaces and other amenities are distributed across urban areas (the floor spaces and the additional spaces). These distributions create specific relationships between spaces, thereby increasing the value of these areas for human well-being and social cohesion(Hillier et al., 2010).

1.1.3. Economic Theory of Infrastructure

The theory of infrastructure, developed by (Frischmannt, 2005), addresses the question of how to manage infrastructure resources, such as transportation systems, environmental resources, and communication networks, that provide both public and private benefits. This theory focuses primarily on demand-side economics, rather than supply-side economics, to better understand how value is created and realized by individuals who gain access to these infrastructure resources. The demand-side analysis emphasizes that infrastructure resources are critical to value creation because they serve as inputs into various production processes that often produce public and nonmarket goods, thereby generating positive externalities that benefit society.

The management of these infrastructure resources in an open and accessible manner is considered socially desirable if it encourages greater participation in activities that lead to economies of scale. A key principle of this theory is that resources should be openly accessible to everyone in the community, regardless of the identity of the end user, especially for resources that are naturally available to all because their characteristics prevent them from being owned or controlled by any one individual. Consequently, (Frischmannt, 2005) argued that restricting access to infrastructure resources such as information, the Internet, and ecosystems could prevent society from fully realizing their value. For natural resources and environmental services, however, he suggested that the value of ecosystem services should be quantified by creating a market to avoid problems of congestion and degradation, thus avoiding negative externalities.

1.1.4. Environmental Justice Theory

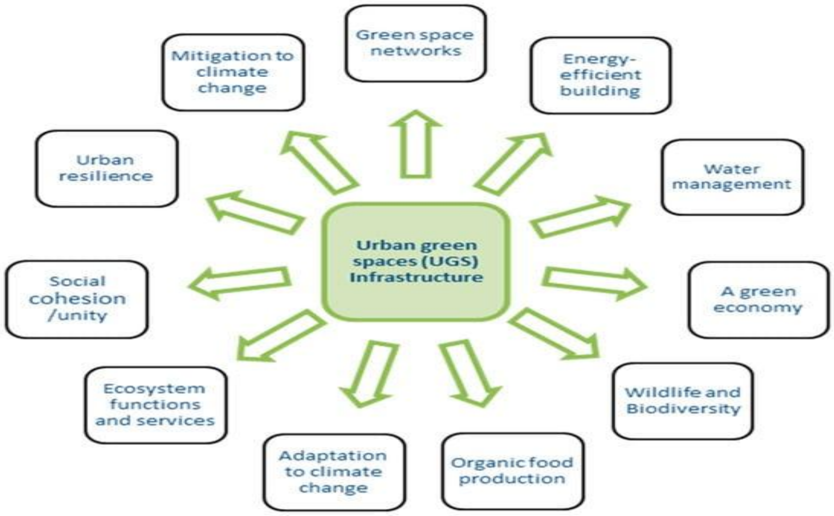
The environmental justice theory, which was first developed in 1987 in the United States as a response to the concept of "environmental racism," highlights the disproportionate exposure of people of color, particularly African Americans, to high levels of pollution while receiving fewer environmental benefits. This theory emerged as a reaction to the systemic environmental discrimination experienced by these communities during that period. Scholars who developed the theory sought to understand the relationship between people and their environment by exploring various environmental dimensions. A particular focus has been on inequities in the distribution of resources such as green spaces, public transit, and access to fresh food, as well as the nature of environmental protection. The environmental justice theory aims to investigate why minority communities have been historically marginalized(Schlosberg, 2004).

One of its recent advancements involves refining the understanding of the mechanisms and processes that drive environmental injustice(Sze & London, 2008). According to (Gallagher, 2008), environmental injustice is not merely an isolated harmful event, action, or outcome, but rather a complex history of political, social, and economic interactions that lead to and perpetuate instances of perceived injustice. In recent years, environmental injustice has been exacerbated by "green gentrification," a process in which urban districts are transformed into greener spaces, increasing property values and making them more attractive to affluent communities. This, in turn, has resulted in the displacement of lower-income populations to other areas (Gould & Lewis, 2018).

1.1.5. Green Self-governance Approach

Green self-governance can be defined as a specific form of governance in which citizens play a significant role in the realization, protection and management of green spaces. It is a system by which citizens manage green spaces across residential areas through a variety of practices or activities, depending on the resources available and certain rules for the improvement of amenities and social cohesion. This form of governance enables citizens to act autonomously from external forces. This approach is a response to the criticisms often levelled at traditional, centralized governance, which relies on a top-down approach(Mattijssen, Buijs, & Elands, 2018). As proposed by (Mattijssen, Buijs, Elands, et al., 2018), the green self-governance approach extends beyond the physical urban green space management. It has the potential to contribute to urban green space management, social cohesion, and environmental education, among other benefits, while removing the financial constraints often experienced by authorities. Further posit that, in recognizing the legitimacy and autonomy of citizens, local authorities can foster a sense of stewardship, thus empowering them to act as key stakeholders in urban green space management. In this sense, local authorities assume an essential role in supporting citizens, thereby facilitating the bottom-up approach.

The following graph illustrates the conceptual framework of urban green spaces, highlighting their role in sustainability, climate resilience, and urban planning. It visually represents the connections between green spaces, environmental benefits, and urban quality of life.



Graph 2: Conceptual framework for the study (Rayan and al,2022)

1.2 Theoretical framework: Understanding Green Cities and Urban Green Spaces

Cities are responsible for a significant share of global energy consumption, accounting for between three-fifths and four-fifths of the world's total energy use due to the intense activities taking place within them. Despite occupying a mere 3% of the Earth's surface, these urban centers are responsible for the generation of four-fifths of the global gross domestic product (GDP)(Associate & Nistor, 2021). The significance of green cities lies in their reduced environmental impact compared to traditional cities. Green cities prioritize social well-being by enhancing social equity and quality of life while fostering stronger collaboration between research institutions, universities, and economic stakeholders(Hameed, 2020). Moreover, green cities have been shown to stimulate higher levels of innovation and productivity, driven by technological advancements, enhanced healthcare systems, and improved working environments(Associate & Nistor, 2021). These enhancements contribute to cost reductions and increased profitability. However, the development of entirely sustainable cities faces challenges due to the rapid pace of urbanization, which manifests not only in the expansion of existing cities but also in the transformation of rural areas into urban centers. Rising urbanization brings new challenges, particularly concerning increased resource consumption, including energy, and the growing movement of goods and people.

The objective of green cities is to ensure equitable access to various services and activities for all population groups. Additionally, green cities promote integrated production and consumption systems, allowing industries to efficiently use raw materials produced by neighboring sectors.

The development of industrial clusters within green cities offers substantial economic advantages, including reduced congestion costs and decreased operational and infrastructure expenses.

In the context of sustainable urban development, compact urban forms are often regarded as more advantageous due to their capacity to reduce transportation distances, enhancing urban energy efficiency and curbing infrastructure-related energy demands. This approach aligns with the principles of green city planning, where land use efficiency, reduced carbon emissions, and better integration of green elements are prioritized. Beyond the economic advantages, green cities offer substantial social benefits, including the reduction of poverty, enhancement of social equity, and the creation of employment opportunities, many of which are green jobs in environmentally sustainable sectors. Health and environmental benefits include lower pollution levels, reduced health risks, and improved ecosystem services.

The transition to green cities necessitates the greening of key urban sectors, including transportation, buildings, energy, vegetation, water management, food systems, waste management, infrastructure, and digital technology. Many countries are actively working toward Sustainable Development Goal 11 (SDG 11), which focuses on building inclusive, safe, resilient, and sustainable cities and communities through targeted government programs(Rigg, 2024). The main objective of the Green Cities Action Programme is to increase people's wellbeing through increased availability of and access to products and services provided by green spaces including urban and peri-urban forestry, agriculture and by sustainable food systems(FAO, 2020). The concept of green cities, also referred to as "eco-cities" by some authors, aims to enhance economic, environmental, and social conditions while ensuring long-term sustainability for future generations (Rigg, 2024).

Urban green spaces are the main natural landscape elements in cities and play a significant role in sustainable urban development, by offering ecological, economic, and social benefits(Xu et al., 2020). They can provide residents with a variety of services and amenities, including enhancing the beauty of the environment, regulating temperature, purifying air, improving overall environmental quality, and providing recreational opportunities (Baur, 2018).

They can be classified as parks, gardens, children's playgrounds, residential green spaces, and other open natural areas(A. C. K. Lee et al., 2015).

With the intensification of urban development, the commercialization of landscaping, and the increase in population and leisure activities, urban green spaces are being reduced and destroyed. The result is a deterioration of the ecological environment and quality of life (Wang et al., 2015). The non-use value, an intrinsic property of eco-environmental resources, corresponds to the value attributed to their mere existence and heritage (Jean-baptiste et al., 2015). Highlighting this value can enable decision-makers to raise public awareness of the existence and heritage value of urban green spaces, thus promoting their conservation and rational use (Pietrzyk-Kaszyńska et al., 2017). Previous studies explored the ecological benefits of urban green spaces, interactions between the well-being of the public and the social and cultural functions of urban green spaces and the role that urban green spaces could play in mitigating climate change (Sun et al., 2019).

Following this, it is important to examine how urban green spaces contribute to ecological balance, climate resilience, and the well-being of urban populations. In the context of Senegalese cities, where challenges such as urban sprawl, pollution, and inadequate infrastructure persist, integrating green space planning into urban policy is becoming increasingly urgent. Understanding the level of knowledge that urban households have about green cities and green spaces is therefore crucial, as it influences their perceptions, engagement, and support for sustainability initiatives.

After examining the knowledge of green spaces and green cities, the next sub-section will assess satisfaction with the management of urban green spaces.

1.3 Satisfaction with the Management of Urban Green Spaces

1.3.1 Theoretical review

The development and preservation of urban green spaces are highly important in the development of cities, and abundant studies have been conducted to understand the functions and services they provide (Xu et al., 2020). Urban green spaces (UGS), which include parks, botanical gardens, playgrounds, and residential green spaces, are key elements of modern urban design (Lafortezza et al., 2013) and provide space for interaction between people, the built environment, and the natural environment. According to (WHO Regional Office for Europe, 2016), UGS promote mental and physical health by providing psychological relaxation and stress relief, stimulating social cohesion, supporting physical activity, and reducing exposure to air pollutants, noise, and excessive heat. Improving access to UGS in cities is also recognized in UN Sustainable Development Goal 11, which aims to make cities and human settlements inclusive, safe, resilient, and sustainable (Maes et al., 2019).

The various characteristics of urban green spaces (UGS) provide significant benefits to users, with factors such as proximity, size, and availability playing a crucial role in their utilization (de Vries & Snep, 2019). These elements are interconnected, diverse, and complex (de Vries & Snep, 2019). The size of a UGS influences how it is used; larger spaces are more conducive to physical activities, while smaller spaces are often preferred for socializing and relaxation. Proximity to residential areas is another key determinant of park usage.

Research shows that individuals living closer to a park are four times more likely to visit it at least once a week compared to those residing farther away(D. A. Cohen et al., 2007). Similarly, (Coombes et al., 2010) found that the frequency of visits decreases as the distance from green spaces increases.

The limited effectiveness of public green spaces in benefiting residents is well-established. However, residents significantly contribute to greening efforts by managing and protecting green spaces on their private properties (Moussa, 2024). Sustainable management of private yards can enhance ecosystem services and promote environmental connectivity between private and public green spaces, reducing ecosystem disservices Aronson et al., n.d.). In this regard, the attitude of dwellers is essential for the sustainable management of urban green spaces (Ajewole et al., 2019), and individual behavior is a key factor . The ability of urban green spaces to provide ecosystem services is contingent on the management actions undertaken by the dwellers and the influencing factors (Comission, 2016). Satisfaction with the management of urban green spaces in Senegal is essential for ensuring their effective use and the long-term benefits they offer to residents and the environment.

1.3.2 Empirical Review

The behavior of people in managing urban green spaces is motivated by a number of factors. Firstly, the benefits of green space perception must be considered, as well as the social status of the people associated with their lifestyles and life stages.

Furthermore, discretionary income is a significant factor, as are people's preferences for aesthetics, safety and property values(Aronson et al., n.d.).

For instance, in Dhaka city, Bangladesh, an increased perception of the benefits of urban green spaces, coupled with a more profound understanding of the cultural ecosystem services they provide, has been shown to lead to an enhancement in urban green space management initiatives (Sultana & Selim, 2021).

Furthermore, the management of green spaces is influenced by various factors, including the authorities' provision of seed assistance, the prevailing sentiment regarding the importance of green spaces, and accessibility to these areas. (Shakeel & Conway, 2014) found that household size and tenure length influence landscaping activities in Mississauga, Canada. (Grove et al., 2014) identified that factors such as family ownership, family size, and marital status are associated with vegetation cover on private residential land in New York City, USA. In a study of San Juan city, Meléndez-Ackerman et al. (2014) found that residential yard green management practices are strongly influenced by yard area and, to a lesser extent, by the age of the respondent and their own house.

Empirical studies from African cities have shown that the management of urban green spaces is driven by socioeconomic, geographical and environmental factors. In Lagos, Nigeria, (Ajewole et al., 2019) demonstrated that household contributions to urban green space management, whether financial, material, or in the form of volunteer hours, are significantly influenced by gender, marital status, and average monthly income. In the city of Kumasi, Ghana, revealed that urban green space management decisions are influenced by a person"s origin, whether urban or rural, their education level, and their short-term interests such as aesthetics, food, fodder, fuel, wood, air quality improvement, shade, windbreak, flood mitigation.

Beyond size and proximity, the quality and characteristics of UGS significantly impact user satisfaction(Tate et al., 2024). Factors such as proper maintenance, the availability of facilities, and overall attractiveness contribute to the appeal of green spaces. Features that promote physical activity, such as well-maintained pathways and a perceived sense of safety, further enhance their usability(Coombes et al., 2010). Additionally, larger green spaces play a vital role in fostering neighborhood social networks, strengthening community interactions and cohesion (Panter et al., 2008). Furthermore, (Zhou & Rana, 2012) study revealed that cultural background and educational status influence preferences for different landscapes, highlighting the impact of professional bias on individuals connections with nature(Fleming et al., 2016).

The impact of age and gender on green space usage has also been documented.

Specifically, (Cerin et al., 2008) reported that teenagers and older individuals visit UGS less frequently, while (D. A. Cohen et al., 2007) found that men tend to use parks more often than women. As UGS benefits become increasingly central to urban society, understanding visitors' attitudes and perceptions of these spaces is essential for urban planners(Grahn & Stigsdotter, 2010). The perception of UGS is influenced by a variety of cognitive, emotional, and behavioral factors (Ma & Dill, 2015).

Research has demonstrated that urban green spaces (UGS) enhance residents' well-being by promoting community, reducing loneliness, and fostering social support, ultimately boosting personal resilience (Ekkel & de Vries, 2017; Arnberger, 2012). UGS also provide mental and physical health benefits, such as through 'green exercise' activities like walking or cycling, which occur in natural settings (Mackay & Neill, 2010).

Additionally, access to UGS is linked to various psychological and emotional benefits (Maes et al., 2019), while they also support mental health, reduce stress, and improve cognitive functions (Barton & Pretty, 2010).

Another key role of UGS is enhancing social capital and cohesion by offering spaces for social interaction, which helps foster a sense of community and reduce loneliness (Davis & Naumann, 2017). The characteristics and amenities of urban green spaces can further strengthen social ties (Fan et al., 2011), while providing opportunities for contact with nature (Y. C. Lee & Kim, 2015). UGS are also critical for mitigating urban heat, improving air quality, and reducing noise pollution (Panter et al., 2008; Sicard et al., 2018).

Moreover, they serve as informal learning spaces, helping to develop children's imagination and understanding of diversity, and provide valuable sites for environmental and ecological research (Sicard et al., 2018; Zhou & Rana, 2012). The following sub-section develops the concept of willingness to pay (WTP) after evaluating the literature review of the satisfaction with urban green space management.

1.4 Willingness to Pay for the Management of Urban Green Spaces

1.4.1 Theoretical review

The development and preservation of urban green spaces play a crucial role in enhancing the overall quality of life in cities. Previous research has extensively explored the various functions and services these green spaces provide, including their ecological benefits, their impact on public well-being, and their social and cultural functions (Xu et al., 2020). Additionally, urban green spaces are increasingly recognized for their potential in mitigating climate change effects (Sun et al., 2019).

Understanding the value that individuals place on these green spaces is essential for informed urban planning and management. One way to assess this value is through the concept of Willingness to Pay (WTP), which estimates the amount people are willing to spend to maintain or improve these spaces. This study adopts a theoretical framework based on Random Utility Theory (RUT) and Lancaster's Theory of Value, both of which are integral to understanding how individuals evaluate and express their preferences for urban green spaces. These frameworks offer valuable insights into the economic valuation of green spaces and provide a solid foundation for assessing the WTP of urban residents for their preservation and enhancement. Lancaster (1971) advanced an alternative approach to the conventional notion that goods are consumed in their totality. Lancaster contended that it is the characteristics of a good, rather than the good itself, that generate utility for the consumer(Dawkins, 2022). This approach finds particular relevance in the context of non-market goods, such as urban green spaces, where the value of the green space itself is complemented by its attributes (air quality, biodiversity, accessibility, psychological well-being, etc.). Consequently, individuals' preferences for green spaces are determined by the benefits they provide, based on their specific characteristics.

2) Random Utility Theory (RUT):

The random utility theory (RUT), as formalized by McFadden (1980), posits that individuals are rational decision-makers who seek to maximize their utility by choosing the alternative that provides them with the greatest benefit. This theory finds wide application in discrete choice models, where individuals' decisions are influenced by both observable and unobservable factors(Dawkins, 2022).

According to RUT, the probability of an individual choosing to pay for an urban green space depends on the utility they derive from it. This aligns with Lancaster's approach, where choices are based on the specific characteristics of the good rather than the good itself. In this study, these theoretical frameworks help assess WTP by considering the attributes of urban green spaces and how different stakeholders perceive their value.

1.4.2 Empirical review

The role of socio-economic characteristics in influencing public use of urban green spaces (UGS) has been a subject of considerable scholarly interest(Panter et al., 2008). Research has indicated that individuals with lower incomes exhibit a lower propensity for engaging in physical activity and face limited access to affordable UGS facilities.

Conversely, higher-income households tend to reside in closer proximity to a variety of green spaces(Panter et al., 2008). Previous studies have estimated the non-market value of environmental resources using scientific and sound valuation methods. Non-market valuation is an economic approach that assigns monetary value to environmental goods and services that are not directly traded in the market. This approach can inform decision making in environmental planning and management (Jim & Chen, 2009).

Many studies have evaluated the willingness to pay (WTP) for urban green spaces, with examples from various countries. In the city of Abidjan, Kouadio et al. (2018) advanced the notion that the financial contributions received from residents for the provision of ecosystem services by public green spaces could play a pivotal role in the effective management of these spaces and the promotion of private urban green spaces through the allocation of subsidies. This financial support could assist residents in covering the substantial costs associated with acquiring plants from landscapers or nurserymen in the market.

In the city of Dar es Salaam, Tanzania, Hassan & Mombo (2017) found that the perception of households regarding the quality of green spaces and their benefits, level of education, and duration of residence positively influenced their willingness to participate in urban green spaces management. Conversely, the perceived cost, age, gender, marital status, and source of income negatively influenced this willingness.

In Senegalese cities, the development and management of urban green spaces are crucial for improving the quality of life and environmental sustainability. The value placed on these spaces is influenced by various factors, including knowledge, satisfaction with management, and residents' willingness to pay (WTP) for their preservation and enhancement.

To better understand this, we will first explore in the following section the knowledge of green cities and urban green spaces in Senegalese cities, followed by an examination of the satisfaction levels regarding their management. Finally, we will assess the WTP of residents, which will provide the importance they attribute to green spaces management. This approach will allow us to evaluate urban green space management in Senegal from a comprehensive perspective.

1.5 Resilience: Concept and definition

To deal with these different urban challenges, the urban professionals and city leaders adopt increasingly the framing concept of **"resilience**" which, however, poses the problem of precision and operationalization (Ahern, 2011).

Resilient cities are cities that can operate efficiently and provide services in distressed conditions. Resilient cities can better absorb the type of shocks and stresses identified. Rather than focusing on vulnerability, focusing on resilience means emphasizing what can be done by a city or community itself, building on natural, social, political, human capital, existing financial and physical resources, while strengthening its capacities. According to the Figueiredo(2018) , The Resilience is increasingly understood as a fundamentally dynamic property of complex socio-technical systems: "the capacity of individuals, communities, institutions, businesses, and systems within a city to survive, adapt, and grow, no matter what kinds of chronic stresses and acute shocks they experience".

From the viewpoint of economics, resilience provides a systematic approach to reduce vulnerability and economic loss and improve the situation of the people in distress climatic (Bastaminia & al., 2017). These losses and damages resulting from the loss of urban green spaces lead to a decrease in insurance values linked to resilience, increasing the vulnerability of cities to shocks such as heat waves, floods, storms, landslides and even food crises (Wangai and al., 2016).

The term „resilience" derives from the Latin word "resilio" which means to „bounce back or rebound. It was used scientifically in English by Francis Bacon in the first decades of the 17th century to describe the strength of echoes (Alexander, 2013). Over time, the concept of resilience stimulates the debate among scientists about a primary perspective, which is still ongoing. Some believe it is an ecological concept, while others attribute it to physics (Serre & Heinzlef, 2018)(Manual & Settings, n.d.). However, the term resilience is used first in social sciences studies such as psychology and psychiatry for cognitive systems and social interaction between individuals, communities, and institutions(Waller, 2001).

The concept of resilience has been developed first in the form of engineering resilience as the ability to bounce back to a single equilibrium (one stable state), then in the form of ecological resilience as a measure of robustness or buffering capacity before a disturbance forces a system from one stable equilibrium to another, and last in the form of evolutionary resilience as the ability to adapt in reaction to a disturbance(Duckworth, n.d.).

Therefore, the concept of resilience has been subject of several definitions which are similar in terms of some system's characteristics such as robustness, recoverability, redundancy, intelligence and adaptability etc. Solicited recently by different disciplines, the concept of resilience has become more visible even though the scholars are not unanimous; some consider it as a process of the system, while others believe that resilience is a result reflecting the system's ability(Kong et al., 2023). To this effect, urban planning and design researchers apply resilience to protect better urban green spaces and biodiversity for the ecosystem services. Thus, urban resilience appears as the city"s ability to simultaneously maintain human and ecosystem functions over the long term (Blessin et al., 2022).

According to the 100 Resilient Cities program(Courtial-sabatier, 2022), resilience is defined as "the capacity of individuals, communities, institutions, businesses, and systems within a city to survive, adapt, and grow, no matter what kinds of chronic stresses and acute shocks they experience" ("Series Editors," 2022)(Keane, 2014). Its measurement calls for the appropriate indicators, which include the service delivery and regulatory functions of urban spaces with the municipal planning processes, communication systems, business environment, and structural and infrastructure-related factors (Bahadur & Pichon, 2016).

Thus, it requires suitable indicators and measures that consider its key attributes, either quantitative or/and qualitative or objective, or/and subjective, depending on the available information (Bousquet et al., 2016).

1.5.1 Resilience Assessment Approaches

Admittedly, there is substantial literature on resilience assessment, but there remains to be a consensus on resilience measurement. Thus, despite the development of several resilience measurement indices, such as the climate disaster resilience index, integrated resilience index, socio-ecological index, and urban resilience index, there is empirically and theoretically a need for consensual resilience measurement indices (Alfani et al., 2015).

However, the most appropriate way to measure climate resilience for a particular context is to look at the elements to include in the measurement. For instance, a multidimensional index is required for the climate resilience measurement for urban areas, which are complex systems.

As a result, the objective approaches are generally employed in developed countries, especially for metropolitan areas and megacities, which need socioeconomic and biophysical data mostly lacking in developing countries(Dhar & Khirfan, 2017). In the case where data are unavailable, the subjective decision from directly the people's perception is solicited for selecting the components/dimensions instead of selecting the components with the risk of leaving out key elements. Thus, this subjective approach appears as an alternative to the objective approach or as complementary (Of et al. 2014).

1.5.2 Resilience measurement

The objective approach involves measuring resilience directly through defined indicators or stated variables derived from measuring observable items(Clare et al., 2017). The multidimensional approach defines these indicators or variables by considering several dimensions (Alfani et al., 2015). Therefore, the indicators such as income level, access to food, and access to essential services such as health, assets, and social safety nets are included at the household or individual level.

At the community level, the quality of the environment and natural resources management institution, access to communal resources, quality of protective infrastructure, levels of peace and security, availability of contingency resources or social safety nets, and social participation in the community are considered. At the national scale, indicators such as transparency, access to information, control of corruption and fraud, accountability, participation, and engagement are included. Significantly, these different scales are intimately intertwined as an individual's resilience is influenced by the community's resilience, which is widely influenced by the national level (Peters et al., 2016). As a result, aggregating composite indicators are used with the increased risk of correlation between the allocated variables' weights (Manual & Settings, n.d.). Although the objective approach is guided by an overarching conceptual framework usually designed by technical experts external to the individuals or households, it remains the norm dictating a broad degree of understanding of resilience processes at all scales Under this approach, resilience is seen as a latent variable broken down into multiple capacities that assign proxy indicators as measures (Clare et al., 2017).

Thus, the application of the objective approach has certain shortcomings, such as the difficulty of getting the relevant indicators from social, political, and economic factors, the need for a broad sample size that is time-consuming and costly, and the failure to consider the people's self-assessment(Peters et al., 2016).

Considering these weaknesses of the objective approach, (Jones & Tanner, 2017) revealed that the resilience contains not only the tangible variables such as livelihood, income, but also the subjective variables such as the risk perception, beliefs, culture, social norms, and social cohesion.

Through this subjective approach, the relevance of resilience indicators remains in the hands of the households driving their development processes (Tyler et al., 2016). Basically, this approach is highlighted in literature via two indicators of resilience:

1) **Indirect independent indicators** estimated based on the households' well-being regressed on selected variables (Alfani et al., 2015). Indeed, household resilience within the city is determined by comparing pre- and post-disaster well-being to maintain general well-being (Of et al. 2014). According to (Alfani et al., 2015), the smaller the difference in well-being, the more resilient the household. However, this measure requires panel data which is scarce in many contexts. Also, using cross-sectional data requires two groups; the treated groups experienced the shocks, and the control groups did not; disasters such as drought usually hit all the people without exception, insofar as it is the same city.

2) **Direct indicators** are constructed with several dimensions that are not latent as considered in the objective approach but are measurable variables estimated using the Principal component analysis or Partial Least Squares(Jones & Tanner, 2017). Indeed, despite the lack of consensus about the number of dimensions to be considered, many studies maintained three capacities such as the capacity to adapt, capacity to absorb, and capacity to anticipate perceived through the four points Likert scale ranking, not at all likely=1, not very likely=2, very likely=3, and extremely likely=4 (Jones et al., 2018).

In sum, as each city regarding its main challenges and characteristics at different scales, should adopt its proper urban resilience measurement index (Beceiro et al., 2022).

SECTION 2: Materials and methods

This section provides an overview of the research methods used to analyze urban green spaces knowledge, satisfaction and willingness to pay. It includes data collection techniques, sampling methods and study area descriptions. To evaluate the willingness to pay, we first determine the knowledge of green cities and green spaces in Senegal, after their satisfaction about the management of urban green spaces.

3.1 Research design and data collection methods

3.1.1 A Unified Approach for Analyzing Knowledge, Satisfaction, and Willingness to Pay

This research employed a cross-sectional study design, using diverse data collection methods. Semi-structured interviews were conducted with household heads, urban farmers, and municipal representatives as the primary units of analysis. Field observations focused on critical aspects such as knowledge of green cities and green spaces, satisfaction, and willingness to pay. Specifically, the study explores how knowledge of green cities and green spaces in urban contexts like Senegal is influenced by socioeconomic, demographic, and environmental characteristics. These observations, supported by notes and photographs, provided a comprehensive view of the local context, as recommended by Leonard et al. (2024).

The research instrument used was a semi-structured questionnaire, which included questions aimed at three key stakeholder groups: farmers, urban households, and municipalities. The questionnaire began with an explanation of the study's purpose and a definition of urban green spaces (UGS). It was structured in four sections: the first addressed socio-demographics, the second focused on socioeconomic characteristics, the third explored perceptions of climate change, urban green spaces, satisfaction, and the characteristics, facilities, and infrastructure of UGS, while the fourth measured understanding or perception of the benefits of UGS.

The general business census report of 2016 provided the total number of urban farmers across different regions of Senegal, which informed the selection of the study regions. Based on this data, the number of farmers was assumed to be equal to the number of households, with one municipality selected per department in each chosen region, as shown in the table below.

These methods allowed for a comprehensive understanding of the various issues, characteristics, and intrinsic aspects related to urban agriculture within the selected regions, aligning with the approach outlined by Leonard et al. (2024). We present below the equation along with the detailed steps of the sampling process:

$$n = \frac{\frac{z^2 \times p(1-p)}{\varepsilon^2}}{1 + \frac{z^2 \times p(1-p)}{\varepsilon^2 N}}$$

Where N = population size; ε = margin of error (percentage in decimal form); z = z-score. The sample size is 344 producers.[1]

Table 1: Sampling Distribution of Urban Farmers, urban households and Municipality

Areas	Urban Farmers	Weight	Adjusted weight	Producer sample	Household	Municipality
Dakar	1891	55%	40%	140	140	5
Diourbel	217	6%	10%	35	35	2
Saint-Louis	215	6%	10%	35	35	1
Thiès	918	27%	30%	105	105	3
Ziguinchor	98	3%	5%	18	18	1
Kaolack	122	4%	5%	18	18	1
Total	**3461**	**100%**	**100%**	**351**	**351**	**13**

a) Data Collection and Sampling Strategy

Based on the ANSD report (2016 and updated data from 2023), we identified the number of urban farmers, urban households, and municipal agents in Senegal. The total sample comprised 547 individuals, including 273 urban households, 261 urban farmers, and 13 municipal representatives. Data collection took place between October and December 2023 using structured questionnaires administered face-to-face. The quantitative data were analyzed using Stata software, with descriptive statistics such as means, frequencies, and percentages used to explore key indicators.

b) Sample Distribution by City and Justification

To ensure geographical diversity, the sample was distributed proportionally across six cities based on the relative presence of urban agriculture, as reported by ANSD (2016).

We assumed that each urban farmer could represent an urban household, which allowed us to determine each region's weight in the final sample. These households represent a subset of the full dataset collected for this study. Initially, the research design targeted a total of **351 urban households** across six Senegalese cities. However, due to **fieldwork limitations, time restrictions, and respondent availability**, the final sample size was slightly reduced. Ultimately, we surveyed **273 urban households** and **13 municipal representatives**.

The final sample remains sufficiently robust to ensure meaningful and representative analysis. It captures key socio-economic and geographic variations, and includes multiple stakeholder perspectives (urban households and municipal authorities) essential for analyzing climate resilience and the role of urban green spaces in Senegalese cities distributed as follow:

• **Dakar (82 households):** the largest urban center and economic hub, justifying the highest number of respondents.

• **Thiès (55 households):** experiencing rapid urban growth with significant peri-urban green space practices.

• **Saint-Louis and Diourbel (41 households each):** a moderate but relevant role in urban green space dynamics.

• **Ziguinchor and Kaolack (27 households each):** similar contributions to urban green initiatives, which justified an equal sample size.

Thirteen municipalities were also approached for the study. However, only 13 municipal representatives participated, primarily due to time constraints or availability issues. Their contributions were key to understanding urban governance and climate resilience policies at the local level. This methodological approach provides a balanced and multi-actor perspective on urban agriculture and resilience in Senegalese cities, integrating insights from households, producers, and municipal authorities. The total sample used in this study consists of **286 respondents**, distributed as follows: **273 urban households**, located in the six selected cities, **13 municipal agents**, representing local authorities and their involvement in managing urban green spaces and climate resilience.

This sample of 286 participants enabled a comprehensive analysis of the **social, economic, and environmental dynamics related to urban green spaces and climate resilience**, integrating diverse stakeholder perspectives across the six urban regions of Senegal. As demonstrated on the table below:

CITIES	Urban households **n=273**	Municipalities **n=13**
Dakar	82	4
Thies	55	3
Saint-Louis	41	2

Diourbel	41	2
Ziguinchor	27	1
Kaolack	27	1

3.1.2 Area of interest and geographical scope

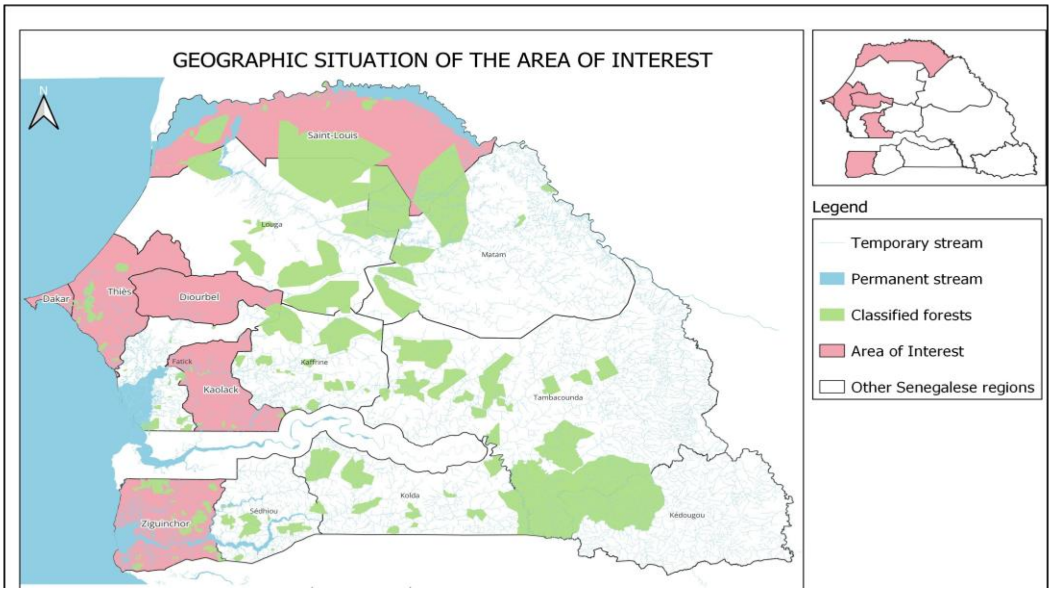
As a member of the Economic Community of West African States (ECOWAS), Senegal occupies a pivotal position in the regional landscape. With a population exceeding 17 million, the country's demographic trends underscore the imperative for effective urban planning and management. As part of this research, six Senegalese cities were selected to analyze the dynamics of urban agriculture and its relationship to urbanization, climate resilience, and sustainable development. The cities: Dakar, Saint-Louis, Ziguinchor, Diourbel, Kaolack, and Thies are strategically important to the agricultural and economic landscape of Senegal. Each city represents unique characteristics in terms of agricultural practices, climatic conditions, and urban development challenges.

Dakar, the capital and largest city, serves as a central hub for commerce, trade, and urbanization. However, it faces challenges related to the encroachment of urban sprawl on agricultural land. The Dakar region, being the most populous, serves as a case in point for the challenges and opportunities posed by urbanization in Senegal. Saint-Louis, with its rich historical significance, contributes not only to agriculture but also to the tourism sector. Ziguinchor, located in the fertile Casamance region, is well-known for its agricultural production, particularly in crop cultivation. Diourbel and Thies, both prominent agricultural cities, focus on the production of essential crops such as millet, sorghum, and groundnuts.

These cities are situated in regions with a tropical climate, characterized by a distinct wet season from June to October, which supports their agricultural activities. Each of these cities has been selected based on its unique demographic and agricultural profile, making them suitable for the study of urban agricultural dynamics in Senegal. The study aims to explore the challenges and opportunities each city faces, particularly in terms of urban green spaces, resilience to climate change, and sustainable development.

This study focuses on six Senegalese cities, as shown in the map below, to analyze urbanization dynamics, with an emphasis on their specific challenges related to urban agriculture, resilience to climate change, and sustainable development.

Area of interest



Graph 3: Geographic situation of the area of interest

These data and cities are valid for determining the three objectives, namely knowledge, satisfaction, and willingness to pay (WTP).

3.2 Methodology 1: Analysis of the Determinants of Knowledge on Green Cities and Green Spaces

The **Multivariate Probit (MVProbit)** model to analyze the simultaneous relationships between multiple binary outcomes each representing knowledge of green spaces or green cities.

The model assumes that these binary outcomes are interrelated and that there are shared underlying factors that influence these outcomes. This approach will facilitate a more comprehensive understanding of the socio-economic, demographic, and environmental influences on public knowledge of green spaces and green cities(Sharna et al., 2022). In this study, we will use the Multivariate Probit (MVProbit) model to examine the factors that influence public knowledge of green spaces and green cities in Senegalese cities.

We adopt the methodology outlined by Sharna et al. (2022) in their analysis of the impact of social, institutional, and environmental factors on the adoption of sustainable soil management practices in Bangladesh, adapting their approach to assess the factors influencing knowledge of green cities and green spaces in Senegal.

This approach allows us to explore the multidimensional influences on public knowledge of green cities and urban green spaces, providing a comprehensive analysis tailored to the Senegalese context.

3.2.1 Model description

Empirically, the model is specified as follows:

$$y_{i1}^*, y_{i2}^*, \dots \dots, y_{im}^* = X_i \boldsymbol{\beta} + \varepsilon_i \qquad \textbf{(1)}$$

For each individual I, we model the latent (unobserved)knowledge of green cities and green spaces as a function of explanatory variable X_i . where:

y_{im}^* is the latent variable for the m-th dimension of knowledge (e.g., knowledge of green cities, knowledge of green spaces), X_i is a vector of explanatory variables, $\boldsymbol{\beta}$ is a vector of coefficients to be estimated and ε_i is a vector of error terms, assumed to follow a multivariate normal distribution.

Binary outcome: The observed outcomes y_{im} (e.g., ''aware''vs.''not aware'') are binary and determined by a threshold function:

$$y_{im} = 1 \quad if \;\; y_{im}^* > 0 \qquad \textbf{(2)}$$

$$y_{im} = 0 \quad if \;\; y_{im}^* \leq 0 \qquad \textbf{(3)}$$

Knowledge of green cities (Equation 1): $y_{i1}^* = X_i \beta_1 + \varepsilon_{i1}$, the observed binary outcome for knowledge of green cities (y_{i1}^*) is determined as follows:

$$y_{i1}^* = \begin{cases} 1 & if \; y_{i1}^* > 0 \\ 0 & if \; y_{i1}^* \leq 0 \end{cases} \qquad \textbf{(4)}$$

Knowledge of green spaces (Equation 2): $y_{i2}^* = X_i \beta_2 + \varepsilon_{i2}$, the observed binary outcome for knowledge of green cities (y_{i1}^*) is determined as follows:

$$y_{i2}^* = \begin{cases} 1 & if \; y_{i2}^* > 0 \\ 0 & if \; y_{i2}^* \leq 0 \end{cases} \qquad \textbf{(5)}$$

After separately examining the different variables related to knowledge of green spaces and knowledge of green cities, we combined them into a single variable.

The multivariate probit (mvprobit) model allows for the simultaneous analysis of several correlated dependent variables. In our case, we have two dependent variables representing environmental knowledge:

$\boldsymbol{Y_1}$: Knowledge of Green Cities

$\boldsymbol{Y_2}$ **:** Knowledge of Green Spaces

We combine these two variables into a single term, $\boldsymbol{Y}^* =$, *which we will refer to as "Knowledge in Green Urbanism" (KGU). Thus, we have:* $\boldsymbol{Y}^* = \begin{bmatrix} \boldsymbol{Y_1} \\ \boldsymbol{Y_2} \end{bmatrix}$

The equation of the mvprobit model is then defined as follows:
$Y_i^* = X_i\beta + \varepsilon_i, \quad i = 1, 2 \ldots$ **(6)**

Y_i^* is the latent variable corresponding to knowledge about green cities and green spaces, X_i is the vector of explanatory (independent) variables.

β is the vector of coefficients associated with the explanatory variables. ε_i ~N(0,Σ) is the error term following a multivariate normal distribution with covariance matrix Σ, which captures the correlation between the two dependent variables.

3.2.2 Description of the variables

Explanatory Variables **(**X_i): The vector X_i includes:

Sociodemographic Factors: Gender_female: Gender (1 = Female, 0 = Male), Age_household, Size_household,

Education Level: Primary_edu, Secondary_edu, Superior_edu

Sector of Activity: Main_activity_Service, Main_activity_trade: Employment in trade, Main_activity_others: Other sectors

Climate Change Awareness: Climate_Change_Observations: Perception of climate change effects and **Constant (α)**

The model can thus be expressed as follows:

$$\boldsymbol{Y_1}^* = \alpha_1 + \beta_1 Gender\_female + \beta_2 Primary\_edu + \beta_3 Secondary\_edu + \beta_4 Superior\_edu + \beta_5 Main\_activity\_service + \beta_6 Main\_activity\_\_trade + \beta_7 Main\_activity\_others + \beta_8 Climate\_Change\_observations + \beta_9 Age\_household + \beta_{10} Size\_household + \varepsilon_1 \quad \textbf{(7)}$$

$$\boldsymbol{Y_2}^* = \alpha_2 + \gamma_1 Gender\_female + \gamma_2 Primary\_edu + \gamma_3 Secondary\_edu + \gamma_4 Superior\_edu + \gamma_5 Main\_activity\_service + \gamma_6 Main\_activity\_\_trade + \gamma_7 Main\_activity\_others + \gamma_8 Climate\_Change\_observations + \gamma_9 Age\_household + \gamma_{10} Size\_household + \varepsilon_2 \quad \textbf{(8)}$$

ε_1 and ε_2 are the **error terms** corresponding to the dependent variables $\boldsymbol{Y_1}^*$ (Knowledge of Green Cities) and $\boldsymbol{Y_2}^*$ (Knowledge of Green Spaces), respectively. They represent the random deviations or unobserved factors that influence the dependent variables in the model.

3.3. Methodology 2: Analysis of the satisfaction about the management of urban green spaces

To properly analyze the determinants of satisfaction with urban green spaces management in Senegal, we applied the ordered logistic model, grounded in the utility maximization theory from neoclassical economics. This theory helps to understand how respondents make decisions regarding their satisfaction with the management of green spaces.

The ordered logistic model is commonly used to analyze ordinal dependent variables, such as satisfaction levels, which are ranked (satisfied, neutral, not satisfied). This model assumes that respondents' satisfaction is influenced by the relative perceived utility of different management practices.

3.3.1 Theoretical model

The theoretical foundation of the model is based on the idea that individuals' decisions are guided by the utility they expect to maximize from their choices. Each level of satisfaction can be seen as motivated by a random utility, with the probability of each level being chosen based on the relative utility of each option(Zhu et al., 2015).

In this context, we assume that respondents' satisfaction with urban green spaces management is influenced by their perceived utility derived from various factors, such as the quality and availability of green spaces, management practices, and the socio-economic characteristics of the respondents (King et al., 2017).

Furthermore, the perceived utility is assumed to be influenced by urban factors such as the city's layout and the local government's planning strategies. In addition to socio-economic characteristics such as income, education, and household size, we also include factors like environmental awareness and the perception of sustainability, as these may influence respondents' satisfaction with green spaces management. This theoretical model is designed to assess the various determinants influencing the satisfaction of Senegalese households with urban green spaces management, with a particular focus on urban planning and management practices that impact their daily lives and the quality of their environment.

3.3.2 Empirical model: Model and variables description

Ten green space benefits referenced broadly in the literature were selected, and the respondents' level of agreement against each statement was measured using a 3-level Likert scale (1= satisfied, 2=neutral and 3=not Satisfied). An ordered logit model was conducted to determine factors influencing satisfaction with use of urban green spaces.

The ordered logit model is used with dependent variables with more than two responses(Steve Hatfield-Dodds, 2007) and it is more robust and offers more advantages than the ANOVA used for categorical outcome variables (Jaeger, 2008).

Explanatory variables:

The dependent variable is the satisfaction derived from the use of the urban green spaces, and explanatory variables are those hypothesized to influence the satisfaction. Respondents' satisfaction with each green space was rated on a 3-point Likert scale on three aspects: quality, social benefits, and environmental benefits. These aspects contain several items; therefore, a composite score of each of these aspects was obtained using factorial analysis. Generating composite scores using weighted factor scores is essential for scores to be used as independent or dependent variables (DiStefano et al., 2009).

Then**, the variables of our model** include household gender, household education, household age, household size, environmental awareness and perceptions of sustainability. In this study, we follow the methodology outlined by Rai et al. (2022) in their analysis of user satisfaction and the social and environmental benefits of urban green spaces, adapting their approach to assess satisfaction with the management of green spaces in Senegalese cities. The ordered logit model used in the study is based on Equation (1) (Rai et al., 2022).

$$Y^*{}_i = \beta' X_i + \varepsilon \qquad \textbf{(9)}$$

where $Y^*{}_i$ is the unobserved measure of the satisfaction (dependent variables), X_i is the vector of explanatory variables, β' is the vector of regression coefficient to be estimated, and ε is the error effect. The ordered logistic regression model used in the study to determine the factors influencing the satisfaction on urban green space is given by Equation (2):

$$\boldsymbol{Y_1}^* = \alpha_1 + \beta_1 Gender\_female + \beta_2 Primary\_edu + \beta_3 Secondary\_edu + \beta_4 Superior\_edu + \beta_5 Age\_household + \beta_6 Size\_household + \beta_7 awareness + \beta_8 sustainable\_feeling + \lambda \qquad \textbf{(10)}$$

3.4 Methodology 3: Willingness to pay about urban green spaces management

Various methods have been used to evaluate the average WTP of eco-environmental resources, such as arithmetic mean (Liu and Zhang, 2018; Jin et al., 2016), parameter estimation (Chen and Qi, 2018), and regression (Shi et al., 2014; Hao et al., 2018). Based on a comprehensive evaluation of these methods, we will use the logistic regression model to estimate the willingness to pay (Xu et al., 2020).

To estimate the **Willingness to Pay (WTP)** using logistic regression, we assume that the dependent variable (WTP) is binary, where 1 represents a positive response (willing to pay) and 0 represents a negative response (not willing to pay). The logistic regression model estimates the relationship between WTP and independent variables such as gender, education level, main activity, observations on climate change, age, size of the household, and income.

Logistic Regression Equation: The logistic regression model can be specified as follows:

$$Logit\ (P(y=1)) = \boldsymbol{Y_1}^* = \alpha_1 + \beta_1 Gender\_female + \beta_1 Primary\_edu + \beta_3 Secondary\_edu + \beta_4 Superior\_edu + \beta_5 Main\_activity\_service + \beta_6 Main\_activity\_\_trade + \beta_7 Main\_activity\_others + \beta_8 Climate\_Change\_observations + \beta_9 Age\_household + \beta_{10} Size\_household + \beta_{11} income\_household + \varepsilon_1 \quad \textbf{(11)}$$

Where y is the binary dependent variable representing Willingness to pay (WTP), where y=1 if the individual is willing to pay, and y=0 otherwise.

- $Logit(P(y=1)) = \log\left(\frac{(P(y=1))}{1-(P(y=1))}\right)$ **(12)**

is the log-odds of the probability of being willing to pay. The independent variables are the factors that may influence the willingness to pay.

SECTION 3: RESULTS

5.1 Econometric Analysis of the Determinants of Household Knowledge Regarding Green Cities and Green Spaces: A multivariate Probit Model

This sub-section presents the econometric analysis of the determinants of household knowledge about green cities and green spaces in Senegal, using the Multivariate Probit model. The table below presents the estimation results, highlighting the key socio-economic, demographic, and environmental factors that significantly influence this knowledge.

Table 2: MVPROBIT Model: Knowledge of Green Cities and Green Spaces

VARIABLES	**Mvprobit**	**Mvprobit**	**Mvprobit**
Gender_female	-0.257	-0.119	
	(0.212)	(0.218)	
primary_edu	**0.355**	**0.903*** **	
	(0.240)	(0.230)	
Secondary_edu	**1.020*** **	**1.388*** **	
	(0.241)	(0.262)	
Superior_edu	**1.520*** **	**1.858*** **	
	(0.359)	(0.452)	
Main activity_Service	**0.846***	**1.094***	
	(0.492)	(0.621)	
Main activity_trade	0.217	0.395	

	(0.255)	(0.260)	
Main activity_others	-0.100	0.419	
	(0.257)	(0.261)	
climate_change observations	**1.147*** **	**0.908*** **	
	(0.422)	(0.279)	
Age_household	-0.007	0.006	
	(0.007)	(0.007)	
size household	**-0.025**	**-0.045** **	
	(0.019)	(0.019)	
Constant	**-1.295** **	**-1.177** **	**0.702*** **
	(0.591)	(0.522)	(0.150)
Observations	253	253	253
Wald chi2	104.5	104.5	104.5
Prob>chi2	0	0	0
Standard errors in parentheses			
***** p<0.01, ** p<0.05, * p<0.1**			

Interpretation of Results from the Multivariate Probit Model (mvprobit): The coefficient for gender (Gender_female) is negative for both types of knowledge, but not significant. This suggests that women may have a lower probability of possessing this knowledge compared to men, though this effect is not statistically significant. Education Level (primary_edu, secondary_edu, superior_edu): The probability of knowing about green cities and green spaces increases with higher education levels.

Primary education has been shown to have a positive effect and significant on knowledge of green spaces (significant at 1%), but not on green cities. The coefficients are positive and significant at the 1% level ($p<0.01$) for secondary and higher education, suggesting that education plays a key role in acquiring this two knowledge.

Main Activity (Main activity_Service, Main activity_Trade, Main activity_Others): The impact of working in services is positive and significant ($p<0.1$) on knowledge of green cities and green spaces, while trade and other activities do not have a significant impact. Climate Change Observations (climate_change observations): A positive and significant effect ($p<0.01$) on knowledge of green cities and green spaces, indicating that individuals exposed to or sensitized to climate change have more knowledge about these topics. Age of Household Head (Age_household): The coefficients for this variable are close to zero and not significant, suggesting that there is no clear impact on knowledge.

Household Size: A negative and significant effect ($p<0.05$) on knowledge of green spaces is observed. This indicates that individuals in larger households are slightly less likely to possess this knowledge.

The general significance of the Model: The Wald test (Wald chi2 = 104.5, Prob > chi2 = 0) indicates that the model is globally significant, suggesting that all explanatory variables contribute significantly to explaining knowledge of green cities and green spaces. This model allows for analyzing how individual characteristics and socio-economic factors influence the probability that an individual has knowledge of green cities and green spaces.

The objective is to identify the primary factors influencing awareness of green urban planning and to formulate recommendations for improving access to environmental information in the context of the transition to a green and resilient economy.

The findings indicate that education plays a pivotal role in shaping knowledge of green cities and green spaces. Individuals with higher levels of education demonstrate a greater degree of awareness regarding these concepts, suggesting the necessity for public policies to prioritize the incorporation of environmental subjects into educational programs to facilitate a transition to sustainable urban development.

Employment in the service sector and exposure to climate change significantly increase the likelihood of possessing such knowledge. Gender and age do not appear to have a significant effect, whereas household size may negatively influence knowledge of green spaces. The sector of activity has been demonstrated to influence awareness of environmental issues. Workers in the service sector, for instance, are more likely to have this knowledge, which may be related to their greater exposure to urban and environmental issues in this sector.

In contrast, people working in trade and other sectors do not show a significant impact, indicating a possible lack of environmental information in these fields. Direct experience of climate change also plays a key role; those who perceive concrete effects of climate change are more likely to understand the importance of green infrastructure. This highlights the necessity for enhanced communication and dissemination of environmental impacts to cultivate support for sustainable planning policies.

The findings indicate a negative effect of household size on green space knowledge, suggesting that larger families may prioritize economic and social concerns. This observation supports targeted education policies, especially since these households also show slightly lower satisfaction, possibly due to inadequate infrastructure or different priorities.

The political and economic implications of these findings are as follows: In the context of rapid urban growth and the transition to a green economy, these results highlight the pivotal role that education, awareness, and well-adapted public policies can play in the adoption of green infrastructure and the resilience of African cities and facilitating a just and sustainable urban transition. Education and climate change awareness emerge as the predominant determinants of satisfaction with green spaces. The implementation of environmental education from primary school and the reinforcement of modules related to sustainable urban planning in secondary and higher education is imperative. The development of sector-specific awareness campaigns, particularly in sectors where the impact on knowledge of green infrastructure is minimal (trade, other sectors), is also crucial.

The reinforcement of information on climate change to improve perceptions of ecological infrastructure and encourage its adoption is essential. The implementation of inclusive strategies that consider the economic constraints of larger households is necessary to ensure a green transition that is accessible to all social groups.

Probit Model: To further analyze the determinants of knowledge about green cities and green spaces, a Probit model is estimated after the Multivariate Probit (MVProbit) to verify the robustness of the results, simplify interpretation, and assess the individual effects of explanatory variables on each dimension separately. The estimated Probit model analyses the probability that an individual knows the concepts of green cities and green spaces as a function of a set of explanatory variables. As demonstrated on the table below:

Table 3: Probit model

VARIABLES	Probit	Probabilities
Gender_female	-0.123	(0.216)
Primary_edu	0.950***	(0.236)
Secondary_edu	1.367***	(0.262)
Superior_edu	1.787***	(0.453)

Main_activity_service	1.071	(0.677)
Main activity_trade	0.400	(0.257)
Main activity_Others	0.419	(0.263)
Climate_change_observations	0.955***	(0.292)
Age_household	0.003	(0.007)
Size-household	-0.039**	(0.019)
Constant	-1.207**	(0.527)
Observations	253	
Wald chi2	94.93	
Prob>chi2	0	
Standard errors in parentheses		
*** p<0.01, ** p<0.05, * p<0.1		

The results highlight the significant impact of education in enhancing knowledge of green cities and green spaces, while household size exerts a negative influence on awareness, potentially due to resource constraints. Direct experience with climate change has been shown to enhance environmental knowledge, emphasizing the necessity for awareness campaigns. Gender, age, and sector of activity demonstrate no significant effects. The study's policy recommendations include the integration of environmental education from primary school, the implementation of participatory awareness strategies, and the targeting of large households with tailored initiatives to promote sustainable urban development and resilience.

5.2 Econometric Analysis of the Determinants of Household satisfaction regarding the management of green Spaces: An ordered logistic model (Ologit)

This sub-section presents the econometric analysis of the determinants of Household satisfaction regarding the management of Green Spaces.

a) **Ordered Logit Model Interpretation:**

In this Ordered Logit (Ologit) model, the dependent variable represents satisfaction with the management of urban green spaces, measured on an ordinal scale (1 = satisfied, 2 = neutral, 3 = dissatisfied). The objective is to analyze how various socio-economic factors influence this satisfaction. As we demonstrate in the following table:

Table 4: An ordered logistic model (Ologit)

Variables	Ologit	Prob
Gender_female	-1.128***	(0.374)
Main_activity_trade	0.091	(0.389)
Primary_edu	-0.834	(0.722)
Secondary_edu	-0.740	(0.886)
Superior_edu	-0.928	(1.083)
Age_household	-0.009	(0.013)
Size_household	-0.024	(0.043)
Awareness	0.037	(0.408)
Sustainable_perception	0.289	(0.355)
Lamda	-1.837*	(0.963)
/cut1	-4.549***	(1.312)
/cut2	-2.704**	(1.270)
Observations	155	
Wald chi2	21.60	
Prob>chi2	0.0173	

Standard errors in parentheses
***p<0.01, **p,0.05, *p<0.1 **p<0.05

The study reveals that women express greater satisfaction with urban green space management compared to men, a difference that may be attributed to varied usage patterns or expectations. Economic activity, education level, age, and household size do not significantly impact satisfaction. Furthermore, environmental awareness and perceptions of sustainability do not demonstrate a significant impact. However, a substantial Lambda coefficient suggests the presence of unobserved factors influencing satisfaction, highlighting the need for further investigation. The model's threshold parameters confirm its validity.

Conclusion and Policy Implications:

The results of the ordered logistic model show that gender (female particularly) is the main factor influencing satisfaction. Women are more satisfied with the management of green spaces than men. This should be considered in urban planning policies by implementing green spaces tailored to the needs of different social groups. Education level does not appear to be a significant factor in determining satisfaction, suggesting that access to and the quality of green spaces may have a greater influence on satisfaction than education level. Economic activity in trade does not have a significant effect on satisfaction, indicating that improving green spaces may not be a priority for traders. Awareness and perception of sustainability do not directly influence satisfaction, implying that urban policies should consider more than awareness campaigns and focus on concrete actions to improve the quality of green spaces.

The following part will discuss implications for urban management policy. First, it is essential for policymakers to pay close attention to the preferences of different social groups, particularly the differences in perception between men and women. Second, concrete actions on green space quality (maintenance, accessibility, appropriate infrastructure) should be prioritized over awareness campaigns. Third, understanding hidden factors affecting satisfaction would help optimize investments in urban green space management. Fourth, although many studied variables do not have a significant effect on satisfaction, gender emerges as a key determinant. To enhance perceptions of urban green space management, a diversified approach is imperative, tailored to the diverse expectations and utilization patterns of these spaces. The presence of endogeneity bias indicates that unmeasured factors influence satisfaction. **The transition to the Generalized Ordered Logit Model (Gologit) is imperative.**

b) Transition to Generalized Ordered Logit Model

In light of the outcomes of the proportional odds assumption test, which means that the impacts of explanatory variables are not constant across satisfaction levels, it is necessary to estimate the Generalized Ordered Logit (Gologit) model to capture these variations and obtain a more precise analysis of the determinants of satisfaction with urban green space management. In this case, the transition from the Ologit model to the Gologit model is justified by the violation of the proportionality assumption of effects. This assumption stipulates that the impact of explanatory variables on the probability of being in a given satisfaction category remains constant across all classification levels. Nevertheless, the findings reveal that this effect fluctuates across satisfaction levels, particularly for the gender variable (Gender_female). This finding highlights the necessity for a more adaptable model, such as Gologit, which addresses this limitation and facilitates a more nuanced examination of satisfaction determinants. As we demonstrate in the following table:

Table 5: Generalized Ordered Logit Model

VARIABLES	(1) Ologit	Prob	(2) Ologit	Prob
Gender_female	0.490	(0.749)	-1.445***	(0.428)
Main_activity_trade	-1.483*	(0.770)	0.482	(0.444)
Primary_edu	-0.271	(1.376)	-1.178	(0.909)
Secondary_edu	-1.875	(1.637)	-0.850	(1.083)
Superior_edu	-3.516*	(1.945)	-0.747	(1.322)
Age_household	-0.031	(0.022)	-0.010	(0.015)
Size_household	-0.028	(0.068)	-0.016	(0.049)
Awareness	-1.038	(0.681)	0.387	(0.440)
Sustainable_perception	0.669	(0.631)	0.233	(0.387)
lambda	-1.256	(1.774)	-2.517**	(1.283)
Constant	5.808**	(2.399)	2.989*	(1.547)
Observations	155		155	
Wald chi2	55.79		55.79	
Prob>chi2	05		3.12e-05	
Standard errors in parentheses		*** p<0.01, ** p<0.05, * p<0.1		*** p<0.01, ** p<0.05, * p<0.1

The Gologit model allows us to examine how the determinants of satisfaction with green spaces vary by relaxing the proportionality of effects assumption. The table presents results from two models: an Ordered Logit (Ologit) and a Generalized Ordered Logit (Gologit).

The Gologit model is particularly useful when the proportional odds assumption of the Ologit model is violated, as indicated by the significant lambda parameter (-2.517**), suggesting that the effect of explanatory variables varies across satisfaction levels.

Gender (Female): In the Gologit model, being female is associated with a significantly lower likelihood of higher satisfaction with green spaces (-1.445***). This result suggests that women are less likely than men to report being very satisfied with green spaces, which may reflect differences in usage patterns or concerns such as safety. This finding aligns with previous studies, including Cohen et al. (2007), which showed that men are generally more likely to use parks than women.

Main Activity (Trade): Individuals engaged in trade show a negative and significant coefficient (-1.483*) in the Ologit model, suggesting lower satisfaction levels. However, this effect is not significant in the Gologit model, indicating that the impact may vary across different satisfaction thresholds.

Education Levels: Higher education levels are associated with more critical views of green spaces. Notably, individuals with superior education show a significant negative coefficient (-3.516*), implying higher expectations and possibly greater awareness of environmental issues.Age and Household Size: Both variables show small and insignificant coefficients in both models, indicating no substantial impact on satisfaction levels. Awareness and Sustainable Perception: While these variables have positive coefficients, suggesting a trend towards higher satisfaction among environmentally aware individuals, the effects are not statistically significant.

Conclusion: The Gologit model provides a significant understanding of the determinants of satisfaction with green spaces. Significant factors include gender and education level, highlighting the need for targeted policies to address the specific concerns of different demographic groups.

Women demonstrate a lower propensity for dissatisfaction, indicating the necessity for specific design considerations, such as safety and accessibility. Retailers demonstrate more stable satisfaction, highlighting the potential role of green spaces in local economic development, such as increasing commercial attractiveness.

Higher education is associated with more stable satisfaction, potentially reflecting greater environmental awareness and engagement. In addition, specific structural factors have been identified as having a significant impact on satisfaction, highlighting the necessity for a more comprehensive evaluation of urban planning and green space management policies. The violation of the proportional odds assumption justifies the use of the Gologit model, offering a more flexible approach to analyzing ordinal outcomes.

Political implications and Recommendations: Strengthening access to higher education could stabilize individuals' satisfaction, while supporting commercial activities could enhance economic resilience and satisfaction. Exploring latent determinants (such as income, living conditions, and access to services) could improve the understanding of satisfaction, guiding the implementation of targeted awareness programs. These programs should focus on enhancing environmental education and engagement initiatives to cultivate a greater public appreciation for green spaces. Additionally, the improvement of maintenance and management practices, including the quality, accessibility, and the management of green spaces, is essential to minimize dissatisfaction. Integrating green spaces into local economic strategies could further leverage their potential to stimulate commercial activity and support urban development. Finally, designing population-specific strategies requires further research on diverse user expectations to tailor green space planning and promote inclusive urban design.

5.3 Willingness to Pay for the Management and Improvement of Green Spaces: A logistic model Analysis

Following the analysis of satisfaction with urban green space management, we investigated the factors influencing individuals' willingness to financially contribute to the enhancement and management of these spaces.

Our approach included conducting association tests, such as the Pearson test, examining the frequency distribution of willingness to pay for the preservation of urban green spaces, and applying a logistic regression model to identify significant predictors.

a) Analysis of the Association between Perception of Climate Change and Willingness to Pay for the management of urban green Spaces: Pearson test

The table below shows the association test about climate change perceptions and WTP.

Table 6: Pearson test

Willingness to pay	**Climate change perceptions**	**No (%)**	**Yes(%)**	**Total**
Yes (1)	Yes(1)	86.8	96.4	88.9
No (2)	Yes(1)	13.2	3.6	11.1
Total		100	100	100
Pearson Test				
Chi² test	**Value** = 4.1056			
	Pr = 0.043			

The aim of this analysis is to assess the determinants of willingness to pay for the management of urban green spaces, in relation to perceptions of climate change. This table shows that 96.4% of people who have observed climate change are willing to pay for the management of urban green spaces. In contrast, only 86.8% of those who have not observed climate change are willing to pay. This suggests a relationship between perception of climate change and willingness to pay.

Chi² test shows a Pearson chi2(1) value = 4.1056 Pr = 0.043, indicating the difference between observed and expected values. The p-value = 0.043: Less than 0.05, so there is a significant association between climate change perception and the probability of willingness to pay (willingness_to_pay). In this study, three key factors influence individuals' willingness to support climate resilience initiatives:

1. **Perception of Climate Risks**: Individuals who have directly observed climate change impacts tend to have an increased perception of environmental risks, making them more inclined to support environmental protection efforts.
2. **Awareness and Information**: Those who recognize climate change are often better informed about its adverse effects, such as floods, droughts, and pollution. This awareness correlates with a greater willingness to contribute financially to adaptation and resilience solutions.

3. **Proximity Effect**: The more immediate and tangible a problem is perceived, the more likely individuals are to take action. When climate change is not seen as an urgent or personal issue, people tend to be more skeptical or less motivated to address it.

These findings underscore the importance of raising public awareness and making the impacts of climate change more relatable in order to encourage proactive engagement in environmental initiatives.

b. Frequence distribution relationship between willingness to pay and the preservation of urban green spaces

Table 7: frequence distribution WTP and the preservation of UGS

WTP_UGS	Freq.	Percent	Cum.
1-Yes	56	22.13	22.13
2-No	197	77.87	100.00
Total	253	100.00	

The study reveals that 22.13% of urban households (around 56 people) are willing to pay to preserve urban green spaces, while 77.87% (197 urban households) are not. Thus, less than a quarter of respondents expressed financial consent for these spaces. Several factors may explain this low willingness to pay. Urban green spaces, as public amenities, offer benefits to all residents, regardless of individual financial contributions. Nevertheless, this universal accessibility can lead to situations where some households enjoy these benefits without contributing to their maintenance. This challenge is exacerbated by budget constraints, making households prioritizing essential needs over environmental contributions. The limited awareness of the advantages of green spaces and the lack of knowledge about the management of the funds also reduce the willingness to pay. Nevertheless, individuals with higher education, income, and firsthand experience of climate change effects are more likely to financially support green space initiatives, recognizing their environmental and social value.

c. Analysis of the determinants of willingness to pay for the preservation of urban green spaces: Logistic regression

The following table shows the logistic regression of the relationship between willingness to pay and the preservation of urban green spaces.

Table 8: Logistic regression of the determinants of willingness to pay for the preservation of urban green spaces

Logistic regression Log likelihood= -104.9222	Number of obs=253 LR chi2(12)=57.63 Prob>chi2=0.0000 PseudoR2=02155					
Dependent Variable						
Willingness_to_pay	**Coefficients**	**Std.Err.**	**z**	**P>|z|**	**[95% Conf.**	**Interval]**
Independant variables				0.618	-.6113334	1.028886
Gender_female	.208	0.418	0.5	0.684	-.8312	1.266
Primary_edu	.217	0.535	0.41	**0.001**	.596	2.507
Secondary_edu	1.55	0.487	3.18	**0.00**	1.499	4.003
Superior_edu	2.751	0.6387	4.31	0.61	-1.909	1.120
Main_activity_service	-.394	0.773	-0.51	0.694	-1.242	.8271
Main_activity_trade	-.207	0.528	-0.39	0.359	-1.478	5.351
Main_activity_others	-.471	0.513	-0.92	0.064	-.0859	3.128
Climate_change_observations	1.520	0.819	1.86	0.111	-.0053	.0518
Age_household	.023	0.014	1.59	0.711	-.086	.058
Size_household	-.013	0.036	-0.37	0.56		
Income						
2	1.955	0.535	3.66	**0**	.907	3.003
3	1.312	0.560	2.34	**0.019**	.215	2.410
-cons	-5.726	1.435	3.99	0.000	-8.540	-2.913

Logistic regression analysis of willingness to pay for the preservation of urban green spaces highlights three main determining factors: level of education, income and perception of climate change. The analysis indicates that education level has a significant role in influencing willingness to pay for urban green spaces. Respondents with a primary education are found to be more than willing to pay compared to those with no education, with a p-value of 0.001.

This association becomes even more pronounced with secondary education, which shows a highly significant positive association (p = 0.000), indicating that individuals with secondary education are much more likely to contribute financially. Conversely, the impact of higher education, despite having a high coefficient, is not statistically significant (p = 0.61), which may be due to the small sample size in this category, resulting in a large standard error.

In terms of gender, the variable "female" is not statistically significant (p = 0.684), suggesting that gender does not have a notable impact on willingness to pay. Furthermore, variables associated with primary economic activity, including employment in services, trade, or other activities, do not show statistically significant effects. The variable reflecting climate change observations also demonstrates no statistically significant effect (p = 0.111), although the positive coefficient suggests that those who have perceived climate change effects may be more willing to pay.

Regarding demographics, the age of the household head (p = 0.711) and household size (p =0,56) do not significantly affect willingness to pay. These findings imply that basic demographic factors have limited influence in this context. However, income levels are strong predictors. Specifically, income level 2, categorizing middle-income households, is significant (p = 0.000), indicating that these individuals are much more likely to be willing to pay. Income level 3 (higher-income households) also shows a statistically significant positive effect (p = 0.019), confirming the role of economic capacity in shaping willingness to support green initiatives.

Policy implications highlight that strengthening environmental education, implementing progressive contribution schemes, and increasing public awareness of climate risks can enhance support for green space conservation initiatives. To achieve this, it is essential to reinforce environmental education to improve the acceptability of green policies, introduce progressive contributions and tax incentives to promote equitable participation, and raise awareness of the tangible effects of climate change to foster greater support for green initiatives.

In the following subsection, we present the results from municipalities through tables and figures to illustrate the initiatives undertaken by the Senegalese government, based on our survey conducted with municipal stakeholders.

5.4 Municipal 2. Strategies for Green Cities and Climate Resilience in Senegal

Urban resilience to climate change has emerged as a pressing concern for municipalities, particularly in rapidly urbanizing regions such as Senegal(Rouhana et al., 2015). As climate challenges intensify, local governments assume a pivotal role in implementing strategies to enhance sustainability, mitigate environmental risks, and promote green urban development(Schwarz et al., 2017).

This study uses a survey conducted across six cities in Senegal to analyze municipal agents' perceptions of climate change, their concerns regarding urban resilience, and the initiatives undertaken to develop green spaces and sustainable urban environments. The study examines how municipalities manage green spaces, their policies for climate adaptation, and the effectiveness of their interventions in enhancing urban resilience.

5.4.1 Perceptions and Concerns of Municipal Agents Regarding Climate Change in Senegal: Insights for Enhancing Urban Resilience

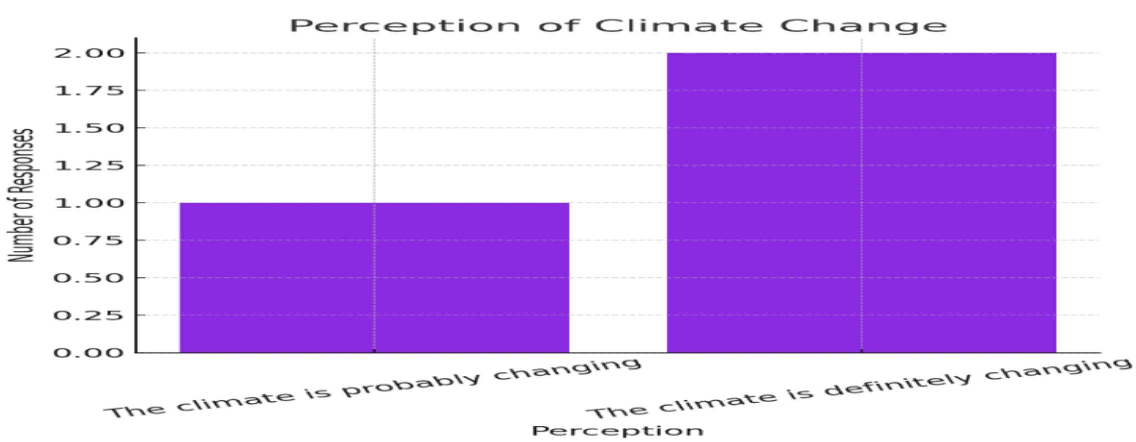
The perceptions and concerns of municipal agents regarding climate change in Senegal are of critical importance in order to understand how local policies can be adapted to enhance the resilience of cities to its impacts(City of Dakar & 100 Resilient Cities, 2016).

As key local actors, municipal agents play an essential role in implementing adaptation and mitigation strategies at the local level. Their perception of climate change directly influences the decisions made within municipalities and the implementation of initiatives aimed at reducing climate risks. This sub-section analyzes survey data from 13 municipal agents across Senegalese cities, highlighting their perceptions of climate challenges and the strategies they prioritize to enhance local resilience. The following table presents Climate Change Perceptions among Local Authorities**:**

Table 9: Climate Change Perceptions among Local Authorities

Questions	Responses	Scores
Is the climate probably changing?	Yes	13
Is the climate really changing?	Yes	13
The climate is probably not changing	No	0
Natural processes as to human activity	Twice	10
Mainly natural processes	Mainly natural	7
Mainly human activity	Mostly natural	6
Only natural processes	Only natural	4
Somewhat concerned	Not very concerned	0
Not at all concerned	Not very concerned	2
Not very concerned	Not very concerned	1
Very concerned	Very concerned	12

Municipal agents have demonstrated a substantial degree of acknowledgement of climate change and its human causes, with the majority expressing profound concern. This increased awareness has the potential to facilitate the mobilization of climate finance, the investment in green economic initiatives, and the implementation of sustainable policies. However, the absence of concern among a minority of agents highlights the necessity for awareness campaigns to promote collective action and to maximize the economic and environmental benefits of climate change. As we illustrate in the graph below:



Graph 4: representation of perceptions of municipalities about climate change

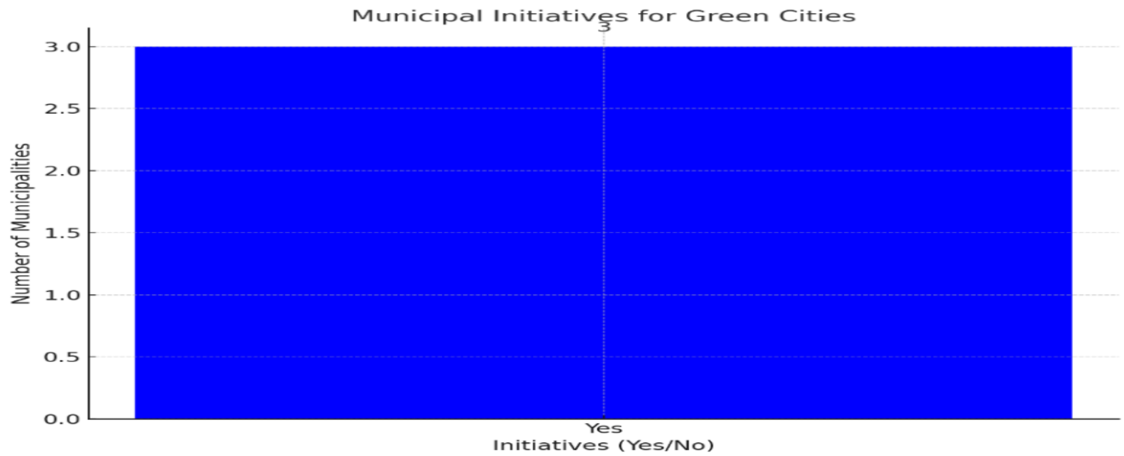
The bar chart titled "Perception of Climate Change" visually represents how a group of municipalities perceives climate change. The horizontal axis, designated as the X-axis named perception ("The climate is probably changing", "The climate is definitely changing"), delineates various categories of perceptions related to climate change, including "Very Concerned," "Moderately Concerned," "Slightly Concerned," "Not Concerned," and "Uncertain." Each point on this axis symbolizes a distinct perspective or level of concern regarding climate change.

The vertical axis (Y-axis) named Number of responses shows the number of responses or municipalities that expressed each specific perception or how many participants chose each option. The height of the bars in the "Perception of Climate Change" chart indicates the level of shared opinion among municipalities. A high bar (Very Concerned) represents a widely shared opinion, while a short bar (Not Concerned) indicates a less common view. This provides insight into the prevailing sentiment and level of concern regarding climate change within this group of municipalities. This indicates that most respondents are convinced that climate change is happening, while a smaller group remains cautious, suggesting it is probably changing. The majority belief that the climate is truly changing reflects a growing awareness of the effects of climate change, especially its impact on the economy and production methods. The impact on economic sectors highlights this perception could influence investment, adaptation, and resilience decisions in climate-sensitive sectors such as agriculture, energy, and urban planning.

Public policy adaptation: With the majority acknowledging real climate change, decision-makers may be prompted to implement more ambitious climate adaptation policies, such as energy transitions, climate-smart agriculture, and sustainable resource management.

5.4.2 Assessing Municipal Initiatives for Urban Green Cities and Their Role in Enhancing Climate Resilience

In this section, a descriptive analysis will be conducted to evaluate the impact of municipal initiatives on urban green cities. This will be followed by an examination of their role in enhancing climate resilience. This examination will include an exploration of the distribution of municipal initiatives, such as urban agriculture and green spaces. The frequency and scope of these initiatives will also be assessed to understand their effectiveness and contribution to sustainable urban development. As shown in the graph below:



Graph 5: representation of municipalities initiatives related to Green Cities

The bar chart indicates the commitment of Senegalese municipalities to green city initiatives, including urban agriculture, green spaces, and resilient infrastructure. The analysis indicates several municipalities have already implemented projects aimed at improving urban resilience, with a clear positive trend in the adoption of such strategies.

It is particularly important to note that Senegal has launched several notable green city programs, including Dakar Ville Verte, Tivaouane Ville Verte, Diamniadio Ville Verte, and Akon City, demonstrating the country's commitment to building more sustainable and climate-resilient urban environments. These initiatives have the potential to generate economic benefits, including job creation, cost savings, and enhanced food security. However, disparities in resources across municipalities necessitate the implementation of more robust policy support to ensure inclusive participation in these efforts.

5.4.3 Green Spaces Management and Climate Resilience Initiatives in Senegalese Municipalities

Traditionally, the management of urban green spaces has historically been the responsibility of municipalities (local authorities). However, there has been an increasing involvement of local communities in this management, either independently or in cooperation, due to the lack of funding during the process to support its cost (Mattijssen, Buijs, & Elands, 2018). This responsibility places them at the core of the decision-making process, while other stakeholders assume a more marginal role or collaborate with them(N. Ali, 2017). In this regard, the knowledge and experience of local communities are of paramount importance.

According to the WHO (2002), a local community refers to a group of people sharing a culture or nationality within a specific location, which is especially relevant in urban green space management. As Khirfan & El-Shayeb (2020) note, involving communities in managing these spaces improves well-being and social cohesion. Urban green space management includes daily tasks such as planting, watering, fencing, and equipment maintenance (Lindgren, 2010). Local community involvement helps counter biodiversity loss linked to urbanization and brings socio-ecological benefits, enhancing adaptive capacity to climate change (Version et al., 2016; Qian Yoong et al., 2017).

Examples from Manchester (UK) show communities leading green initiatives like gardening and habitat restoration, assessed through volunteer efforts (Version et al., 2016). In Yokohama, Japan, factors like age, perceived green space adequacy, and social benefits influence stewardship (Sakurai et al., 2015). Community members are often motivated to create and manage spaces meaningful to them (Hassan, 2017). Cognitive and emotional factors shape long-term engagement and foster a sense of ownership, though poor planning limits this commitment (Masterson et al., 2017; Azadi et al., 2011). In Senegal, various urban development projects are currently being implemented, while others have already been established. The information gathered through our survey with municipalities is as follows:

1. AGRISEN A project focused on the production and packaging of vegetables using agroecological practices. It promotes sustainable agriculture and supports urban and peri-urban agriculture, contributing to greener urban environments and local food systems.

2. PROVALE-CV (Water Value Chain Development Project): Led by the Ministry of Agriculture, this project aims to: Increase agricultural production and employment, improve value chains, Operate in regions like Niayes, Peanut Basin, and Casamance. It enhances climate resilience and sustainable land use in urban and peri-urban areas through better water management and agricultural practices.

3. PROMOVILLE (Urban Modernization Program): Aims to promote endogenous and sustainable economic growth in cities by: Improving urban mobility and infrastructure, creating jobs, and Enhancing climate resilience and social cohesion. It directly supports urban development and modernization.

4. PROGEP (Stormwater Management and Climate Change Adaptation Project) Focuses on: Reducing urban flooding, enhancing urban resilience to climate change, Creating and managing urban green spaces.

Initially implemented in Dakar suburbs (Pikine, Guédiawaye), PROGEP integrates green infrastructure and nature-based solutions into city planning. These projects reflect Senegal's commitment to sustainable and climate-resilient urban development through: Green infrastructure (PROGEP), Sustainable agriculture (AGRISEN, PROVALE-CV), Modernized urban services (PROMOVILLE). Together, they aim to create inclusive, resilient, and green cities aligned with national and global development goals.

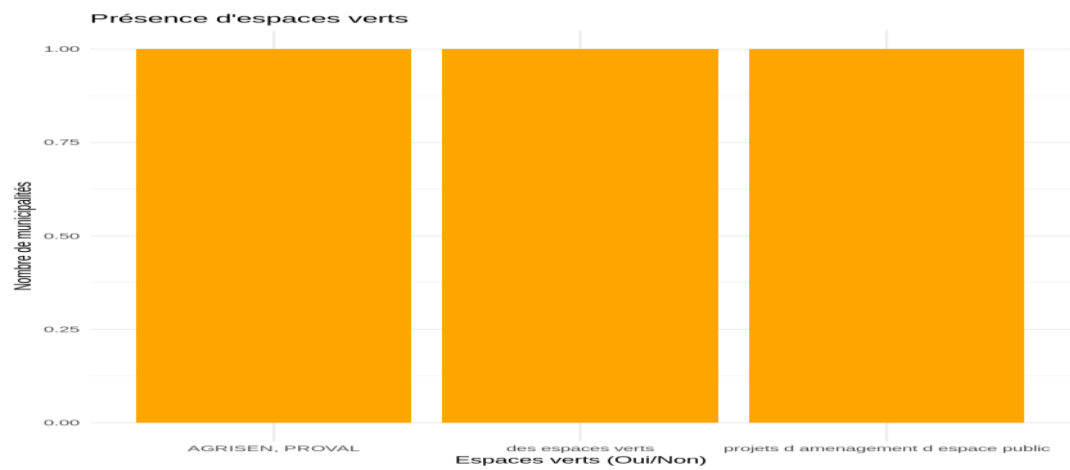
This sub- section thus explores municipal initiatives for green spaces and climate resilience, revealing efforts toward sustainable urban development, environmental quality, and adaptive capacity, as shown in the following table.

Table 10: Green Spaces Projects initiatives in Senegal

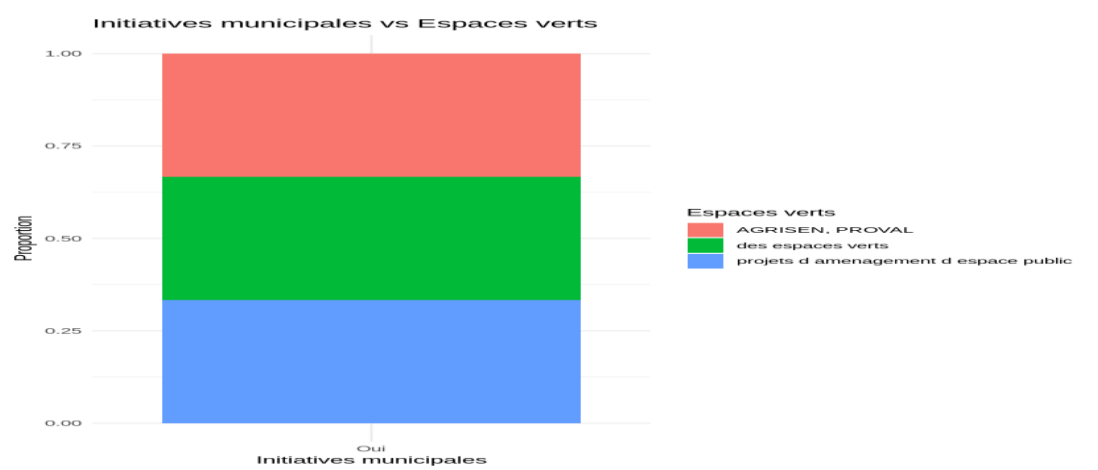
Projects	**Yes**	**No**
Green Spaces Initiatives	8	5
Project on the light	12	1
Project development Public space	13	0
AGRISEN	6	7
PROVAL	5	8
PROMOVILLE	13	0
PROGEP	10	3
OTHERS		

This table illustrates the frequency of green spaces and climate resilience initiatives in relation to various urban projects in Senegal. It shows that initiatives such as AGRISEN and PROVAL have been implemented, with a focus on green spaces and public space development. However, projects such as Promoville or those focused on lighting are either absent or unreported. The absence of certain projects, such as Promoville, suggests missed investment or funding opportunities, which could slow the expected positive impact on sustainable urban development.

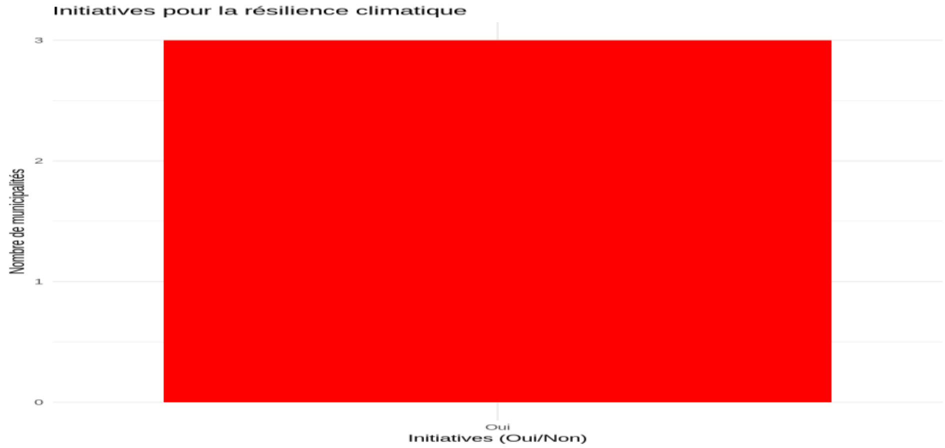
Three municipalities recognize having green spaces or climate resilience initiatives, while none report the absence of such efforts, reflecting a clear commitment to integrating green spaces and enhancing climate resilience. We illustrate through these graphs which shows the presence of green spaces across cities and municipality initiatives.



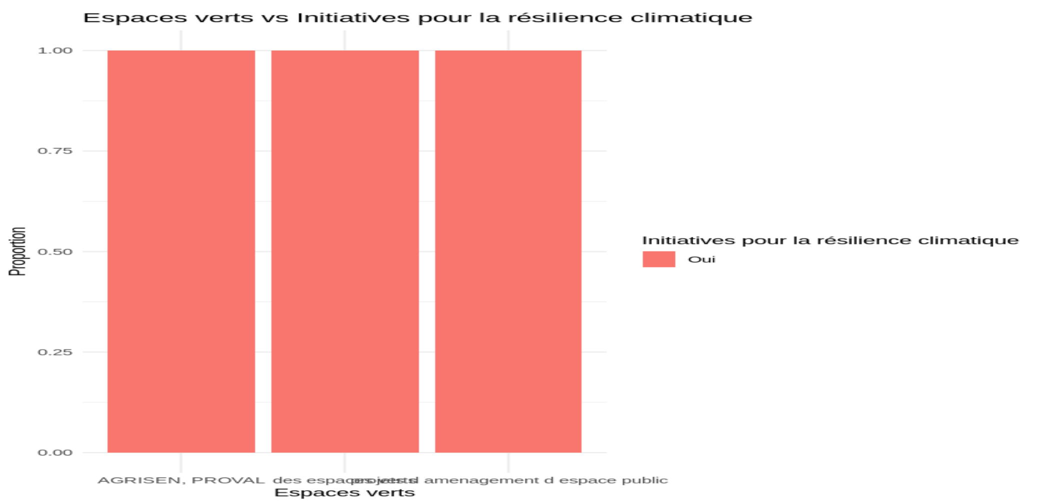
Graph 6: Representation of the presence of green spaces and the number of municipal initiatives.



Graph 7: Representation of the presence of green spaces and the number of municipal initiatives."



Graph 8: Representation of Climate Resilience Initiatives through municipalities



Graph 9: Cross-Analysis between green spaces and climate resilience

The graphs illustrate the relationship between municipalities' commitment to green initiatives and the implementation of green spaces in Senegal. It shows a positive correlation between green initiatives and the presence of green spaces, indicating that municipalities with more green initiatives tend to have more green spaces. This suggests that environmental sustainability is being actively integrated into urban planning.

Furthermore, the graph emphasizes that all green space projects contribute to climate resilience efforts, highlighting their role in addressing climate change. Investments in green infrastructure, such as parks and urban gardens, are crucial for climate adaptation, helping reduce urban heat, improve air quality, and lower climate risks like flooding.

These initiatives also provide long-term economic benefits by increasing property values, attracting investment, and creating jobs in sectors like urban agriculture and landscape management.

5.5 The Green Economy and Socio-Economic Benefits of Urban Green Spaces in Senegal

The transition to a green economy in Senegal is strongly linked to the development of urban green spaces, as these areas play a fundamental role in promoting sustainability, socio-economic development and climate resilience. Urban green spaces contribute significantly to the local economy by generating green jobs in sectors such as landscaping, horticulture, urban farming, and environmental services, particularly benefiting women and youth. These employment opportunities contribute to enhancing urban economic resilience.

In addition, green infrastructure enhances the livability of cities by improving the health, well-being, and overall quality of life of residents. Municipalities in Senegal play a key role in the expansion and management of these spaces. Through the implementation of policies that support and allocate resources to the development of community gardens, urban agriculture, and public parks, they ensure that these spaces are accessible and sustainable for all urban residents. The integration of these green spaces is not only vital for the economic transition to a green economy but also for building resilience to climate change in urban areas of Senegal. The benefits of these spaces are significant social, economic, and environmental, making them critical to creating a sustainable and resilient urban future.

Conclusion and Policy recommendations

The present chapter examined the public's knowledge of green cities and green spaces, satisfaction with the management of urban green spaces, and the willingness to pay (WTP) for their improvement in Senegal. The findings highlight that knowledge of green cities and green spaces is influenced by various socio-economic and demographic factors, including education, income, and access to environmental information. Higher levels of education and awareness campaigns play a crucial role in shaping individuals' understanding of urban sustainability and green infrastructure. The results of the study indicate that satisfaction with urban green space management varies, with some respondents expressing contentment with the current state of green spaces, while others highlight challenges such as inadequate maintenance, accessibility issues, and limited integration into urban planning. These findings underscore the need for more effective policies and community engagement to enhance the quality and accessibility of urban green spaces. The willingness-to-pay (WTP) analysis further reveals that individuals who demonstrate higher awareness and satisfaction with urban green spaces are more likely to contribute financially to their improvement. Socioeconomic status, environmental awareness, and perceived benefits of green spaces significantly influence WTP, suggesting that targeted policies, including public-private partnerships and incentive mechanisms, could enhance sustainable urban green development. Finally, the chapter provides valuable insights into how knowledge, satisfaction, and willingness to pay towards green spaces interact. These findings lay the foundation for policy recommendations aimed at promoting green cities, enhancing urban resilience, and fostering sustainable urban development.

Finally, this research contributes to the growing body of literature advocating for equitable, inclusive, and climate-resilient urban futures in Africa. In this context of rapid urbanization and global challenges, it highlights the critical importance of green spaces in Senegalese cities-not only as ecological resiliency, but also as vital assets for health, well-being, and climate resilience. Citizens across Senegal are encouraged to deepen their understanding of green spaces, assess their satisfaction with current management, and reflect on their willingness to support and invest in these spaces. At the same time, municipalities must prioritize the integration of green infrastructure into urban planning and actively engage communities in the co-governance of these natural assets. In this way, "the future of our cities will be determined not only by buildings and roads, but also by the spaces where nature and people meet".

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CHAPTER 2: BUILDING A FOOD-RESILIENT CITY THROUGH URBAN AGRICULTURE: A CASE STUDY OF SENEGAL

Abstract: This study investigates the role of urban agriculture in enhancing climate resilience and food security in Senegalese cities, focusing on urban households, urban farmers, and municipal governments. The primary objective is to assess the impact of urban agriculture on food security and climate resilience, with a particular emphasis on the factors influencing urban households' engagement in agriculture and the role of urban farmers in adopting sustainable practices. The study also explores the critical role of municipal governments in supporting urban agriculture through policy and resource allocation. Primary data were collected through surveys and in-depth interviews with urban households, farmers, and municipal officials in selected cities. A multinomial logistic model was used to analyze the decision-making of urban households regarding participation in urban agriculture, while a decision tree model was applied to identify the determinants of climate-smart practices among urban farmers. The study found that urban agriculture plays a significant role in improving food security by providing fresh, locally grown produce and enhancing resilience to climate change. Urban farmers' adoption of practices such as crop diversification and efficient irrigation contributes to mitigating the effects of climate change, while municipalities are essential in facilitating the growth of urban agriculture through sustainable land-use policies and resource management. The study concludes with recommendations for policymakers to integrate urban agriculture into urban planning, promote climate-resilient agricultural practices, and strengthen the collaboration between municipal governments, farmers, and communities to build sustainable and resilient urban food systems.

Keywords: Urban agriculture, climate resilience, food security, Senegal, urban households, urban farmers, municipalities, climate-smart practices, decision tree model, multinomial logistic model.

Introduction

A- Context and Problem statement

The majority of the global population currently resides in urban areas, which are increasingly exposed to a range of complex and interrelated challenges. These challenges include natural disasters, pandemics, terrorism, poverty, and food insecurity. These challenges are further intensified by rapid urbanization, climate change, and global socioeconomic shocks (FAO, 2020; Local & Governments, n.d.). The ongoing global pandemic has highlighted the fragility of global food supply chains and the vulnerability of cities that rely heavily on external resources for food, water, and energy.

In light of these challenges, the development of urban resilience, defined as a city's capacity to absorb, adapt, and transform in the face of shocks without compromising essential functions—has emerged as a pivotal aspect in the realm of sustainable urban planning. A fundamental aspect of this resilience is food security. As evidenced by the preponderance of no communicable diseases and mortality attributable to poor diets worldwide (Ola, 2021), ensuring access to adequate, nutritious, and affordable food for all urban residents, particularly the most vulnerable, is a fundamental pillar of resilient cities (FAO, 2019; Local & Governments, n.d.).

In many developed urban areas, food systems are heavily dependent on globalized supply chains, making them particularly vulnerable to geopolitical, environmental, and economic disruptions (Brar et al., 2020; Steve Hatfield-Dodds, 2007). The consequences of these vulnerabilities are already evident, as rising food prices and supply disruptions disproportionately affect the urban poor (Burki, 2022; Cockx, 2024). In this context, localized food systems and urban agriculture (UA) emerge as crucial strategies to improve resilience.

Urban agriculture, defined as the cultivation of food in and around cities, offers a practical and multi-dimensional approach to enhance urban food systems (Of, 2023). Urban agriculture can take many forms, from community gardens, private vegetable plots, rooftop farms, and edible walls to technologically advanced, soil-free growing methods such as hydroponics and aquaponics (La Rosa et al., 2014; Ola, 2021). Beyond the cultivation of food, urban agriculture also includes practices such as beekeeping, small-scale poultry farming, and permaculture in public spaces, parks, and boulevards (Steve Hatfield-Dodds, 2007).

Historically, the United Nations Agency (hereafter, "UA") played a vital role in enhancing food security and boosting morale during crises, such as the "Dig for Victory" campaign in the United Kingdom and the "Victory Gardens" in the United States during World War II (Food and Agriculture Organization [FAO], 2020). More recently, urban agriculture experienced a period of renewed interest during the COVID-19 barriers, particularly in the Global North (Brar et al., 2020). Beyond its direct impact on enhancing food availability, UA has been shown to promote social cohesion, generate employment opportunities, and foster public health through enhanced access to fresh produce (Faye et al., 2022; Local & Governments, n.d.). Additionally, it contributes to climate mitigation by reducing urban heat island effects and recycling organic waste (Faye et al., 2022).

The relevance of UA is particularly relevant in African cities, where urban poverty, food insecurity, and malnutrition are on the rise due to rural-urban migration, high cost of living, and dependence on external food supplies (Ba & Cantoreggi, 2018; National Agency for Civil Aviation and Meteorology of Senegal et al., 2013). In Senegal, approximately 70% of the food consumed in urban areas is sourced from rural zones, while only 29.5% of urban households in Dakar are considered food secure (Burki, 2022). Furthermore, food insecurity in Senegal is significantly associated with climate variability, as evidenced by the 2011–2012 drought, which had a substantial impact on food access and livelihoods (ANACIM, WFP, 2013).

Despite the mounting evidence of the numerous benefits of UA, its full potential remains underutilized in urban planning, particularly in Sub-Saharan Africa. There is a limited understanding of how UA can be effectively applied at the policy level, institutionalized, and integrated into public policy frameworks to strengthen the resilience of food systems. There is also a lack of empirical data on how UA works at different scales, from households to municipalities, and under what conditions it is most effective in improving food security and resilience (Of, 2023; FAO, 2019). This chapter explores the role of urban agriculture in building food-resilient cities in Senegal by examining how UA contributes to urban food security, community resilience, and sustainable development.

B-Research Question, Objectives and hypothesis

1. **The research question is:** How does urban agriculture contribute to food security and climate resilience in Senegalese cities?
2. **The general objective** of this study is to analyze the contribution of urban agriculture to improving food security and enhancing climate resilience in Senegalese cities.
3. **Specific objectives** are outlined as follows:

1) To evaluate the role of urban agriculture in strengthening the food systems of urban households and farmers in Senegal.
2) The study will examine how urban agriculture fosters climate resilience in Senegalese cities through sustainable practices.

To achieve these specific objectives, the following hypothesis are proposed:

4. **Research Hypothesis**

H1: Higher household income, remittances, and education of the household head positively impact food security in urban households, enabling them to invest in food production and purchase, thus reducing food insecurity.

H2: Urban agriculture improves food security for urban farmers by providing access to financial support, training, and proximity to agricultural land, which enhances their ability to produce food and meet their household's needs

H3: Urban agriculture enhances climate resilience by reducing vulnerability to climate shocks through sustainable practices, as evidenced by descriptive statistics and geospatial analysis using NDVI, precipitation, and temperature data across diverse urban settings.

C- Contribution to Literature

This essay contributes to the growing body of literature on urban resilience and food security by providing empirical insights into the role of urban agriculture in the Senegalese context a region where rapid urbanization and climate change intersect with persistent challenges of food insecurity and socio-economic vulnerability. While existing studies have explored urban agriculture in various global contexts, limited research has been conducted in Sub-Saharan Africa that simultaneously considers the household, community, and municipal levels.

This work provides a multi-scalar analysis of how urban agriculture contributes to the construction of resilient food systems and climate resilience by focusing on six Senegalese cities and examining diverse actors' urban households, urban farmers, and local government stakeholders such as urban municipalities.

Moreover, the study adds value by identifying enabling and constraining factors that affect the successful integration of UA into urban development strategies. This research also contributes to the conceptual understanding of urban agriculture (UA) in relation to climate resilience, environmental sustainability, and local governance. It demonstrates the importance of place-based, context-specific approaches in addressing global challenges such as food insecurity and climate change.

D- Structure of the study

Building on these contributions, the essay is structured as follows. Firstly, the first section provides a comprehensive review of the theoretical frameworks related to urban resilience, food security, and the multifunctionality of urban agriculture, while also discussing existing empirical studies from African and global contexts. Secondly, the second section presents the methodology employed in the study, including the selection of study areas, data collection instruments, and analytical strategies. Thirdly, the third section analyzes the results of the field survey, focusing on both urban households and urban producers, in order to explore the relationship between urban agriculture and food security. Fourthly, the fourth section examines how urban agriculture can contribute to building city resilience in the face of climate change. This section mobilizes various geographical approaches and includes an analysis of municipal strategies and governance frameworks to better understand the role of local authorities in scaling up urban agriculture as a climate adaptation tool.

Section 1- Literature review

1.1 Urban agriculture and food security: Global context

The planet is currently facing the challenge of meeting the food needs of its population, with more than 7 billion inhabitants(UNFPA, 2019). The issue of global food security is increasingly pressing in cities, which have become home to more than half the world's population in just a few years(Ba & Cantoreggi, 2018). This phenomenon is particularly pronounced in cities of the Global South, which already face significant challenges due to high levels of poverty. In this context, urban and peri-urban agriculture (UPA) is emerging as a crucial element in ensuring the food supply of these cities(Duží et al., 2017).

The recent concept of food security has given more attention to households, and individuals than its availability at international, national, regional and state levels(Steve Hatfield-Dodds, 2007). According to the Food and Agriculture Organization (FAO)(FAO, 1996), food security exists when all people, at all times, have physical and economic access to sufficient, safe, and nutritious food to meet their dietary needs and food preferences for an active and healthy life.

Food security exists when food is available to everyone at all times, they have means of access, and that it is nutritionally, adequate in terms of quantity, quality and variety also that it is acceptable, within the given culture (FAO, 2004)and (Steve Hatfield-Dodds, 2007). This implied food must be available to the people to an extent that will meet some acceptable level of nutritional standards in terms calorie, protein and minerals which the body needs; the possession of means by the people to acquire it and consistency in its supply at all times(Steve Hatfield-Dodds, 2007).

Between 2010 and 2020, for example, domestic rice production increased only marginally, while the country's population grew by more than 20% (Facility et al., 2022) .

The term "urban and peri-urban agriculture" (UPA) is employed to denote all agricultural activities that take place within or on the periphery of urban areas(Urbaine et al., 2001). It is estimated that UPA accounts for between one third and one quarter of global agricultural consumption (Padilla). The food function of UPAs has been the subject of extensive research in numerous studies, frequently concentrating on cities in the Global South(Zezza & Tasciotti, 2010).

The majority of these studies have approached the food function of UPA from the perspective of its role in the food security of urban populations, particularly in the strategies of poor urban households(Ba & Cantoreggi, 2018).

However, in an urban context characterized by the ubiquity of commercial and monetary exchange, a limitation of the food function of UPA to its role as a subsistence activity appears to be a simplification of a more complex phenomenon. Indeed, UPA is also a source of income generation and allows urban farming households to diversify their diets significantly(Zezza & Tasciotti, 2010) In this sense, the commercial aspect of UPA is an important asset for urban farming households.

1.1.1 Urban agriculture and food security in Senegalese cities: *Urban agriculture: A multifunctional activity with multiple contributions*

Food insecurity has increased in Senegal, particularly in urban centers, due to cities' heavy reliance on rural food(National Agency for Civil Aviation and Meteorology of Senegal (ANACIM), WFP's Office for Climate Change, Environment and Disaster Risk Reduction, WFP's Food Security Analysis Service, 2013).This has been compounded by continued rural depopulation, a growing urban population, and recent government policies aimed at reducing food imports and increasing local production(WFP, 2023). Available data show that annual production of rice, a staple food in Senegal, has struggled to keep pace with population growth.

UPA fulfils several functions in the areas where it is practiced. This multifunctionality, well documented in research (Ba & Cantoreggi, 2018) provides limited insight into the perceptions or functions that farmers assign to their production areas. It appears that farmers in Dakar primarily consider the spaces they occupy in urban or peri-urban areas as full-fledged agricultural production zones. While 70% highlight income generation, the environmental function of these agricultural areas is also emphasized. In fact, 45% and 44% of the farmers consider their agricultural space to be a recycling zone for urban waste and a green space for the city, respectively.

The educational function is also evident in the results, with 25% of farmers seeing their farmland as an educational tool for students in the region. Only 18% of farmers see their farmland as a land reserve for the city, which will eventually be replaced by real estate projects or major infrastructure (Ba & Cantoreggi, 2018).

1.1.2 *Challenges and Economic impacts of urban agriculture in Senegal*

The diagnosis of urban agriculture has been analyzed to illustrate the full dynamics of this activity, its impact on the economy of agri-urban households and its contribution to household and regional food security. However, the future of this sector is threatened by growing constraints, some of which stem from its limited recognition by those responsible for urban spatial planning. Land and water constraints represent significant challenges for urban and peri-urban agriculture in Dakar. Regarding land, plots are comparatively diminutive, with an average of 0.38 ha per producer(Ba & Cantoreggi, 2018), and this circumstance is anticipated to deteriorate as urbanization advances and agricultural land is converted into residential zones. The Senegalese land tenure system, characterized by its ambiguity contributes to the insecurity experienced by farmers. The over-exploitation of groundwater due to population growth has led to saline intrusion and water salinization in areas previously suitable for horticulture (Guèye-Girardet, 2010).

Producers are exploring alternative options, such as mini-boreholes or connection to the SDE water distribution network. However, the latter option is vulnerable due to government priorities and water shortages. While urban agriculture in Dakar is commercially oriented, it remains essential for the food security of urban households, particularly in areas like the Niayes of Pikine and Malika, and Lendeng in Rufisque.

UPA in Dakar, particularly market gardening, is an activity that is almost exclusively (95%) male dominated. This phenomenon is attributed to the prevailing socio-cultural context in Senegal, where women have limited access to land and are predominantly engaged in the commercialization of harvests. The farmers involved are predominantly adults, with 46% of those surveyed having accumulated over 20 years of experience in urban agriculture. The average age of the farmers was 49, ranging from 19 to 80 years old. Notably, despite the high unemployment rate among the youth, only 18% of the farmers surveyed were young. This phenomenon can be attributed to the precarious nature of the activity, its marginalization by public authorities (kedowide, 2010), and the predominance of elderly and retired individuals seeking supplemental income in a context where the pension system is largely inadequate. The analysis identified three primary constraints faced by farmers: land insecurity (74%), water scarcity for irrigation (62%), and soil and water salinization (27%).

These findings are consistent with those of previous studies by Gaye and Niang (2010), IAGU (2011), and Niang (2014). Other challenges, though less significant in terms of frequency, are nonetheless notable, including access to credit (19%), climatic constraints such as flooding (18%), and irrigation quotas for farmers using SDE water (15%). Furthermore, challenges vary depending on the production zone, including the high cost of water for farmers using SDE water and the poor quality of treated wastewater for market gardeners in the Grande Niayes of Pikine(Ba & Cantoreggi, 2018).

The economic impact of urban agriculture, both in terms of production and financial income, especially in developing countries such as Senegal, is well documented. A number of studies have underscored the role of urban agricultural activities in augmenting the food supply of rural-urban households, conceptualizing these activities as a means of self-consumption(Cockx, 2024).

1.2 Urban agriculture and city resilience

An increase in climate change-related extreme weather events and natural disasters, as well as chronic shocks, impact on food production, processing, and distribution along the entire food supply chain(Ola, 2021). Cities are particularly vulnerable to disruptions in essential food supplies, and climate change increases this vulnerability(FAO (Food and Agricultural Organizations of the United Nations), 2011). Urban economies struggle when rural agricultural production is adversely affected by storms, floods, shifting seasonal patterns, droughts or water scarcity. In addition, changes in temperature and rainfall patterns affect the types of crops that can be grown in a given area(Nelson et al., 2007).

Rising food prices caused by food supply disruptions have a direct impact on urban consumers, who rely almost entirely on purchasing food rather than growing it themselves(Ola, 2021). Vulnerable populations already experiencing or at risk of food insecurity are most affected (Africa, 2008). In addition, the impact of climate change on agricultural productivity in certain rural areas may lead to increased migration to cities for economic or environmental reasons, resulting in the rapid growth of slums.

There is increasing recognition that the combined impacts of climate change, rapid urbanization, and ongoing population growth could threaten the resilience of cities worldwide to food shocks. The importance of urban resilience is gaining attention, highlighting the strong link between resilience and the sustainability of socio-ecological systems(RUAF, 2009).

Resilience is defined as a measure of the ability of a household, city or nation to absorb shocks and stresses(RUAF, 2009). Resilient cities are characterized by increased self-reliance and their ability to cope with or recover from stresses or catastrophic events(De Zeeuw et al., 2011). Urban agriculture (UA) is increasingly recognized as an integral part of sustainable urban planning. It enhances carbon sequestration in green spaces, while urban forests and green roofs contribute to lowering urban temperatures(Newman, 2010).

Urban Agriculture refers to the production of food such as vegetables, fruit, meat, eggs, milk and fish - and non-food items - such as fuel, herbs, ornamental plants, tree seedlings and flowers - within urban areas and their peripheries. This production is for household consumption and/or the urban market, along with related small-scale processing and marketing activities(Noi & Nam, 2018).

Urban Agriculture takes place on various types of land, including private, leased or rented land in peri-urban areas, backyards, rooftops, vacant public land such as industrial estates and school grounds, roadsides, and even in prisons and other institutions, as well as in ponds, lakes and rivers(Ba & Cantoreggi, 2018). This practice is seen as a way to build resilience by co-locating food production and consumption(De Zeeuw et al., 2011). Blay-Palmer, Santini, Dubbeling, Renting, Taguchi, and Giordano (2018: 10) noted that UA serves to shorten supply chains that are highly vulnerable to climate-related impacts and resource scarcity due to their extensive global linkages(Ola, 2021).

1.3-Theoretical and Conceptual Framework: Urban agriculture, Food security and climate resilience

Several studies have shown that urban agriculture (UA) which involves food production in urban environments enhances urban resilience by reducing residents' vulnerability to food supply disruptions (Zezza & Tasciotti, 2010).

Urban agriculture encompasses farming activities in public and semi-public spaces (schools, streets, boulevards, community gardens), as well as private spaces (backyards, rooftops, balconies) (Steve Hatfield-Dodds, 2007; Ola, 2021). In Senegalese cities, urban agriculture includes hydroponics, aquaculture, small-scale poultry farming, beekeeping, and permaculture in parks and public orchards (La Rosa et al., 2014).

Although not a new phenomenon in Senegal (Ba & Cantoreggi, 2018), rapid urbanization and the urgent need to combat food insecurity have led policymakers and researchers to explore strategies to strengthen and promote participation in this sector. A conceptual framework for examining the relationship between urban agriculture, food security, and climate resilience in African cities, particularly Senegal, focuses on how urban farming can enhance food security while supporting climate resilience.

Urban agriculture in Senegal includes practices such as community gardens, rooftop farming, and livestock rearing, with emerging technologies such as solar-powered irrigation or hydroponics improving sustainability and productivity. The enhancement of food security, particularly in low-income areas with constrained access to traditional food supply chains, is a pivotal function of urban agriculture. The contribution of this factor to the stability of food systems is evident in its capacity to reduce dependence on external sources, thereby increasing resilience to climate-related shocks (Ba & Cantoreggi, 2018).

These activities not only provide fresh produce but also enhance resilience to climate challenges, such as droughts or floods, by promoting sustainable agricultural practices. Farmers' ability to use innovative technologies like solar-powered irrigation or rainwater harvesting can further improve productivity and help mitigate the impacts of climate change on food systems. This practice has been shown to contribute to improved local biodiversity and the provision of ecosystem services, including enhanced soil health and pollination, thereby fostering climate resilience(Ndiaye, 2012).

Moreover, urban agriculture has been observed to reduce environmental risks associated with water scarcity and energy shortages by integrating efficient water use and renewable energy solutions into farming practices. Households residing in urban areas stand to benefit from urban agriculture by increasing their access to fresh, nutritious food. Households, particularly those in low-income urban areas, often face difficulties accessing affordable and healthy food through traditional supply chains(Ndiaye, 2012). Engagement in urban farming or support for local urban agriculture initiatives can strengthen food security, reduce dependence on external food sources, and buffer against disruptions caused by climate change or economic instability.

The relationship between urban agriculture, food security, and climate resilience is bidirectional. Urban agriculture strengthens food security by increasing local food production and enhances climate resilience by creating more sustainable and adaptable urban environments.

Conversely, ensuring food security also contributes to climate resilience by guaranteeing access to nutritious food during periods of climatic stress or disruptions(Ola, 2021). In our study, we examine the nexus between urban agriculture, food security, and climate resilience of three pivotal stakeholders: urban farmers, urban households, and urban municipality agents. However, the present study will focus on urban farmers and urban households, while the role of urban municipality agents will be explained using graphs and tables to illustrate their influence on urban agriculture and climate resilience

Section 2: Methodology: Exploring Urban Agriculture and Food Security Among urban Farmers and urban Households in Senegalese Cities

This section provides an overview of the research methods used to analyze urban agriculture's impact on food security. It includes data collection techniques, sampling methods, and study area descriptions.

2.1 Research Design and data collection methods

2.1.1 Research Design

This research employed a cross-sectional study design, utilizing multiple data collection methods. Semi-structured interviews were conducted with household heads, urban farmers, and municipal representatives as the primary units of analysis. Key informant interviews were also carried out using a structured interview guide to gather additional insights from experts. Field observations focused on critical aspects such as food security levels, resilience, agricultural practices, technological use in urban agriculture, housing structures, and access to utilities like electricity and water for both urban households and farmers. These observations, supported by notes and photographs, provided a comprehensive view of the local context, as recommended by Leonard et al. (2024).

2.1.2 Sources and Methods of Data Collection

The study employed diverse data collection methods to reach urban farmers, households, and the urban actors involved in the urban agriculture landscape, such as municipal agents and other stakeholders. The general business census report of 2016 provided the total number of urban farmers across different regions of Senegal, which informed the selection of the study regions. Based on this data, the number of farmers was assumed to be equal to the number of households, with one municipality selected per department in each chosen region, as shown in the table below.

These methods allowed for a comprehensive understanding of the various issues, characteristics, and intrinsic aspects related to urban agriculture within the selected regions, aligning with the approach outlined by Leonard et al. (2024). We present below the equation along with the detailed steps of the sampling process:

$$n = \frac{\frac{z^2 \times p(1-p)}{\varepsilon^2}}{1 + \frac{z^2 \times p(1-p)}{\varepsilon^2 N}}$$

Where N = population size; ε = margin of error (percentage in decimal form); z = z-score. The sample size is 344 producers.[1]

Based on urban agriculture and household data from the National Agency of Statistics and Demography (ANSD), this table presents the distribution of urban farmers, households, and municipalities across six Senegalese cities. We applied adjusted weights to ensure representative sampling across study areas.

Table 11: Sampling Distribution of Urban Farmers, urban households and Municipality

Areas	Urban Farmers	Weight	Adjusted weight	Producer sample	Household	Municipality
Dakar	1891	55%	40%	140	140	5
Diourbel	217	6%	10%	35	35	2
Saint-Louis	215	6%	10%	35	35	1
Thiès	918	27%	30%	105	105	3
Ziguinchor	98	3%	5%	18	18	1
Kaolack	122	4%	5%	18	18	1
Total	**3461**	**100%**	**100%**	**350**	**350**	**13**

Initially, the research design targeted a total of 351 urban households and 350 urban producers across six Senegalese cities. However, due to fieldwork limitations, time restrictions, and respondent availability, the final sample size was slightly reduced.

Ultimately, we surveyed: 273 urban households, 261 urban producers, and 13 municipal representatives.

The final sample remains sufficiently robust to ensure meaningful and representative analysis. It captures key socio-economic and geographic variations, and includes multiple stakeholder perspectives urban households, urban farmers, and municipal authorities essential for analyzing climate resilience, food security, and the role of urban agriculture in Senegalese cities. As we demonstrated on the table below:

Table 12: Final Distribution of Surveyed Urban Stakeholders Across Selected Cities

This table presents the final number of respondents from urban households, urban farmers, and municipal representatives interviewed during the field survey conducted across six cities.

CITIES	**Urban Households n=273**	**Urban Farmers n=261**	**Municipalities n=13**
Dakar	82	65	4
Thies	55	50	3
Saint-Louis	41	45	2
Diourbel	41	45	2
Ziguinchor	27	28	1
Kaolack	27	28	1

The total sample used in this study comprises **547 respondents**, including **273 urban households**, **261 urban farmers**, and **13 municipal representatives** across six urban regions of Senegal. The distribution was based on data from the National Agency of Statistics and Demography (ANSD, 2016), which provided insights into the presence of urban farmers in each region.

Dakar, being the largest urban center and economic hub, accounted for **82 households** and **65 farmers**, along with **4 municipal representatives**. **Thiès**, known for its rapid urbanization and peri-urban farming, included **55 households**, **50 producers**, and **3 municipal representatives**. **Saint-Louis** and **Diourbel**, with moderate but significant urban agriculture activity, each had **41 households**, **45 farmers**, and **2 municipal representatives**.

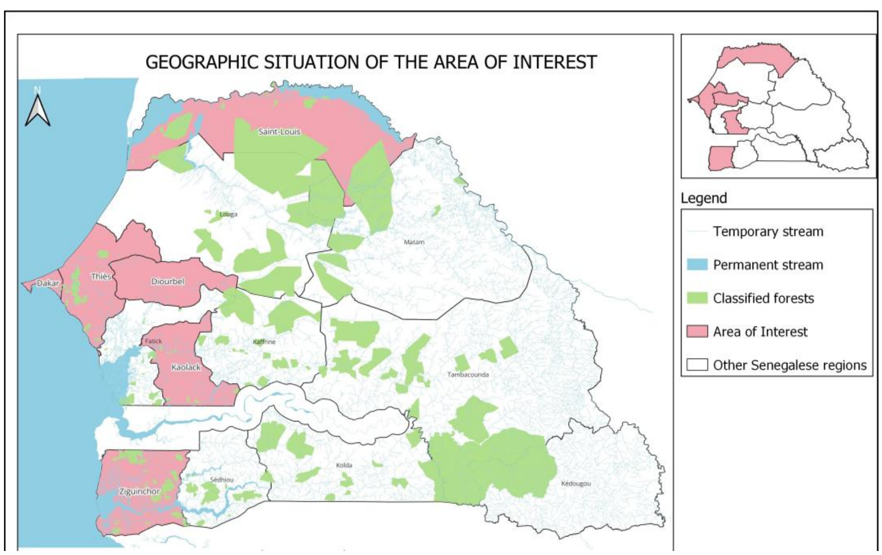
Kaolack and **Ziguinchor**, both contributing similarly to urban farming, were represented by **27 households**, **28 farmers**, and **1 municipal representative** each.

This distribution ensured geographic diversity and proportional representation of urban agricultural practices. The 13 municipal representatives, although initially more were targeted, were those who agreed to participate despite time or logistical constraints. Finally, the study sample enabled a comprehensive analysis of urban agriculture and climate resilience, incorporating the perspectives of households, active farmers, and local governance actors across Senegal's main urban areas.

2.1.3 Area of interest and geographical scope

This study focuses on six Senegalese cities: Dakar, Saint-Louis, Ziguinchor, Diourbel, Kaolack, and Thies to explore the dynamics of urban agriculture, urbanization, and climate resilience. These cities were selected for their unique agricultural profiles and challenges related to urban development. The research involved 547 participants, including urban households, farmers, and municipal representatives, with data collected from October to December 2023. The study aims to understand the role of urban agriculture in sustainable development and resilience to climate change in these cities.

Area of interest



Graph 10: Geographic situation of the area of interest

2.2 Methodology for Urban Households and Urban Farmers' Food Security in Senegal

These cities study areas provide the context for assessing the socio-economic status (SES) determinants influencing food security in urban households and urban farmers in Senegalese cities, while also investigating the influence of drivers of urban agriculture on the SES of urban farmers.

The quantifiable data was analyzed using Statistical software R. Separate analyses on households, farmers, and urban households' interests in urban agriculture (specifically focusing on food security and resilience to climate change) in Senegalese cities were conducted for comparison and reported at three levels:

a) At the univariate level (using frequency counts and percentages); b) at the bivariate level (using Pearson's correlation); and c) at the multivariate level (using logistic regression analysis). Furthermore, the survey undertook an analysis of municipal strategies for urban agriculture, employing graphical and tabular representations.

2.2.1 Urban Households Model: Multinomial Logistic Regression

For urban households, the analysis aimed to evaluate the socio-economic determinants of food security, categorized as **low**, **medium**, or **high**. The dependent variable in this case was **food security**, and the independent variables included socio-economic characteristics.

1. The **Univariate analysis** encompassed the descriptive summary for each variable.
   To study characteristics of households, techniques for summarizing data for continuous variables were used and these include Mean, variance and standard deviation while the frequencies and percentages were used for categorical variables. This was supported by qualitative data from the survey and key informant interviews.
2. **Bivariate Analysis**: Cross-tabulations were performed to test potential associations between each of the independent variables and the dependent variable. The statistical significance of these relationships was determined using the P-value (P=0.05), with all significant variables at this level being considered for multivariate analysis. This was done using Pearson's chi-square test, and Fisher's exact test was also applied (Leonard et al., 2024). The test chi square x^2 used is in the form:

$$x^2 = \sum_{i=1}^{r}\sum_{j=1}^{c}\frac{\left(O_{ij} - E_{ij}\right)^2}{E_{ij}}$$

O_{ij}=the observed frequency in the ith row and jth column

E_{ij}=the expected frequency in the ith row and jth column, Chi-square is tested at a 0.05 level of significance i=1……………………………………………r

j=1……………………………………………

3. **Multivariate analysis:** Multivariate analysis was conducted to determine which factors were more strongly associated with the socio-economic status (SES) of urban households. The socio-economic status (SES) variables considered included total food security, urban agriculture (urban_agriculture), gender of household head (gender_household), marital_status (marital_status), age of household head (age_household), household income (household_income), household size (size_household), education level (education_household) and remittances_household).

   As Food security is a categorical variable with more than two categories, the appropriate model to analyze this type of dependent variable is the multinomial logistic regression model.

   Multinomial logistic regression was used because it considers the potential confounding effects of independent variables on each other, thereby identifying the independent association of each predictor variable with the dependent variable.

   This method provides a robust framework for understanding the key determinants of urban household food security (Leonard et al., 2024). The model is given by:

$$log\left(\frac{P_{ij}}{P_1}\right)=\alpha_j + \beta_j \times i \text{ ....}$$

   Where: αj represent the constant

   P_{ij} represent the probability of the jth category

   β_j s represents regression coefficients, ×i s represent independent variables

   P_1 is the probability of the base category

   The relative risk ratios were interpreted as relative probabilities, that is; the probability of falling in the jth category of social-economic status rather than the base category social-economic variable. Variables with a p-value of <= 0.05 was considered to be important in explaining the outcome of interest. Independent variables that were not significant at the bivariate level won't be considered at this level of analysis.

In our study, we first conducted a descriptive analysis of the variables before performing significance and dependence tests.

2.2.2 Urban Farmers Model: Decision Tree Model

For urban farmers, a **decision tree model** was used to explore the determinants of food security and urban agricultural practices. The decision tree analysis segments urban farmers based on socio-economic characteristics and farming-related variables, identifying key factors influencing food security outcomes.

1. **Univariate Analysis**: Descriptive statistics were performed for the urban farmers to summarize the data, including measures of central tendency, dispersion, as well as frequency distributions and percentages (mean, variance, standard deviation, etc.).
2. **Bivariate Analysis**: Cross-tabulations were conducted to explore the relationships between socio-economic and farming variables and the food security status of urban farmers. Significant associations were identified using **Pearson's chi-square test** and **Fisher's exact test**, with p-values ≤ 0.05 considered significant.
3. **Multivariate Analysis (Decision Tree)**: The decision tree model was employed to examine the socio-economic and agricultural factors influencing food security outcomes among urban farmers. The decision tree algorithm splits the data into subsets based on the most important variables, helping to understand the decision-making process behind urban farmers' practices and their associated food security levels. The results from the decision tree model highlighted the key predictors of food security among urban farmers, considering factors such as UA_years practices, main constraint, source of funding etc.

SECTION 3: Results: Impact of Urban Agriculture Models on Household Food Security

To better understand the relationship between urban agriculture and food security, the analysis was conducted in three steps. First, a univariate analysis was carried out to describe the main characteristics of the households and key food security indicators. Secondly, a bivariate analysis was used to explore associations between urban agriculture and food security outcomes using contingency tables. Thirdly, a multivariate analysis was performed using a multinomial logistic regression model to identify the socio-economic and demographic determinants of food security levels among urban households and urban farmers.

This section presents the findings from the analysis exploring the relationship between urban agriculture models and household food security. Various socio-economic and demographic variables were examined to understand how different factors influence food security levels among urban households. In this section, we will present the results from urban households, followed by the results from urban farmers.

3.1 Food security among urban households: Univariate and bivariate analysis

This section presents the combined univariate and bivariate analysis conducted to explore the socio-economic characteristics of urban households and their relationship with food security. Descriptive statistics provide an overview of household profiles and food security components, while bivariate analysis helps identify potential associations between urban agriculture practices and food security outcomes.

Urban agriculture practices were observed across a wide range of household profiles. The majority of households engaged in urban farming were characterized by lower to middle income levels, with significant variations in household size, education, and access to remittances. Preliminary insights indicated that households practicing urban agriculture showed relatively better food security outcomes than those that did not. The following descriptive statistics highlight key components related to food security within the sampled urban households.

a) The relationship between urban agriculture and food security

a1) Descriptive statistics

Table 2 presents the descriptive statistics for the various components of food security, illustrating the overall conditions faced by urban households in relation to agricultural practices and their impact on food access and security.

Table 13: Descriptive Statistics for Food Security Components and FS general variables

Variables	Min	1st Quartile	Median	Mean	3rd Quartile	Max
Food security 1	0.0000	0.0000	0.0000	0.6044	0.0000	7.0000
Food security 2	0.0000	0.0000	0.0000	0.4725	0.0000	10.0000
Food security 3	0.0000	0.0000	0.0000	0.3553	0.0000	7.0000
Food security 4	0.0000	0.0000	0.0000	0.3297	0.0000	10.0000
Food security 5	0.0000	0.0000	0.0000	0.3773	0.0000	7.0000
Preferred products in urban areas	1.000	1.000	1.000	1.381	2.000	3.000

Access to agricultural market resources	1.000	1.000	2.000	1.985	3.000	4.000
Urban agriculture meets food needs	1.000	1.000	2.000	2.026	3.000	4.000
Perception of agricultural product availability	1.000	1.000	2.000	2.026	3.000	4.000

Table 3 shows the contingency table illustrating the relationship between urban agriculture levels and food security. Low food security is less prevalent across urban agriculture levels, with occasionally higher values. Medium food security is often associated with moderate urban agriculture levels, while high food security is linked to specific, higher levels of urban agriculture. So, medium urban agriculture levels appear to align with medium food security, and high food security is linked to certain higher urban agriculture levels.

Table 14Table of contingence between food security and urban agriculture

Urban Agriculture\ and Food security	Low	Medium	High
0	0	8	1
2	0	2	0
3	0	2	0
4	0	4	0
5	1	9	0
6	2	3	1
7	1	1	0
8	0	2	0
9	0	1	0
13	0	1	0
14	0	1	0
15	0	2	0
20	0	0	1
25	0	2	0
28	0	1	0
30	0	2	0
32	0	1	0
35	0	4	3
37	0	1	0
42	0	3	1
46	0	0	3

48	0	1	10
49	0	2	1
50	1	0	0
56	0	1	0
60	0	0	1
70	0	0	1
72	0	1	0
80	0	1	0
>			

a2) Test de dependance: Fisher Test:

- **H_0 (Null Hypothesis):** Urban agriculture is not significant (has no effect), with p-value > 5%.
- **H_1 (Alternative Hypothesis)**: Urban agriculture is significant (has an effect), with p-value < 5%.

p-value: 0.000, Since the p-value is less than 5% ($p < 0.05$), we reject the null hypothesis and conclude that urban agriculture is significant.

In this context, the result of the Fisher's Exact Test indicates a statistically significant association between urban agriculture and food security. The p-value obtained (0.0005) is well below the 5% threshold, allowing us to reject the null hypothesis (H0) that urban agriculture has no significant impact on food security. Therefore, we accept the alternative hypothesis (H1) that urban agriculture plays a significant role in enhancing food security, suggesting that food security levels may vary significantly depending on urban agriculture practices.

b) The relationship between food security and the gender of the household

b1) Table of contingence between gender and household food security: The table below explains the contingency table

Table 15: Table of contingence Food security and sex of menage:

	Low	Medium	High
Female	22	80	4
Male	20	108	30
Non specified	0	9	0

This table shows the distribution of food security levels among households led by different genders. It indicates that both female-headed and male-headed households predominantly experience medium food security, with male-headed households exhibiting a higher proportion of high food security. Conversely, low food security is distributed equally between the two groups.

Households where the gender is unspecified report medium food security. These patterns may suggest gender inequalities in access to resources that affect food security levels.

b2) Association tests: Fisher test and Pearson test

Table 16: Fisher test and Pearson test

Fisher test	
p-value	0.001
Chi-Square Value (X-squared)	18.529
Degrees of Freedom (df)	4
p-value	0.000
Significance Level (α)	0.05

The low p-value (0.001) and chi-squared result (18.529, 4 df, p = 0.000) indicate a statistically significant relationship between household head gender and food security, with male-headed households generally showing better outcomes. This finding highlights the need for gender-sensitive policies that address the specific challenges faced by female-headed households, such as limited access to land, credit and resources. To address this challenge, targeted support through training, improved access to inputs, and inclusive agricultural programs are recommended.

c) The relationship between marital status and household food security:

The table below shows the contingency table between marital status and household food security

c1) Table of contingence between marital status and household food security

Table 17: Table of contingence between marital status and household food security

	Low	Medium	High
Single	2	17	1
Divorced	5	5	1

Married monogamous	22	114	17
Married polygamous	3	35	13
Non specified	0	9	0
Widowed	10	17	2

Marital status has been demonstrated to influence food security outcomes, with monogamously and polygamously married individuals showing enhanced outcomes due to the stability and resource-sharing that characterize these relationships. In contrast, widowed individuals face elevated vulnerability, while singles and divorced individuals are less represented in the "high" food security category. These patterns highlight economic disparities linked to marital status.

c2) Association Test between Marital Status and Household Food Security: Fisher's Test and Pearson test

- Null **Hypothesis (H_0): There is no association between marital status and household food security.**
- **Alternative Hypothesis (H_1):** There is a significant association between marital status and household food security.

Table 18: Fisher test and Pearson test

Fisher's Test	
p-value	0.001
Chi-Square Value (X-squared)	31.661
Degrees of Freedom (df)	10
p-value	0.000
Significance Level (α)	0.05

The p-value of 0.001 and the chi-square statistic of 31.661 (p = 0.000) both indicate a significant association between marital status and household food security. This finding suggests that food security outcomes vary across different marital groups, such as married, single, divorced, or widowed individuals. The findings highlight the importance of designing targeted interventions that take marital status into account, with particular attention to vulnerable groups such as widows or divorced individuals.

These variations may be attributed to differences in income, household size, or resource access, suggesting the need for tailored support programs that address the specific food security challenges associated with marital status.

d) The relationship between food security and the age of the household

d1) Contingency table: The table below shows the contingency table:

Table 19: Interpretation of the contingency table

	Low	Medium	high
18-30	6	19	2
31-45	11	73	7
46-60	16	61	15
61+	9	34	10

The distribution of food security by age reveals trends where middle-aged households (31-60 years) tend to have better food security, with the highest number of households in both medium and high food security categories. However, the 46-60 age group also has a significant proportion in the low food security category.

Conversely, both younger (18-30 years) and older (61+) households face more challenges, with a higher prevalence of low food security and fewer in the high food security category. These findings suggest that targeted interventions are necessary to enhance food security among younger and older households, while mitigating low food security levels among middle-aged households.

d2) Associative and Significance Test: Fisher's and Pearson test Between Age Intervals and Food Security

- Null Hypothesis (H_0): There is no association between age intervals and food security.
- Alternative Hypothesis (H_1): There is a significant association between age intervals and food security.

Table 20: Fisher test and Pearson test

p-value-Fisher test	0.211
Significance Level (α)	0.05
Chi-Square Value (X-squared)	8.2178
Degrees of Freedom (df)	6
p-value	0.222

The p-values of 0.2119 (Fisher's Exact Test) and 0.2226 (Pearson's Chi-Square Test), both above the 0.05 threshold, indicate no statistically significant association between age intervals and food security.

These results suggest that age does not have a substantial impact on food security status within this sample, and any observed differences are likely due to random variation. As such, age alone is not a determining factor in food security outcomes, highlighting the need for policymakers and researchers to consider additional variables when analyzing the determinants of food security.

e) Relationship between income, size of households and food security:

Income and household size were combined in the analysis because they are closely linked and can jointly influence food security. A given income may be sufficient for a small household but inadequate for a larger one. By analyzing both variables together, it is possible to better understand how their interaction affects food security outcomes, offering a more accurate picture than examining them separately. The table below shows the contingency table between income of households and food security and Fisher & Pearson tests.

e1) Contingency table between income of households and food security

The contingency table shows a clear link between household income and food security. Lower-income households are more likely to experience food insecurity, while higher-income households tend to have better food security. This suggests that addressing income inequality could improve food security, particularly for low-income households.

Table 21: Table of contingency between income of households and food security

	Low	Medium	High
1 or less	1	3	0
2-3	7	8	1
4-5	8	27	0
6+	26	159	33

e2) Fisher's Exact Test between Household Size and Food Security

- Null Hypothesis (H_0): There is no association between household size and food security.
- Alternative Hypothesis (H_1): There is a significant association between household size and food security.

Table 22: Results of the Fisher test and Chi-Square Test

p-value	0.000
Chi-Square Value (X^2)	19.417
Degrees of Freedom (df)	6
p-value	0.003

The p-values of 0.000 (Fisher's Exact Test) and 0.003, both below the 0.05 threshold, indicate a statistically significant association between household size and food security. These findings suggest that larger households may be more vulnerable to food insecurity due to higher resource demands, while smaller households tend to be more food secure. This highlights the importance of incorporating household size into food security policies and calls for further investigation into the underlying factors that link household size to food security outcomes.

f) The relationship between education households and food security

f1) Contingency table between education households and food security:

The table indicates a positive correlation between education level and food security. Households with higher education levels, particularly those with a tertiary education, demonstrate a higher prevalence of adequate food security. While moderate food security is observed across all education levels, high food security is most prevalent among those with a university education. This observation highlights the potential impact of education in enhancing food security. As shown in the table below:

Table 23: Table of contingency between education households and food security

	Low	Medium	High
None	13	46	15
Others to be precised	0	1	0
Coranic schools	9	26	5
Non spécified	0	9	0
Primary	13	42	5
Secondary	4	49	2
Superior	3	24	7

f2) Statistical Analysis of the Association between Household Education Level and Food Security: Fisher's Test and Pearson test

- **Null Hypothesis (H_0):** There is no association between the household education level and food security.
- **Alternative Hypothesis (H_1):** There is a significant association between the household education level and food security.

Table 24: Results of the Fisher's Test and Pearson test

p-value-Fisher test	0.019
Significance Level (α)	0.05
Chi-squared	23.479
df	12
p-value	0.023

The p-values from both tests (0.01949 and 0.02392) indicate a significant association between household education level and food security. Higher education levels are generally linked to improved food security, while lower education levels correspond to greater food insecurity. These findings highlight the importance of enhancing educational opportunities as a strategy to improve household food security outcomes.

g) The relationship between household activity and food security

g1) Contingency table between household activity and food security

The contingency table indicates a relationship between household activity type and food security. Agricultural households have the highest food security, likely due to their direct access to food. Trade and public service provide moderate stability, while "other" activities show variability, often leading to low or medium-sized food security. As shown in the table below:

Table 25: Table of contingency between household activity and food security

	Low	Medium	High
Agriculture	5	58	23
Others to be precised	20	53	2
Trade	13	66	5
Non specified	0	9	0
Public Service	4	11	4

g2) Significativity test of Fisher and Pearson test

Table 26: Fisher and Pearson test

Fisher test	
p-value	0.0004
X-squared	40.346
df	**8**
p-value	2.761e-06

Both Fisher's exact test (p-value = 0.0004) and the chi-squared test ($\chi^2 = 40.346$, p-value = 2.761e-06) reveal a statistically significant relationship between the type of household activity and food security. These findings suggest that households engaged in agricultural activities tend to experience more stable food access, whereas those involved in other types of activities may face higher levels of food insecurity. This underscores the potential positive impact of agricultural engagement on food security.

h) The relationship between food security and remises of households

h1) Contingency between food security and remittances of households: Households that receive remittances tend to exhibit higher levels of food security, with a greater proportion falling within the 'High' category. In contrast, households lacking remittances are more uniformly distributed across the 'Low' and 'Medium' categories. These observations suggest that remittances may contribute to enhanced food security by providing additional income or resources. As shown in the table:

Table 27: Table of contingency between food security and remises of households

	Low	Medium	High
No	39	160	17
No specified	0	12	0
Yes	3	25	17

h2) Association Test between Household Remittances and Food Security: Fisher's Exact Test for Significance

- Null Hypothesis (H_0): There is no significant relationship between remittances received by households and food security.
- Alternative Hypothesis (H_1): There is a significant relationship between remittances received by households and food security.

Table 28: Fisher's Test Results

Fisher's Test	
p-value	0.0004

Chi-Square Statistic (X^2):	36.498
Degrees of Freedom (df)	4
p-value	2.285e-07

The significant p-value (2.285e-07) confirms a strong association between remittances and food security. Households receiving remittances are more likely to have high food security, as these financial transfers positively impact access to sufficient food. Remittances provide crucial income, enabling households to purchase food and withstand economic shocks. To maximize this impact, policies should aim to reduce transaction costs, improve financial access, and support non-recipient households to address disparities and enhance resilience.

3.2 Description of the variables of the model

This study analyzes key household variables to understand their socio-economic and demographic dynamics. These variables are grouped into demographic, socio-economic, and financial categories, each offering valuable insights into household structure, economic status, and resilience. The demographic variables that are analyzed in this study include: age of the household head, household size, and marital status.

These variables are instrumental in delineating the composition and structure of households, which in turn influence economic behavior and decision-making. Socio-economic variables encompass household education level, household economic activity, and urban agriculture practices. The examination of these variables offers insights into the social and economic status of households and their livelihood strategies.

Finally, the financial and well-being variables include household income, remittances, and total food security. These measure the financial resources available to households and their capacity to ensure food security, which is crucial for assessing economic resilience.

The following variables were considered: urban agriculture, gender of the household head (*gender_household*), marital status (*Marital_status*), age of the household head (*age_household*), household income (*income_household*), household size (*size_household*), education level of the household (*education_household*), and remittances received by the household (*remittances_household*).

Quantitatives variables: age _household, size_household, total food security, income_household, are numerical and allow for statistical analysis of trends and correlations.

Qualitatives variables: urban_agriculture, gender_ household, marital_status, education_household, Activity_household, remittances_households describe categorical attributes that help in understanding socio-demographic distinctions.

3.3 Results of the Multinomial Logistic Model: Analysis of Urban Household Cases

The following table presents the results of the multinomial logistic model for urban household cases. The multinomial logistic model reveals key factors influencing food security, including urban agriculture, household income, household size, education, and remittances. Urban agriculture has been shown to significantly improve food security by reducing dependence on markets, and the promotion of urban agriculture could enhance urban food resilience, as shown in the table below:

Table 29: Table of the multinomial logistic model

multinom_model <- multinom (Total_Food_Security_Factor ~ Agriculture_Urbaine + Sexe_Menage +
+ Marital_status+ Age_household + size_household+ income_household+
+ Education_household + Activity_household + Remittances_houshold_
+ data = train_data, decay = 0.1)
weights: 153 (100 variable)
initial value 65.916737
iter 10 value 19.384126
iter 20 value 18.757161
final value 18.756812
Converged

Higher household income and remittances contribute to improved food security by providing additional resources for food purchase and investment in infrastructure. Larger households face more challenges in achieving food security, though this can be mitigated by sufficient income or participation in productive activities.

The education of the household head has been demonstrated to enhance food security through superior resource management and effective decision-making. The age of the household head has been found to be non-significant. Then it is imperative for policies to prioritize economic and structural factors in order to enhance food security, rather than focusing on demographic characteristics such as age.

The results confirm that the hypothesis is verified as higher household income, remittances, and the education of the household head are all found to significantly improve food security by enabling investment in food production and enhancing purchasing power, thereby reducing food insecurity.

b) Correlation and Multicollinearity Analysis of Variables Affecting Food Security

The correlation analysis reveals a number of weak relationships between several variables. There is a slight positive correlation between household age and size, indicating that older households tend to have slightly larger families. Household income shows a modest positive correlation with food security, suggesting that higher income may improve food security to some extent.

Similarly, household size has a weak positive correlation with food security, while household age shows a weak negative correlation, indicating no significant impact on food security. Then the correlations are weak to moderate, indicating no substantial multicollinearity and enabling a reliable analysis of the factors influencing food security. The table below shows the multicollinearity for quantitative variables:

Table 30: Multicollinearity: Calculation of correlation matrix for quantitative variables

Variables	Age_household	Size_household	Income_household	Total_Food_Security
Age_household	1.000	0.176	-0.023	-0.023
Size_household	0.175	1.000	-0.023	0.236
Income_household	-0.022	-0.023	1.000	0.176
Total_Food_Security	-0.023	0.24	0.176	1.000

c) Prediction on the test set

The model demonstrates substandard performance in predicting food security categories. It shows an inability to accurately predict instances of "Low" food security and significant challenges in the "High" category, with one accurate prediction.

The "Medium" category shows the most accurate predictions, with five accurate instances, despite the fact that misclassification errors are observed, such as instances of "High" food security being misclassified as "Medium". As demonstrated on the table below:

Table 31Prediction on the test set

Low	Medium	High
0	0	0
1	5	2
0	1	1

d) Model Performance Evaluation: Global Model Statistics Classification Metrics by Socioeconomic Class

The model shows relatively low predictive performance, with an accuracy of 54.55%, which is only in the low range better than random sampling for a three-category variable. The wide 95% confidence interval (0.2338–0.8325) reflects a high level of uncertainty, likely due to the limited sample size. The No Information Rate (0.6364) suggests that predicting the most frequent class would likely result in enhanced accuracy.

The p-value (0.8273) indicates that the model does not significantly improve on random prediction, and the near-zero kappa coefficient (0.0179) reflects poor agreement beyond chance. While the model performs relatively well in predicting the "Medium" food security category (sensitivity = 71.43%, PPV = 62.5%), it fails to predict the "Low" category entirely (sensitivity = 0%) and shows weak performance in the "High" category (sensitivity = 33.33%, PPV = 33.33%).

Developing targeted policies, especially in the area of urban agriculture, could contribute to strengthening the food security of vulnerable households. As shown in the table below:

Table 32: Classification metrics by socioeconomic class

	Low class	Medium class	High class
Sensitivity	0.000	0.7143	0.333
Specificity	1.000	0.250	0.750
Pos Pred Value	NaN	0.625	0.3333
Neg Pred Value	0.909	0.3333	0.750
Prevalence	0.0909	0.636	0.272
Detection Rate	0.00000	0.4545	0.09091

Detection Prevalence	0.00000	0.7273	0.27273
Balanced Accuracy	0.50000	0.4821	0.54167
Accuracy	**0.5455**		
95% CI	(0.23,0.83)		
No Information Rate	0.636		
P-Value [Acc > NIR]	0.8273		
Kappa	0.0179		
Mcnemar's Test P-Value	NA		

Conclusion for Urban Households: In conclusion, higher household income and remittances significantly contribute to improved food security by providing the means to purchase food and invest in infrastructure. Although larger households may face greater challenges in maintaining food security, these can be mitigated through adequate income or engagement in productive activities. Furthermore, the education level of the household head plays a critical role by enhancing resource management and informed decision-making. In contrast, demographic characteristics such as age have shown no significant effect on food security outcomes.

The results confirm that the hypothesis is verified, as higher household income, remittances, and the education of the household head are all found to significantly improve food security by enabling investment in food production and enhancing purchasing power, thereby reducing food insecurity. Therefore, policies should prioritize economic and structural drivers over demographic ones. Efforts should focus on promoting urban agriculture, generating employment to increase income, expanding access to education, and supporting remittance flows. Additionally, targeted programs for larger households and financial literacy initiatives for remittance recipients could reinforce the positive impact on urban food security.

Section 4: Farmer Model Results: Analyzing Food Security and Urban Agriculture

To better understand the factors influencing food security among urban farmers, this section presents descriptive statistics for quantitative variables, along with the results of Chi-square tests for associations among categorical variables. Relevant graphs are also included to provide visual insights.

4.1) Food security among urban farmers: Univariate and bivariate analysis

This section presents the combined univariate and bivariate analysis conducted to explore the socio-economic characteristics of urban farmers and their relationship with food security. Descriptive statistics provide an overview of household profiles and food security components, while bivariate analysis helps identify potential associations between urban agriculture practices and food security outcomes.

The following table presents the results of the farmer model analyzing food security and urban agriculture. The presentation of the results begins with descriptive statistics and association tests. It is followed by the presentation of the results from the decision tree model, displayed in tables representing the number of nodes.

4.2) Statistics for summary for quantitative variables

The descriptive statistics (Table 33) summarize key variables such as field distance, years of practice in urban agriculture, and annual maintenance contributions. These provide insights into the variability and central tendencies within the sample.

a) Descriptive statistics

Table 33: Descriptive statistics

Variable	Observations	Mean	Std. Dev.	Min	Max
Years of UA practice	257	13.30	10.80	0	60
UA Training	257	1.82	0.39	1	2
Field distance (km)	257	1.60	0.81	1	5
Source of funding	257	1.69	1.57	1	6
Access to funding	257	1.81	0.40	1	2
Method of funding	50	1.42	0.57	1	3

Type of space used	257	1.65	1.09	1	4
Production method	257	1.49	0.89	1	4
Main crop	257	1.02	0.14	1	2
Annual contribution to maintenance (CFA)	NA	197,984	—	0	5,000,000
Size of field (ha)	NA	—	—	NA	NA

Table 34: Summary of Statistics for the dependent Variable.

Variable	Length	Class	Mode
Food shortage in the last 7 days (Q1)	261	Character	Character
Food shortage in the last 7 days (Q2)	261	Character	Character
Food shortage in the last 7 days (Q3)	261	Character	Character
Food shortage in the last 7 days (Q4)	261	Character	Character
Food shortage in the last 7 days (Q5)	261	Character	Character

Table 33 outlines the main features of 257 urban farmers—averaging 13 years of practice, field proximity of 1.6 km, widespread UA training, and varied funding and methods. Furthermore, Table 34 outlines the structure of the qualitative variables used in the analysis, specifically those related to recent food shortages (food security variable).

b) Association tests: Chi-square test for each qualitative variable

Table 35 below presents the results of Chi-square tests assessing the association between various categorical explanatory variables and food security status. These tests help identify which factors are significantly related to food security outcomes, guiding subsequent policy and programmatic recommendations.

Table 35: Test association Chi-square

Variables	X-Squared	df	P-value	Interpretation
UA_training	7.2242	7	0.405	No significant association between **training in urban agriculture** and food security.
Extension services	2.4238	7	0.932	No significant association between **extension services** and food security.
Main_crop	21.859	21	0.407	No significant association between **main crop** and food security.

Production_method	13.913	7	0.052	Slightly significant, a potential association between **production method** and food security.
Use_of_pesticide	3.859	14	0.996	No significant association between **pesticide use** and food security
Source_of_funding	27.643	28	0.483	No significant association between **source of financing** and food security.
Access to funding	8.9082	7	0.259	No significant association between **access to financing** and food security.
Finding_method	3.4853	14	0.998	No significant association between **financing method** and food security
Main_constraint	59.968	28	0.0005	Significant association between **main constraint** and food security.
Type_of_space_used	40.862	21	0.006	Significant association between **type of space used** and food security
Cart_equipment	10.517	21	0.971	No significant association between **cart equipment** and food security.
Hoe_equipment	323.92	35	< 2.2e-16	Highly significant association between **hoe equipment** and food security.
Seeder_equipment	6.0906	28	1	No significant association between **seeder equipment** and food security.
Mower_equipment	9.1141	28	0.999	No significant association between **mower equipment** and food security.
Daba(traditional tool) equipment	73.304	42	0.002	Significant association between **daba (traditional hoe) equipment** and food security.

The regression results provide valuable insights into the **determinants of food security among urban farmers**, revealing both significant and non-significant factors:

Significant variables: "main_constraint," "type_of_space_used,", production method, "hoe_equipment," and "daba_equipment" show significant results (p-value < 0.05), suggesting they are associated with food security.

1. **Main Constraint**: The significance of this variable suggests that the **type of constraint faced by urban farmers** such as lack of land, water, or market access **directly affects their food security**. Addressing these constraints can therefore enhance their resilience and food access.

2. **Type of Space Used**: This refers to whether farmers use private land, public spaces, or rooftops. Its significance indicates that **access to appropriate and secure space for urban agriculture plays a crucial role in improving food security outcomes**.

3. **Production Method**: The production technique—whether traditional, organic, or intensive—has a significant impact. This shows that **certain farming practices are more effective in enhancing yields and food self-sufficiency**, which in turn improves household food security.

4. **Hoe Equipment and Daba Equipment**: The use of specific tools such as hoes and dabas is positively associated with food security. This implies that **even basic agricultural tools can make a difference in productivity**, especially in resource-limited urban settings.

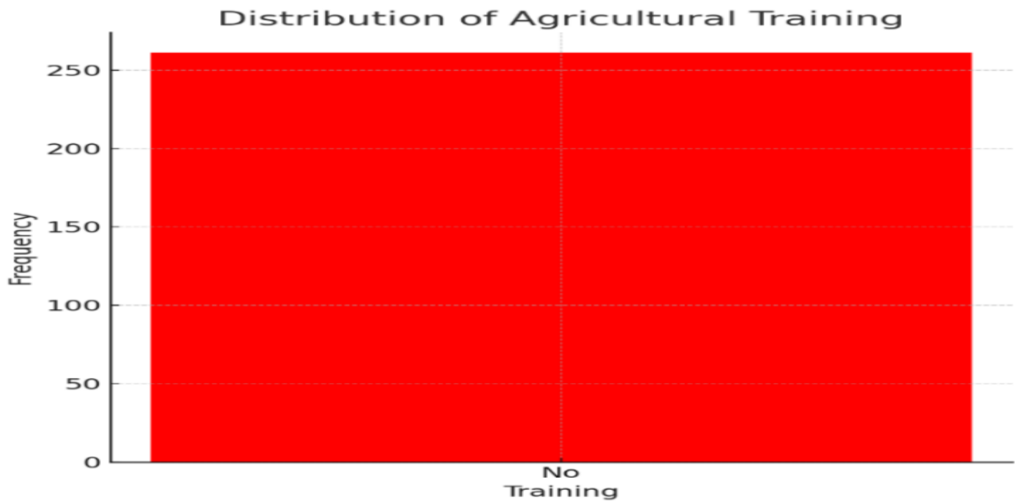
These findings suggest that urban agriculture contributes positively to food security when key enabling conditions **land access, appropriate production methods, and farming tools** are met.

Non-significant variables: Other variables, such as "AU_training," "extension_services,", main crop, extensions services, access of funding, source of funding, method of funding, seeder eauipment, cart equipment, mower equipment and "main_crop," have no significant relationship with food security (p-value > 0.05).

This suggests that **training programs or access to certain equipment alone may not translate directly into better food security**, possibly due to a mismatch between what is provided and what is actually needed by farmers. For example: Trainings may not be practical or context-specific, Extension services may be too general or inconsistent and Funding may not reach the farmers effectively or be too limited.

c) Graphical Presentation of Key Agricultural Factors

In addition to the descriptive statistics and association tests, the results will now be presented graphically, including histograms and bar charts to illustrate various aspects of agricultural training, production methods, field distance, and the number of years of agricultural practices among farmers.



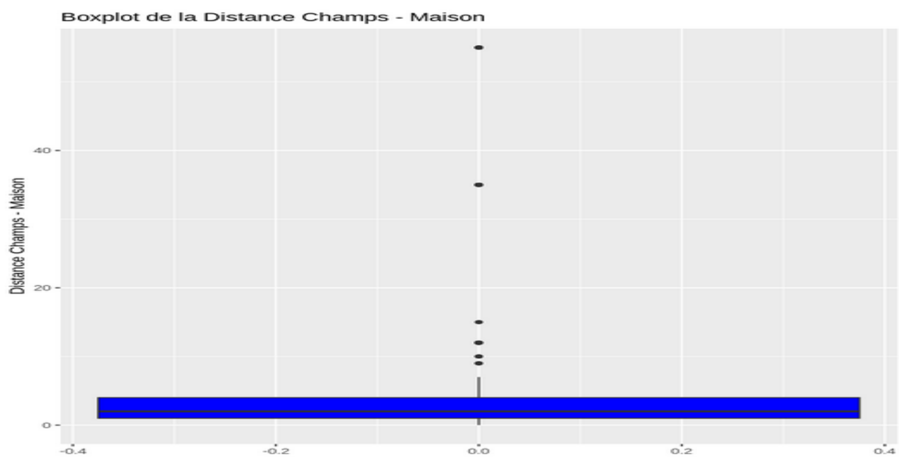
Graph 11; Graph of Agricultural Training Types among Urban Farmers

This bar chart shows the frequency of different types of agricultural training among farmers. Comparing the frequencies can help determine whether specific training programs are associated with better food security outcomes.

For example, farmers who have received more specialized training might be better equipped to address agricultural challenges and ensure their food security. This chart reveals that farmers who have undergone a specific type of training have higher food security scores, leading to the conclusion that this training program contributes to improving food security.

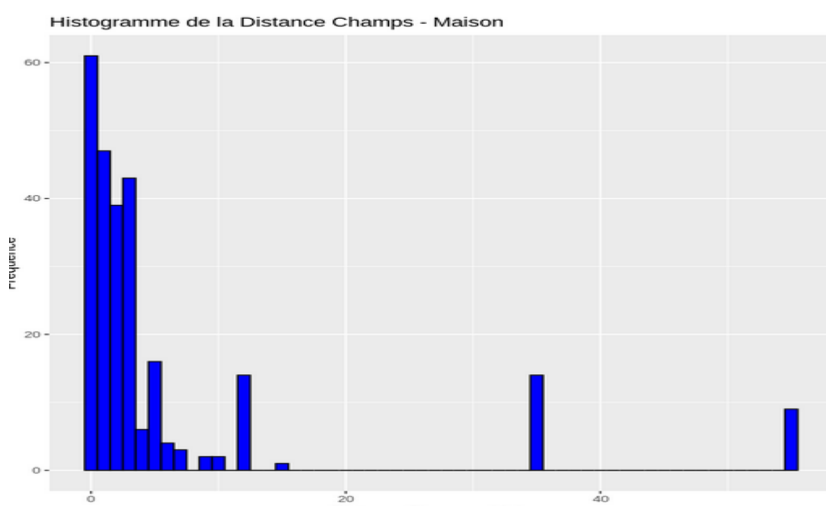
Graph 12: Graph of different production methods

This bar chart presents the frequencies of different production methods (e.g., conventional, organic, etc.). Examining these frequencies may reveal whether certain production methods are associated with food security. For example, if a particular method is more sustainable or efficient, it could contribute to improving the food security of these farmers.



Graph 13: Graph of Farmers' Field Distance

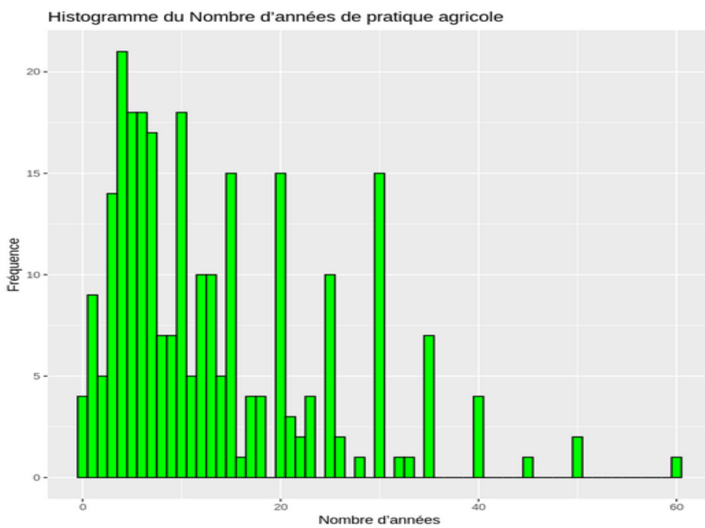
The box plot provides a different view of the distribution of distances between urban farmers and fields. It highlights the median, quartiles, and potential outliers.



Graph 14: Histogram of Farmers' Field Distance

This histogram shows the distribution of distances between farmers' homes and their fields. The shape, centre and spread of this distribution can indicate how accessible fields are to farmer's.

This is important because it can affect their ability to manage their crops effectively and potentially affect their food security. The histogram shows that farmer's with shorter distances to their fields generally have higher food security scores (based on their response variables). This suggests that accessibility to fields plays a positive role in food security.



Graph 15: Histogram of number of years of agricultural practices

This histogram shows the distribution of years of experience in agriculture among urban farmers. Analyzing this distribution can help us understand whether the level of experience plays a role in food security. For example, more experienced farmers may have better yields or more sustainable practices, thus contributing to food security.

5.2 Results Decision Tree Model

We applied the decision tree model to analyze the relationship between urban farmers and food security. The following results highlight the key findings from the model. The dependent variable is food security. The variables included in the model are:

<u>**Qualitative Variables**</u>**:** Urban agriculture training, Extension services, Main crop, Production method, Use of pesticides, Source of funding, Access to funding, **f**unding method, Main constraint, Type of space used

<u>**Quantitatives variables:**</u> Field_distance_km, years UA_practices, annual contribution of maintenance.

a) <u>Decision Tree Model Performance Metrics</u>

Table 36 presents the performance metrics of the Decision Tree model, including the complexity parameter (CP), number of splits, relative error, cross-validation error, and its associated standard deviation, which help evaluate the model's accuracy and generalization capability.

Table 36: Decision tree model result

CP	**Number of divisions (nsplit)**	**Rel error**	**Cross error (xerror)**	**Standard deviation (xstd)**
0.109	**0**	1,00	1.133	0.026
0.042	**1**	0.890	**0.** 933	0.038
0.024	**3**	0. 806	0.939	**0.**038
0.018	**5**	**0.** .757	0.921	0.038
0.010	**7**	0.721	0.915	0.038
0.010	**1**	0.690	0.921	0.038

As the complexity parameter (CP) decreases, the decision tree becomes more complex, leading to more splits and a lower relative error, indicating a better fit to the training data. Initially, the cross-validation error (xerror) decreases, improving generalization, but stabilizes and slightly increases at the lowest CP values, suggesting potential overfitting.

The standard deviation remains stable but rises slightly at the lowest CP, indicating reduced consistency. The model with CP = 0.042 appears to offer the optimal balance between underfitting and overfitting. At the lowest CP (0.010), the model has the best training fit but also the highest number of splits. The cross-validation error continues to improve at first but doesn't decrease significantly after a certain point, implying the model may be overfitting at this complexity. The model with a CP of 0.042 may strike a good balance between underfitting and overfitting.

b) **Importance of Variables in the Decision Tree Model:** The following table explains the importance of variables.

Table 37: Repartition of variables in the decision tree model

Variables	Importance
Years UA_practices	30
Main_constraint	17
Annual_contribution of_maintenance	12
Type_of_space_used	11
Field_distance_km	10
Extension_services	7
Urban_agriculture_training	4
Main_crop	3
Source_of_funding	3
Funding_method	2
Access of funding	2
Production_method	1

The most significant factors identified in the model are years of agricultural practice (30) and main constraints (17), emphasizing the pivotal role of experience and the ability to overcome challenges in ensuring food security. Additionally, annual maintenance contribution (12), the type of space used (11), and field distance (10) have been found to play substantial roles.

Conversely, extension services (7), agricultural training (4), main crop (3), source of funding (3), method of funding (2), access of funding (2) and method of production (1) demonstrated a moderate influence. The findings highlight that experience, resource access, and constraints hold the most significant role in determining outcomes.

c) Decision Tree Model Results: Node Structure and Primary Splits for Food Security among Urban Farmers

The decision tree analysis reveals that urban farmers' food security is profoundly influenced by several key factors, including their experience, the constraints they face, and their access to financing. Farmers with fewer than three years of urban agriculture experience and low financial investment are often the most vulnerable, exhibiting very low food security.

In contrast, those who receive strong financial support, cultivate in spaces suited to their practices, and have access to extension services or specialized training enjoy markedly higher food security. Proximity to their fields also plays an important role by helping to mitigate certain constraints. The results clearly demonstrate that experience, while crucial, is not sufficient to guarantee solid food security without adequate resources and infrastructure support.

These findings highlight the need for a comprehensive approach to strengthen urban farmers' resilience particularly by improving access to financing, providing hands-on training, and facilitating access to suitable and sustainable agricultural spaces. Although only the root node's results are shown here, the complete set of nodes and splits is provided in Appendix X for detailed review.

Table 38: First node result

Node number 1: 207 observations,
complexity param=0.1090909
predicted class= very low
expected loss=0.7971014 P(node) =1
class counts: 42   41   41   41   42
probabilities: 0.203 0.198 0.198 0.198 0.203
left son=2 (146 obs)
right son=3 (61 obs)
Primary splits:
Main_constraint splits as LRLLR,   improve=4.983828, (0 missing)
Access_to funding splits as RL,   improve=2.130430, (0 missing)
UA _Years practices < 3.5   to the right, improve=1.821997, (0 missing)
Type_of_space used_splits as LLRR,   improve=1.811892, (0 missing)
Main_crop_ splits as RRLL,   improve=1.253758, (0 missing)
Surrogate splits:
Funding_method splits as RLL, agree=0.715, adj=0.033, (0 split)
source_of_funding_splits as LLLRL, agree=0.710, adj=0.016, (0 split)

Key Significants variables: Experience in UA, alongside financial investment, constraint mitigation, proximity to agricultural land, access to training and extension services are the most critical factors in moving farmers from "Very Low" to higher food-security categories.

1. **Experience and Agricultural Practices**: The analysis indicates that urban farmers with less than three years of experience in urban agriculture have low food security.

This suggests that experience in urban farming practices is crucial for improving food security. As farmers gain more experience, they become more skilled at optimizing their practices, which can directly enhance food production and availability, thus improving food security.

2. **Financial Support and Investment**: Farmers with access to financial support or investments show higher levels of food security. This demonstrates that the ability to invest in urban agriculture whether through personal or external financial support plays a significant role in increasing agricultural output and access to food. The presence of financial resources allows farmers to overcome financial barriers, improve agricultural productivity, and increase their capacity to meet food needs.
3. **Proximity to Agricultural Land**: The proximity of agricultural fields is also a contributing factor. The closer farmers are to their fields, the more likely they are to manage their crops effectively and consistently. This proximity helps reduce logistical challenges and increases the overall efficiency of food production, thereby improving food security.
4. **Access to Training and Extension Services**: Access to training and extension services was also highlighted as a key factor. Farmers who are trained in urban agriculture techniques or receive agricultural extension services are likely to have better yields and more sustainable farming practices. This in turn strengthens their ability to produce food consistently, ensuring food security over time.
5. **Constraints Faced by Farmers**: The analysis also indicates that certain constraints such as lack of financial resources, inadequate space, or poor infrastructure significantly impact food security. However, farmers who overcome these challenges through support systems (financial, infrastructural, or educational) experience much higher food security.

This demonstrates that overcoming barriers to successful urban agriculture is crucial for improving food security. These fundings show that urban agriculture has a clear and significant impact on food security for urban farmers. The level of experience, access to resources, proximity to farmland, and support systems directly contribute to enhancing their ability to meet their food needs, demonstrating the positive role urban agriculture plays in improving food security.

d) General Statistics and statistics by class

The model shows limited predictive performance, with an overall accuracy of 24%, indicating weak outcome prediction. The 95% confidence interval (0.1306–0.3817) reflects a high level of uncertainty, and the p-value of 0.289 confirms that the model does not significantly outperform random chance.

Additionally, the very low Kappa statistic (0.05) reinforces the minimal agreement between predicted and actual classes, while McNemar's test (p = 0.036) highlights instability in the classification errors. As detailed in the table below, the model particularly struggles with the Low and Very Low categories, displaying poor sensitivity (0.10 and 0.00, respectively) and weak positive predictive values.

Although performance improves slightly for the Medium category (sensitivity of 0.60, detection rate of 0.12), classification errors remain considerable. On the other hand, the model demonstrates relatively high specificity (~0.85), showing it is more reliable in identifying non-target cases. The negative predictive values (~0.80) suggest some consistency in excluding incorrect classifications. However, balanced accuracy remains low across most categories, with a slight improvement only in the Very High class (~0.575). The model's performance is close to random prediction, underlining the need for parameter optimization or alternative algorithms to enhance its predictive ability.

Table 39: Statistics by class and global statistics results

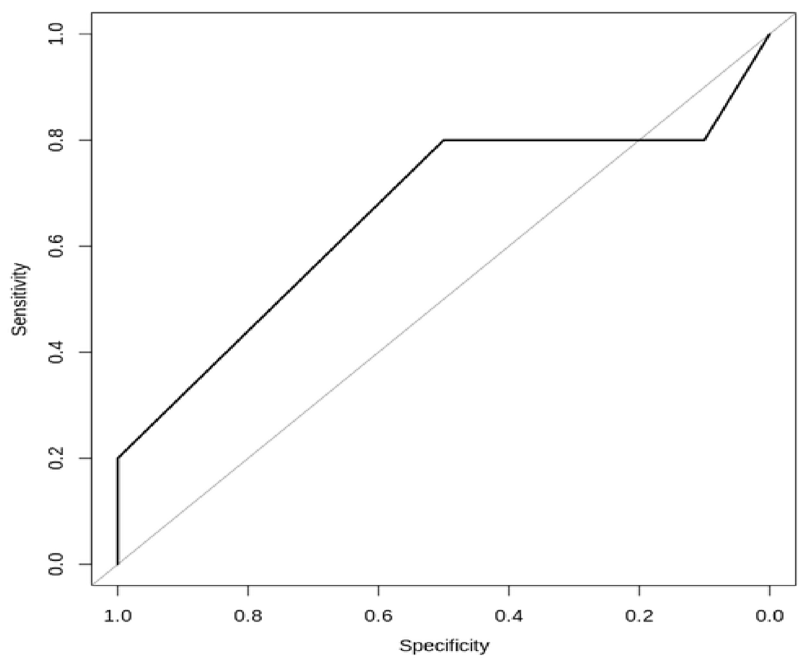
Statistics	Class: Very Low	Class: Low	Class: Medium	Class: High	Class: Very high
Sensitivity	0.1000	0.0000	0.6000	0.2000	0.3000
Specificity	0.8500	0.9250	0.5000	0.9250	0.8500
Pos Pred Value	0.1429	0.0000	0.2308	0.4000	0.3333
Neg Pred Value	0.7907	0.7872	0.8333	0.8222	0.8293
Prevalence	0.2000	0.2000	0.2000	0.2000	0.2000
Detection Rate	0.0200	0.0000	0.1200	0.0400	0.0600
Detection Prevalence	0.1400	0.0600	0.5200	0.1000	0.1800
Balanced Accur	0,4750	0,4625	0,5500	0,5625	0,5750
Accuracy			0.24		
95%CI			(0.1306, 0.3817)		
No Information Rate (NIR)			0.2		

P-Value [Acc > NIR]	0.289
Kappa	0.05
McNemar's Test P-Value	0.036

The decision tree model, while significant for understanding key variables affecting food security, shows weak predictive performance. Despite low accuracy, it offers valuable insights, and future work could improve its effectiveness through optimization or alternative algorithms.

e) Decision Tree Model: ROC Curve Analysis

The following figure presents the ROC (Receiver Operating Characteristic) curve of the Decision Tree model, illustrating its ability to distinguish between classes and assess overall predictive performance based on the trade-off between sensitivity (true positive rate) and specificity (false positive rate).



Graph 16: ROC CURV

The model's performance, as indicated by its area under the curve (AUC), measures up to 0.66, suggesting moderate performance. Generally, an AUC less than 0.5 indicates a less-than-ideal model (with predictions that are less or poorer than random), an AUC between 0.5 and 0.7 suggests an average model, an AUC between 0.7 and 0.9 represents a good model, and an AUC greater than 0.9 is considered excellent. Consequently, with an AUC of 0.66, the model performs moderately, but there is still room for improvement by adjusting its parameters, adding explanatory variables, or selecting a different classification algorithm.

Conclusion on the Urban Farmers Model

In conclusion, the decision tree analysis has highlighted the significant role of agricultural practices and socio-economic factors in determining food security levels. The most influential variables identified, including years of agricultural practice, agricultural constraints, and the type of space used, provide a clear understanding of the factors influencing food security outcomes. The findings suggest that agriculture alone is not sufficient to address the multifaceted challenges of food security. Instead, socio-economic variables such as income diversification, access to markets, and the overall economic stability of households play crucial roles. Low food security is closely linked to inadequate agricultural practices, limited resources, and external shocks, while high food security is driven by improved agricultural practices, socio-economic integration, and market access. To improve food security, it is essential for policymakers to focus on modernizing agricultural practices, promoting economic diversification, and developing robust public policies that address the needs of vulnerable populations. Then by integrating these factors, it is possible to foster long-term food security and enhance the resilience of urban farmers in the face of socio-economic and environmental challenges.

SECTION 5: Enhancing Climate Resilience through Urban Agriculture in Senegalese Cities

Introduction:

As cities in Senegal face increasing climate challenges, building resilience is crucial for sustainable development. Urban agriculture has become an important strategy for enhancing food security, reducing environmental risks, and supporting local economies. This section explores how urban agriculture can help strengthen climate resilience in Senegalese cities. It also explains why these cities were chosen as case studies and outlines the methodology used to assess the role of urban agriculture in climate adaptation.

The ability of households to maintain high levels of food security in the face of climate change depends on their resilience. Climate-smart agricultural practices, such as greenhouse farming, drip irrigation, and agroforestry, help minimize the risks associated with climate variability.

Additionally, access to agricultural insurance can protect households from crop losses caused by extreme climate events, further enhancing their ability to adapt to climate challenges. In this section, we aim to assess how urban agriculture contributes to the climate resilience of Senegalese cities.

5.1 Case study selection and methodology overview

As the capital and most densely populated city, Dakar faces significant pressures from rapid urbanization, limited green space, and coastal erosion, making it a critical site for studying urban adaptation strategies. Thies, known for its vibrant community-driven initiatives, provides a valuable case study in local engagement and grassroots accountability mechanisms. Saint-Louis, highly vulnerable to climate change impacts including flooding and sea level rise, is a priority for exploring innovative adaptation tools.

Ziguinchor, in the Casamance region, with its distinctive agricultural practices and regional dynamics, offers a unique perspective on integrating urban agriculture into adaptation strategies. Kaolack, as a major hub for trade and agriculture, demonstrates the link between economic development and climate resilience. Diourbel, located in .2of water management and food security challenges. Unlike coastal cities like Dakar and Saint-Louis, Diourbel faces different climate pressures, including more significant risks related to water scarcity and droughts. The region is heavily dependent on agriculture, and its vulnerability to changing precipitation patterns and water availability is a major concern for food security.

To understand how urban households and farmers engage in climate resilience strategies, we will begin with a descriptive analysis consisting of tables and graphs. These representations will highlight their perceptions of climate change, the frequency of access to information, trust in public actions, and the adoption of adaptation measures.

By creating this quantitative portrait of their level of engagement, we will be able to contextualize the role of urban agriculture in climate resilience before proceeding with a detailed geospatial analysis.

5.1.1 Descriptive Evidence of Urban Agriculture's Role in Climate Resilience

To illustrate how urban agriculture supports climate resilience, we present two summary tables, one for urban households and one for urban farmers. Each table reports key variables on climate change perception, information access, adaptation strategies, and perceived role, providing a clear comparison of engagement levels across these groups.

a) **Descriptive Statistics: Urban Agriculture and Climate Resilience among Urban Households**

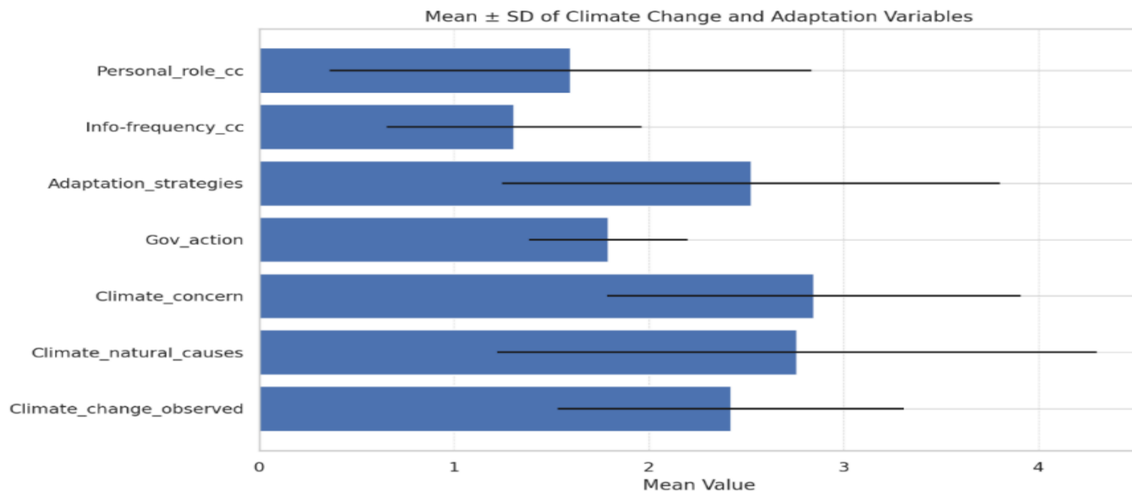
Table 40: Descriptive statistics among urban households

Variables	Mean	SD	Min	Max	N
Climate_change_observed	2.42	0.89	2	6	254
Climate_natural_causes	2.76	1.54	1	7	254
Climate_concern	2.85	1.06	1	5	254
Gov_action	1.79	0.41	1	2	254
Adaptation_strategies	2.52	1.28	1	5	254
Info-frequency_cc	1.31	0.65	1	4	254
Personal_role_cc	1.60	1.24	1	5	254

The results indicate that urban households moderately perceive the effects of climate change (mean = 2.42) and largely acknowledge that it is not solely due to natural causes (mean = 2.76), suggesting a fair understanding of anthropogenic drivers. Their level of concern is relatively high (mean = 2.85), and they believe that the government is taking action (mean = 1.79).

While some adaptation strategies are being adopted (mean = 2.52), the frequency of access to climate change information remains low (mean = 1.31), as does their perceived personal role in addressing climate change (mean = 1.60). This suggests that although environmental awareness exists, urban households may lack the means or motivation to engage actively. In this context, urban agriculture emerges as a strategic opportunity to strengthen their contribution to climate resilience by involving them in tangible, local adaptation practices.

The following graph illustrates how various factors evolve in the context of urban agriculture and climate resilience among urban households in Senegalese cities.



Graph 17: Perceptions of Climate Change, Resilience, and the Role of Urban Agriculture among Urban Households

The chart shows that **observed climate change** and **climate concern** have the highest average scores (around 2.5–2.9), indicating most respondents recognize climate shifts and worry about them, though concern varies widely. **Adaptation strategies** also rate relatively high (mean ≈2.5) with large variation, suggesting uneven uptake of coping measures. In contrast, **information frequency** and **government action** score lower (means ≈1.3–1.8), with tighter consensus, implying limited access to climate information and moderate belief in official responses. Finally, respondents **perceived personal role** (mean ≈1.6) is modest and varied, highlighting a need to better engage individuals in climate adaptation.

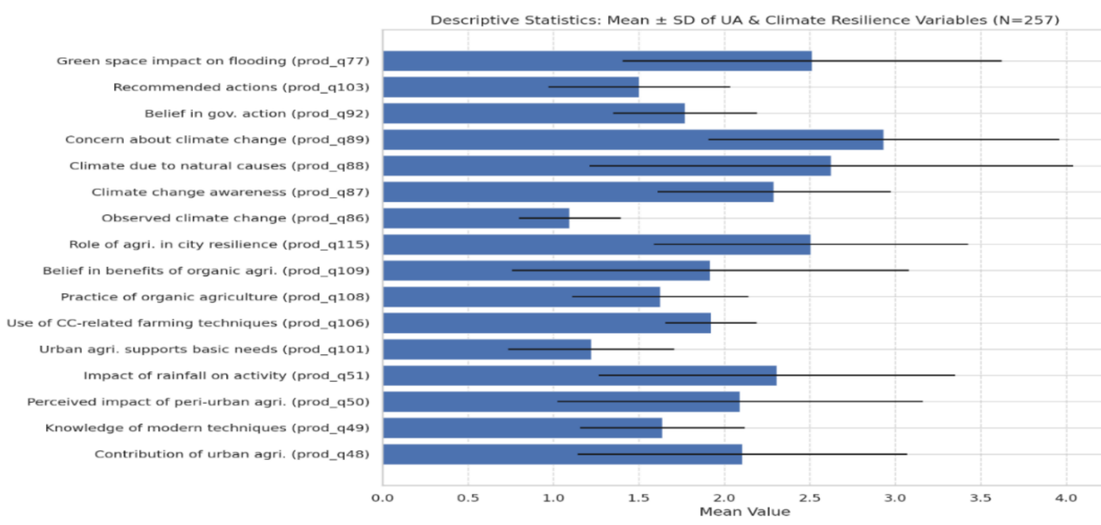
b) Descriptive Statistics: Urban Agriculture and Climate Resilience among Urban farmers

Table 41: Descriptive statistics among urban farmers

VARIABLES	Mean	SD	Min	Max	N
Contribution of urban agri.	2.11	0.96	1	4	189
Knowledge of modern techniques	1.64	0.48	1	2	257
Perceived impact of peri-urban agri.	2.09	1.07	1	4	257
Impact of rainfall on activity	2.31	1.04	1	4	257
Urban agri. supports basic needs	1.22	0.49	1	3	257
Use of CC-related farming techniques	1.92	0.268	1	2	257
Practice of organic agriculture	1.63	0.516	1	3	257

Belief in benefits of organic agri.	1.92	1.161	1	4	257
Role of agri. in city resilience	2.51	0.919	1	4	257
Observed climate change	1.097	0.297	1	2	257
Climate change awareness	2.292	0.682	2	6	257
Climate due to natural causes	2.626	1.414	1	7	257
Concern about climate change	2.934	1.027	1	5	257
Belief in gov. action	1.770	0.421	1	2	257
Recommended actions	1.502	0.531	1	3	257
Perceived green space impact on flooding	2.514	1.108	1	4	257

The descriptive statistics show that respondents generally recognize the role of urban agriculture in supporting basic needs and enhancing city resilience, although the average contribution level remains modest. Awareness of climate change is relatively high, and concern about its impacts is notable. However, trust in government action appears limited. The use of climate-smart farming techniques and organic agriculture practices is emerging but still developing among the surveyed households. The following graph illustrates how various factors evolve in the context of urban agriculture and climate resilience among urban farmers in Senegalese cities.



Graph 18: Descriptive Statistics of Urban Agriculture and Climate Resilience Variables: Mean and Standard Deviation (N=257)

The graph presents the mean and standard deviation for various variables related to urban agriculture and climate resilience. Respondents generally view urban agriculture as important, particularly for supporting basic needs, though opinions on its contribution and impact vary. Regarding climate change, awareness and concern are moderate, with most recognizing it, but views on whether it is caused by natural or human factors show variability. When it comes to government action, the majority of respondents believe that action is being taken, with little variation in responses.

Finally, the impact of green spaces on flooding is seen as moderate, but views on whether it is caused by natural or human factors show variability. When it comes to government action, the majority of respondents believe that action is being taken, with little variation in responses. Finally, the impact of green spaces on flooding is seen as moderate, but again, opinions differ somewhat. The graph highlights both consensus in some areas, such as government action, and diversity in others, like the role of urban agriculture and perceptions of climate change causes.

5.1.2 Geospatial Analysis of Urban Agriculture and Climate Resilience: NDVI, Precipitation, and Temperature Trends in Senegalese Cities

To measure climate resilience through urban agriculture, we conducted a geospatial analysis using satellite data. Google Earth Engine (GEE) is a powerful and innovative platform for geospatial analysis and satellite imagery. It is particularly useful for addressing issues related to the environment, natural resource management, agriculture, smart cities, and other fields.

After using Google Earth Engine, we presented the different regions of Senegal on the map. We then identified the cities and geographical zones within these cities, including Dakar, Thies, Kaolack, Saint-Louis, Ziguinchor, and Diourbel. This approach allowed us to visualize and analyze key areas where urban agriculture could play a role in enhancing climate resilience.

Step 1: Urban Vegetation Analysis: NDVI Calculation and Vegetation Assessment in Senegalese Cities

The objective of this step is to identify areas of urban agriculture using the Normalized Difference Vegetation Index (NDVI). The NDVI is used to differentiate between vegetated and non-vegetated areas. Based on satellite data, the NDVI was calculated for the various selected regions. We first calculate the Normalized Difference Vegetation Index (NDVI), a measure used to assess vegetation health and density.

The following table presents the NDVI values across Senegalese cities. Afterward, we present the NDVI graph to visually show the distribution and condition of vegetation in the area.

Table 42: Cities NDVI average

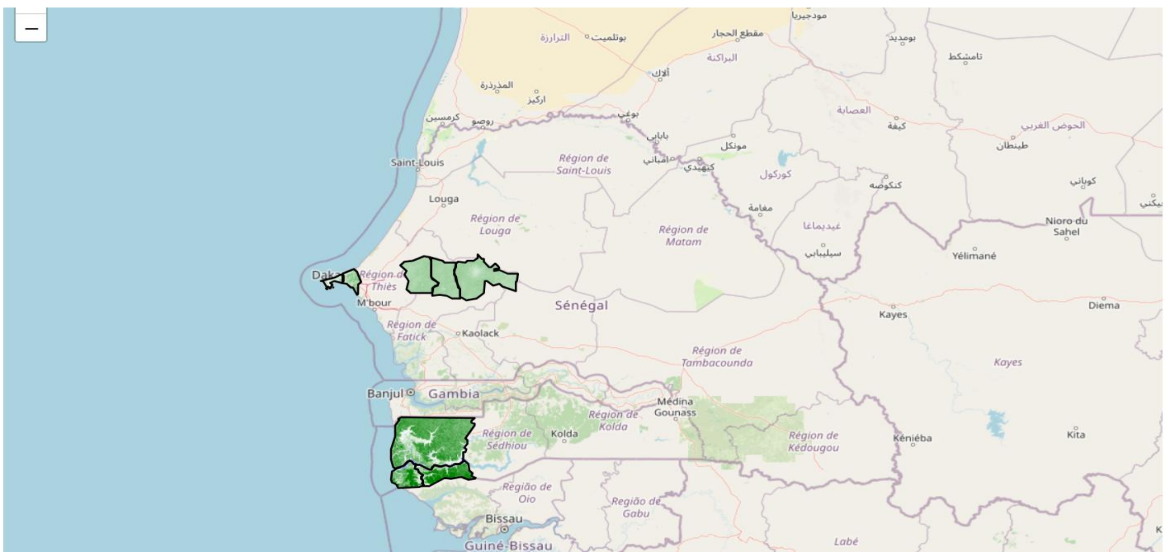
Regions	NDVI
Dakar	**0.172**
Sedhiou	0.225
Ziguinchor	**0.262**
Kolda	0.206
Kedougou	0.197
Tambacounda	0.186
Fatick	0.170
Kaffrine	0.167
Thies	**0.162**
Kaolack	**0.161**
Diourbel	**0.175**
Matam	0.155
Louga	0.144
Dakar	0.172
Saint-Louis	0.124

The NDVI analysis across Senegal's regions using satellite data reveals varying levels of vegetation, with Dakar showing low NDVI values (0.10–0.17), indicating high urbanization and limited green spaces. Diourbel, with a moderate NDVI (~0.175), reflects sparse vegetation typical of semi-arid agricultural areas. Ziguinchor, with higher NDVI values (0.25–0.33), indicates denser vegetation, offering greater potential for agricultural and ecological development.

These variations have significant economic implications: Dakar, with its low NDVI, should focus on expanding urban green spaces, integrating vertical farming, and promoting urban agriculture to improve vegetation, air quality, and climate resilience.

Dakar needs investments in green infrastructure to address urban challenges, Diourbel requires climate-resilient agricultural solutions to improve agriculture, and Ziguinchor has potential for sustainable agriculture and ecotourism. Regions like Ziguinchor and Kedougou, with higher NDVI values, should prioritize agroecology, agroforestry, and ecotourism to foster sustainable growth. Tailored, region-specific policies are essential for promoting sustainable development.

Saint-Louis (0.124), Thies (0.162), and Kaolack (0.161) all shows low NDVI values, indicating sparse vegetation, meaning there are fewer plants or lower plant density in that area.. These regions would benefit from investments in green infrastructure and the promotion of climate-resilient agricultural practices to improve sustainability and resilience. The effective implementation of public policies is crucial for ensuring long-term sustainability across these regions.As shown in the graph below:



Graph 19: Urban vegetation with NDVI values

The map highlights the six urban areas in Senegal where the study on urban agriculture and climate resilience was conducted: Dakar, Thiès, Saint-Louis, Diourbel, Kaolack, and Ziguinchor. These zones represent key urban centers across different cities of the country, selected to reflect diverse agro-ecological and urbanization contexts.

The following table presents the results of the NDVI (Normalized Difference Vegetation Index) analysis across different cities of Senegal, along with tailored policy recommendations aimed at enhancing urban vegetation and promoting sustainable land use.

Table 43: NDVI Analysis by Region: Policy Recommendations

Dakar, Diourbel, Fatick, Kaffrine, Kaolack, Kedougou, Louga, Matam, Saint-Louis, Tambacounda, Thies	Kolda, Sedhiou, Ziguinchor
NDVI Moyen = 0.157	
Recommendations:	
It is imperative that urgent action be taken to increase urban vegetation.	NDVI Moyen =0.207
2. The establishment of community gardens.	**Recommendations:**
3. Development of vertical farming	1. Optimize existing green spaces
4. The creation of urban market gardening zones	
	2. Promote urban agriculture
	3. Develop agroforestry projects

The NDVI analysis reveals lower levels of vegetation (NDVI = 0.157) in regions such as Dakar, Kaolack, and Saint-Louis, highlighting the urgent need to increase urban greenery through initiatives such as community gardens, vertical farming, and market gardening zones. In contrast, greener regions such as Kolda, Sédhiou, and Ziguinchor (NDVI = 0.207) should focus on optimizing existing green spaces, promoting urban agriculture, and expanding agroforestry to maintain and increase their vegetation cover.

Step 2: Precipitation Patterns and Their Impact on urban Agriculture in senegalese regions

The following table presents the precipitation data (in millimeters) for the regions of Diourbel, Dakar, and Ziguinchor, showing the variations in rainfall within each region. This data is essential for understanding the climatic conditions and their implications for agricultural productivity and climate resilience in each area.

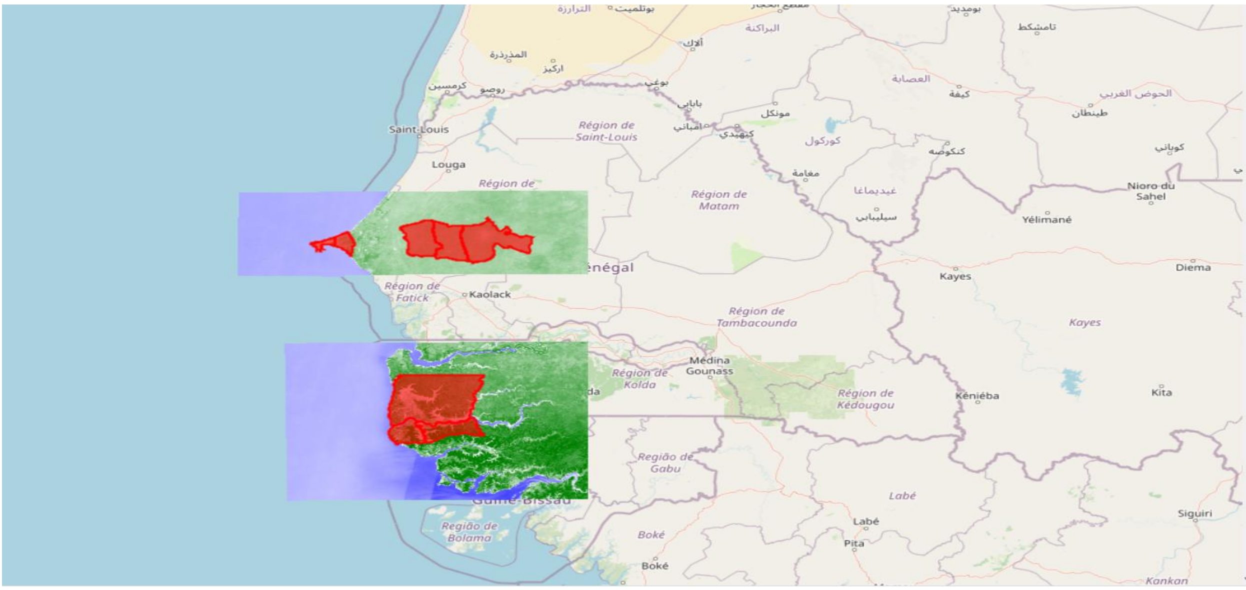
Table 44: Cities Precipitations (mm)

Sites	Normal average	Cumulative
DAKAR-YOFF	Mean (1897-2020)	476.33
DAKAR-YOFF	Normal 1931-1960	561.47
DAKAR-YOFF	Normal 1961-1990	406.59
DAKAR-YOFF	Normal 1991-2020	400.04
Diourbel station	Mean (1919-2020)	579.57

Diourbel station	Normal 1931-1960	699.27
Diourbel station	Normal 1961-1990	513.97
Diourbel station	Normal 1991-2020	518.49
Kaolack station	Mean (1918-2020)	709.22
Kaolack station	Normal 1931-1960	794.10
Kaolack station	Normal 1961-1990	614.13
Kaolack station	Normal 1991-2020	631.88
Kolda station	Mean (1922-2021)	1146.05
Kolda station	Normal 1931-1960	2490.43
Kolda station	Normal 1961-1990	1015.17
Kolda station	Normal 1991-2021	1146.11
Thies station	Mean (1918-2020)	540.15
Thies station	Normal 1931-1960	692.20
Thies station	Normal 1961-1990	466.02
Thies station	Normal 1991-2020	440.33
Ziguinchor station	Mean (1918-2021)	1416.10
Ziguinchor station	Normal 1931-1960	1547.09
Ziguinchor station	Normal 1961-1990	1252.38
Ziguinchor station	Normal 1991-2021	1382.27
Saint-louis station	Mean (1957-2021)	267.52
Saint-louis station	Normal 1961-1990	260.29
Saint-louis station	Normal 1991-2021	271.46

The distinct rainfall patterns experienced by Senegal's various regions have significant economic implications. The regions of Diourbel and Dakar, in particular, face challenges due to low rainfall and water scarcity, necessitating investments in irrigation systems, the cultivation of drought-resistant crops, and the implementation of sustainable urban farming practices. The city of Saint-Louis, on the other hand, is confronted with issues such as soil salinization and water shortages, which demand the development of salt-resistant crops and the implementation of coastal management strategies.

Additionally, the coastal regions offer potential economic opportunities through tourism and fishing. Ziguinchor, benefiting from higher rainfall, has a diversified agricultural sector, but it is confronted with challenges related to flood management. Exploring opportunities in eco-tourism and agroforestry can be a viable strategy for this region. The implementation of customized water management and agricultural adaptation strategies is imperative for enhancing resilience and achieving sustainable development. As demonstrated in the graphic and the graph below:



Graph 20: Representation of precipitations in Senegalese cities

The map shows two main zones in Senegal, highlighted in red and covered with NDVI (Normalized Difference Vegetation Index) images. The highest zone (Dakar, Diourbel, Kaolack, etc.) shows sparse vegetation coverage, reflecting lower NDVI values, while the southern zone (Ziguinchor, Kolda, Sédhiou) appears greener with higher NDVI values. This visual comparison highlights regional differences in vegetation density and supports differentiated urban greening and agricultural policies.

Step 3: Temperature Trends and Implications for Urban Agriculture in Senegalese Cities

An analysis of average temperatures across the Diourbel, Dakar, and Ziguinchor regions reveals distinct climate challenges that significantly impact agricultural productivity, urban planning, and public health.

Diourbel with an average temperature of 39.4°C, faces extreme heat, which limits agriculture by increasing evapotranspiration, reducing water availability for crops, and causing heat stress for livestock.

To address these challenges, investments in heat-resistant crops, irrigation systems, and public health infrastructure are imperative. Dakar, with an average temperature of 30.8°C, experiences the urban heat island effect, which increases energy demand for cooling and stresses peri-urban agriculture. Solutions such as the creation of green spaces, improved land and water management, and sustainable energy infrastructure are crucial. Ziguinchor, with an average temperature of 33.7°C, experiences a warm climate that is conducive to diversified agriculture and agroforestry. However, high temperatures necessitate effective water and soil management to maintain crop yields. The region benefits from agroforestry and ecotourism opportunities, though high humidity and temperature levels increase health risks, requiring enhanced resilience of infrastructure. While Saint-Louis, Thies and Kaolack lacks comprehensive data for thorough analysis, it is likely to encounter similar challenges related to excessive temperatures and heat stress. As such, investments in adaptive infrastructure are essential for all regions, economic development policies should take account of local temperatures to guide investment and strengthen regional climate resilience. As summarized in the table below:

Table 45: Regional Temperature Averages and Their Economic Implications in Senegal

Regions	**Temperature average**	**Main economic implications**
Diourbel	30.8°C.	Vulnerable agriculture and livestock, increased heat stress, need for adapted crops and irrigation
Dakar	39.4°C.	Increased energy pressure, urban heat islands, opportunities for tourism and peri-urban agriculture
Ziguinchor	33.7°C.	Diversified agriculture requires climate management, opportunities in agroforestry and tourism.

Step4: The Role of NDVI, Precipitation, and Temperature in Strengthening Climate Resilience through Urban Agriculture

The relationship between NDVI, rainfall, and temperature plays a crucial role in influencing the potential of urban agriculture and climate resilience in Senegal. Regions like Sedhiou and Ziguinchor, which benefit from higher rainfall, show greater NDVI values, indicating a more favorable environment for agricultural activities.

In contrast, cities such as Dakar and Saint-Louis, characterized by lower rainfall and reduced NDVI, face significant agricultural challenges and require innovative solutions, such as rainwater management, to ensure food security. Temperature also plays a pivotal role, with higher temperatures, especially in semi-arid areas, exacerbating urban heat island effects and heat stress, making agriculture even more difficult. This highlights the importance of adopting strategies such as vertical farming in urban areas with low NDVI values. On the other hand, regions with higher NDVI can benefit from agroforestry and sustainable agricultural practices, which further enhance their agricultural output and environmental resilience.

Enhancing urban vegetation has been shown to strengthen climate resilience, reduce vulnerabilities, and stimulate local economies. The data analysis clearly confirms this hypothesis, demonstrating that urban agriculture strengthens the climate resilience of cities based on observed environmental and climatic characteristics.

Urban agriculture, by promoting the growth of food production and creating employment opportunities in the green sector, directly contributes to climate adaptation. Without these interventions, cities, particularly those with low NDVI values, are likely to face heightened climate risks, economic challenges, and increased food insecurity.

Urban agriculture is a key strategy for building climate resilience in Senegalese cities, especially in regions with low NDVI values like Dakar, Diourbel, and Saint-Louis. This practice addresses multiple challenges: it mitigates the urban heat island effect, improves food security, and enhances overall quality of life through better air quality and fertile soils. Additionally, urban agriculture fosters economic growth by creating job opportunities within agriculture and related sectors.

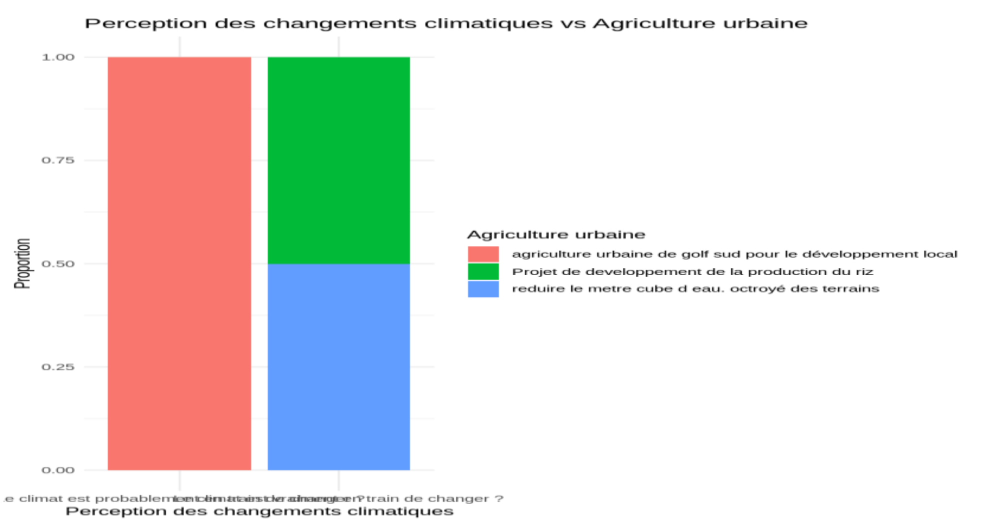
To improve climate resilience in areas with limited vegetation, food import dependence, and scarce green spaces, targeted interventions are crucial. The economic recommendations for these regions stress the importance of boosting urban agriculture and green spaces through initiatives such as vertical farming, community gardens, and investment in green infrastructure. These interventions are essential for reducing vulnerabilities and fostering sustainable development, ultimately ensuring a more climate-resilient future for Senegalese cities.

5.3 Graphical Representation of Urban Agriculture Projects and climate resilience strategies by Municipalities

This section will provide a graphic representation of municipal urban agriculture projects and initiatives, thereby highlighting the various efforts undertaken by local governments to integrate urban agriculture as part of their climate resilience and sustainable development strategies in Senegal. Through this visual representation, the distribution and focus of these initiatives across different municipalities will be explored, offering insights into their role in promoting food security, economic growth, and environmental sustainability. As part of this study, we conducted a survey in **13 municipalities in Senegal** to gather data on these initiatives. We first present the perceptions of climate change and urban agriculture, followed by a graphic of the projects and initiatives related to urban agriculture in Senegal municipalities.

5.3.1 Municipal Perceptions of Climate Change and Urban Agriculture Initiatives in Senegal

This section will concentrate on the perceptions of climate change and urban agriculture practices among the municipalities surveyed in Senegal. The following graphic illustrates how these municipalities perceive the impacts of climate change in relation to urban agriculture initiatives. It provides insights into how local governments and communities recognize the need for sustainable agricultural practices as part of their climate resilience strategies. Then by examining these perceptions, we can better understand the role of urban agriculture in addressing climate challenges and fostering sustainable development in urban areas. Graphically, we have:



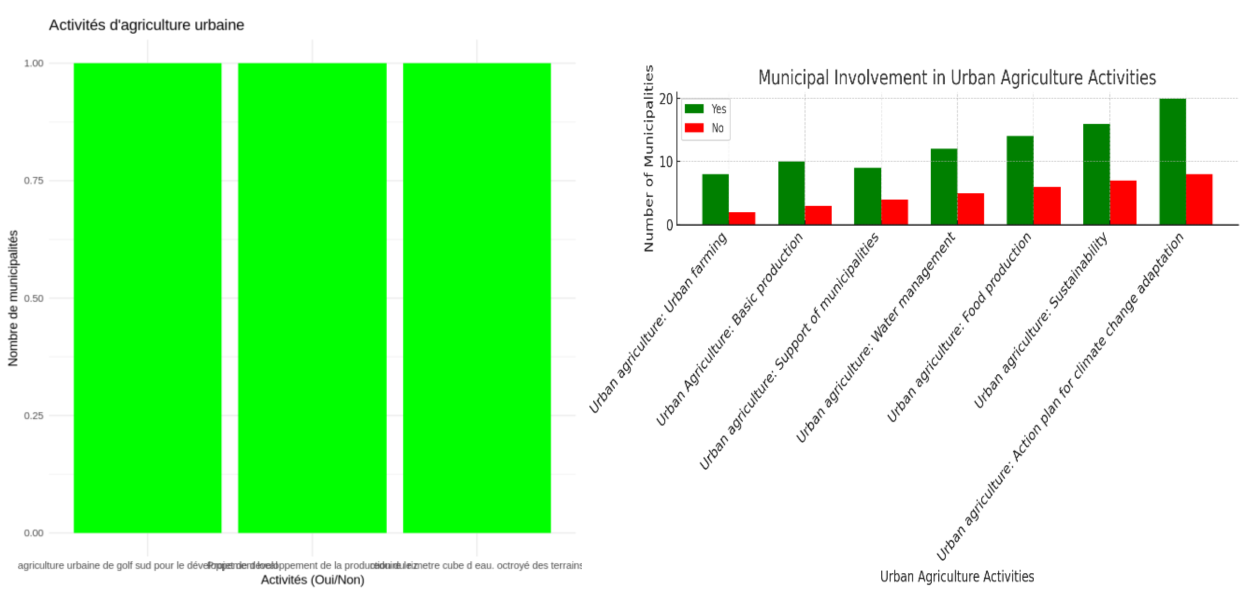
Graph 21: Municipalities perceptions of climate change related to urban agriculture

The graph shows how different urban agriculture projects are linked to climate change perceptions. Golf Sud's urban agriculture is associated with the belief that "the climate is probably changing," while rice production is linked to the perception that "the climate is changing."

Projects focused on water conservation and land allocation also reflect climate change awareness. This highlights the need for resilient agricultural practices, efficient irrigation, crop diversification, and climate-smart agriculture. Additionally, land and water management policies are essential for sustainable food production and economic development. As climate risks increase, urban farmers may adapt their practices, impacting food prices and markets. Investment in supportive policies and infrastructure is key to ensuring sector resilience.

5.3.2 Strengthening Climate Resilience through Municipal Urban Agriculture strategies in Senegal

In this part, the analysis will concentrate on the projects and initiatives that have been implemented by the various municipalities that have been surveyed. The following graph illustrates the distribution and types of urban agriculture initiatives that have been introduced by these municipalities. This provides insights into the scope and diversity of their efforts to promote sustainable urban farming practices. Graphically, we have:



Graph 22: Municipalities initiatives urban agriculture projects

The bar chart highlights municipal involvement in urban agriculture, showing that three municipalities are actively engaged in initiatives such as local agricultural production, water management, and land allocation. These efforts demonstrate the growing interest in urban agriculture's potential for sustainable city development. Urban agriculture enhances food security by providing local food and reducing dependency on external sources. However, challenges like limited resources and infrastructure remain. Municipalities that support urban agriculture see improved food security outcomes, but further investment in infrastructure, market access, and capacity building is needed for long-term resilience. Programs like AGRISEN and PROVAL also support urban agriculture, boosting productivity and income.

General Conclusion: Urban Agriculture as a Pillar of Food Security and Climate Resilience towards the Green Economy Transition in Senegalese Cities

Urban agriculture plays a crucial role in building resilient urban systems and advancing the transition to a green economy, particularly in the face of climate change. It addresses key challenges such as food security, environmental degradation, and climate risks by integrating agriculture into urban planning. Climate-smart practices like crop diversification, agroecology, and efficient irrigation systems help reduce environmental pressures, enhance biodiversity, and mitigate climate change impacts. In Senegal, urban agriculture is especially important in cities like Dakar and Saint-Louis, which face extreme climatic conditions. Nature-based solutions such as rooftop gardens and vertical farming improve food accessibility, reduce temperatures, and enhance urban microclimates. The socio-economic analysis reveals that income, education, and access to financial services influence food security and adaptive capacity. Geospatial assessments show that cities with more vegetation and water resources, like Ziguinchor and Thies, are better equipped to mitigate floods and droughts. Urban agriculture also supports the green economy by creating jobs, promoting resource efficiency, and reducing the carbon footprint of food systems. It fosters economic diversification, job creation, and local investment, particularly through green technologies such as solar-powered irrigation and hydroponics. Municipal governments play a key role by supporting policies that enable sustainable land use, access to resources, and capacity building for urban farmers. Community-based initiatives, especially those empowering women and marginalized groups, further promote social cohesion. Ultimately, urban agriculture is a key strategy for sustainable development in Senegalese cities, boosting resilience, food security, and environmental sustainability while fostering economic and social well-being.

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CHAPTER 3: Building Climate Resilient City: Leveraging the Water-Energy-Food nexus in advancing Green Economy Transition, West Africa case study

Abstract: This paper explores strategies to strengthen the climate resilience of African cities by leveraging the water, energy and food (WEF) nexus and transitioning to a green economy. African cities face numerous challenges related to the impacts of climate change, including water scarcity, energy insecurity, and food insecurity. Adopting an integrated approach that considers the linkages between water, energy, and food systems is essential to building resilience and promoting sustainable development. This article explores the potential of the WEF nexus framework to address these challenges and facilitate the transition to a green economy in African cities. The study used several models, including one specifically designed to analyze the Environmental Kuznets Curve (EKC) equation. bb results indicate that principal component analysis (PCA) facilitated the construction of a food security index for the thirteen sub-Saharan countries Benin, Burkina Faso, Côte d'Ivoire, Gambia, Ghana, Guinea, Guinea-Bissau, Mali, Niger Nigeria, Senegal, Sierra-Leone and Togo from 2000 to 2022. In addition, dynamic panel modeling within a generalized method of moments (GMM) framework was used to obtain reliable parameter estimates. These methods revealed essential information about the interrelated challenges faced by these countries. By optimizing resource use, promoting renewable energy sources, and encouraging sustainable agricultural practices, these countries can improve their resilience to climate change while contributing to economic growth and environmental sustainability. For example, increasing water use efficiency in agriculture, integrating renewable energy into urban infrastructure, and improving food production systems are key strategies. This integrated approach not only addresses immediate climate challenges but also lays the foundation for long-term sustainability and economic development. The EKC posits that as an economy grows, environmental degradation initially increases, peaks, and then declines as the economy develops and adopts cleaner technologies and more sustainable practices. African countries can better navigate the complexities of climate change and build a resilient future by focusing on sustainable development, renewable energy, agricultural sustainability, policy support, and multi-stakeholder collaboration.

Keywords: Climate resilience, African cities, WEF nexus, green economy transition, sustainable development, renewable energy, agricultural sustainability, policy support, West African countries

Introduction

A-Background of the study

The 2015 Paris Climate Agreement was a major turning point in the global effort to mitigate climate change(Ali & Acquaye, 2024). It called on governments around the world to focus on reducing CO2 emissions by 5 billion tonnes by 2030 and achieving net-zero emissions by 2050. This shift has resulted in a significant industrial energy transition, accompanied by a rapid shift to renewable energy sources. Consequently, other critical components of the ecosystem, including water and food systems, are also being impacted. Water, energy, and food are fundamental to sustainable development. The 2015 adoption of the 17 Sustainable Development Goals (SDGs) recognized the interconnectedness of well-being, economic prosperity, and environmental health. Nevertheless, the complex dynamics between water, energy, and food systems, which intersect with global challenges such as poverty, food security, economic development, climate change, and health, pose risks that could hinder progress toward sustainable development and green growth(Ali & Acquaye, 2024).

As the challenges posed by these interconnections continue to evolve, the rapid urbanization occurring across African cities presents both an opportunity and a challenge to address these issues while simultaneously advancing sustainable development goals and green growth initiatives.

African cities are undergoing the fastest urbanization globally, making them among the youngest and most dynamic regions (Representation, 2023). This demographic and spatial transformation is expected to significantly reshape Africa's economic, social, and political landscape in the coming decades. Urbanization, therefore, presents both challenges and immense opportunities to accelerate progress towards global and continental agendas such as the 2030 Sustainable Development Goals (SDGs), the New Urban Agenda, and the African Union's Agenda 2063: *The Africa We Want* (Representation, 2023). As cities continue to expand, urbanization has become one of the defining characteristics of the 21st century. People are increasingly drawn to metropolitan areas due to the promise of economic and social opportunities (Sherwood et al., 2017). In fact, more than half of the global population lived in urban areas by 2014, a figure projected to rise to 66% by 2050 (UN Department of Economic and Social Affairs, 2018).

However, urban populations typically exhibit higher consumption patterns than rural ones, placing greater pressure on natural resources and sustainability (Sherwood et al., 2017).

This growing urban demand highlights the central role of water, energy, and food systems in sustaining life and supporting development. These three sectors are interconnected and mutually dependent, forming the Water-Energy-Food (WEF) Nexus, an essential framework for promoting sustainable development (Segovia-Hernández et al., 2023).

Global projections suggest that demand for all three resources will continue to rise sharply due to population growth, urbanization, changing consumption patterns, economic development, and climate change (Morales-García & Rubio, 2024). Agriculture, for instance, remains the largest global consumer of freshwater, while water is also critical in energy production (Segovia-Hernández et al., 2023).

The theoretical framework underlying the Water-Energy-Food (WEF) Nexus is crucial to understanding the interdependencies between these critical resources and their role in advancing sustainable development. From a theoretical standpoint, the WEF Nexus aligns closely with several key Sustainable Development Goals (SDGs) set by the United Nations, particularly Goals 2, 6, 7, and 12, which focus on achieving Zero Hunger, Clean Water and Sanitation, Affordable and Clean Energy, and Responsible Consumption and Production, respectively (Ali & Acquaye, 2024). These interconnected goals highlight the need for integrated governance systems that ensure efficient use of resources, minimize trade-offs, and promote long-term resilience.

However, environmental sustainability is often compromised by unsustainable practices in the production and consumption of water, energy, and food, highlighting the critical role of these systems in global sustainability efforts. The WEF Nexus offers a comprehensive framework for addressing these challenges, providing a robust foundation for advancing the transition to a green economy while ensuring resource security and sustainability (LO David, 2024).

Through various theoretical frameworks including Securitization Theory, the Malthusian Theory of Population, Game Theory, Institutional Theory, Technology Acceptance Model (TAM), and Innovation Diffusion Theory (IDT), the WEF Nexus offers a comprehensive framework for addressing these challenges, providing a robust foundation for advancing the transition to a green economy while ensuring resource security and sustainability (LO David, 2024).

In many developing countries, especially in Sub-Saharan Africa, weak regulatory frameworks and suboptimal use of economic resources amplify these pressures. These vulnerabilities were further exposed during recent global financial crises, which worsened environmental degradation and hindered sustainable production (Zaman et al., 2017).

Urbanization intensifies the complexity of managing the WEF Nexus. According to Artioli et al. (2017), the rising demand for food, energy, and water in urban areas makes the intersection between the Nexus and urban governance particularly critical, though still underexplored. Their research points to significant gaps in understanding how Nexus challenges manifest in urban contexts, where fragmented institutional structures and limited interdisciplinary collaboration impede integrated policy responses. Two key insights emerge from this body of work. First, urbanization alongside climate change and demographic growth is a key driver of Nexus stress, increasing the risk of resource insecurity.

Second, cities themselves are unique sites for observing and addressing Nexus interdependencies, yet they remain underrepresented in both research and policymaking.

From a practical perspective, resilience in urban systems is shaped by inclusive economic and political institutions capable of managing complexity and protecting vulnerable populations ("Habitat III," 2015). The United Nations' SDGs—particularly Goals 1 and 11 highlight the importance of inclusive, safe, resilient, and sustainable cities. Building social cohesion and avoiding marginalization are crucial for fostering urban resilience and reducing exposure to environmental and socio-economic shocks(Ramani & Hettiarachchi, 2022). In this context, resilience refers to the ability of urban systems to absorb disturbances while maintaining essential functions and structures (Schlör et al., 2018).

Resilient WEF systems require both ecological resilience ensuring that resource ecosystems remain functional and social resilience enabling urban communities to adapt and recover. These systems are deeply embedded in the broader governance framework and influenced by inclusive institutions that manage the urban environment, mitigate ecological pressures, and preserve social cohesion in times of crisis. Thus, ensuring the resilience of the WEF Nexus is vital for maintaining sustainable access to essential resources, particularly in developing regions where vulnerabilities are most acute.

This chapter explores how the Nexus framework can contribute to building climate-resilient cities and supporting the transition toward a green economy, first by outlining the theoretical foundations of resilience within the WEF Nexus, and then by examining practical applications and case studies from African urban contexts.

B. Problem Statement: Enhancing Resilience through the Water-Energy-Food (WEF) Nexus and Addressing Its Challenges

Several interconnected global challenges threaten human existence and demand urgent attention, particularly in developing countries (Cosgrove & Loucks, 1969; Olsson, 2013). Many of these challenges are intricately linked to the production, utilization, and distribution of water, energy, and food resources that are essential for human survival and development (Wen et al., 2022).

One of the major challenges of the WEF nexus lies in efficiently managing resources across multiple spatial and governance scales such as local, regional, and national (Yillia, 2016). In addition, social and environmental security are deeply intertwined with economic development, as the interdependence of water, energy, and food directly impacts food systems and broader societal stability (Segovia-Hernández et al., 2023).

In the context of growing global populations and expanding urban centers, the demand for food is increasing rapidly, while the need to ensure sustainable use of natural resources and minimize environmental degradation remains a pressing issue (Cansino-Loeza et al., 2020). Moreover, the availability, demand, and cost of each of the WEF components along with climate, economic, and geopolitical factors intensify the complexity of the nexus (Segovia-Hernández et al., 2023).

To guide sustainable public policy development, Bazilian et al. (2011) emphasize the importance of considering a range of interlinked parameters: access and quality of resources, rapid global demand growth, environmental constraints, climate interdependencies, regional inequalities, and international trade implications. Leck et al. (2015) further underline key obstacles to effective WEF nexus implementation, including difficulties in interdisciplinary collaboration, institutional fragmentation, and political economy constraints. These barriers must be addressed to make the nexus framework a meaningful tool for environmental sustainability and resilience-building. In this context, "nexus thinking" becomes essential to addressing water, energy, and food security challenges jointly (Yang et al., 2016).

Food insecurity continues to afflict many regions of Sub-Saharan Africa, contributing to poverty, malnutrition, and heightened vulnerability. Zaman et al. (2017) argue for an extensive environmental transformation to tackle these systemic issues, advocating for the development of interactive models aligned with international frameworks such as the Copenhagen Climate Protocol.

Given these multifaceted challenges, building resilience through the Water-Energy-Food (WEF) nexus is not only timely but critical especially in urban contexts where resource demand, climate pressures, and institutional gaps are most significant.

A deeper understanding of how to integrate the WEF nexus into urban governance and resilience strategies is urgently needed.

C. Research Questions, Objectives, and Hypotheses

This chapter examines the critical role of the Water-Energy-Food (WEF) nexus in the context of urbanization, climate change resilience, and transitions toward a green economy, with a particular focus on Sub-Saharan African countries. It emphasizes the relevance of integrating water, energy, and food systems within urban planning frameworks.

Central Research Question:

How can the integration of the Water-Energy-Food (WEF) nexus within urban development strategies enhance climate resilience by supporting the transition to a green economy in West African countries?

General Objective:

- To enhance climate resilience in West Africa by leveraging the Water-Energy-Food (WEF) nexus to facilitate the transition to a green economy.

Specific Objectives:

1. To analyze the interconnections between water, energy, and food systems in West African countries especially in the context of growing urbanization.
2. To identify how these interconnections can support the transition to a green economy.

In order to achieve the specific objectives, the following hypotheses are adopted:

Hypothesis:

H1: Economic growth, industrial activity, environmental degradation, and food security are key determinants of water, energy, and food production in West African countries, with health expenditure and human capital development playing a crucial role in mitigating the negative impacts of industrialization, resource depletion, and ensuring sustainable food systems.

H2: Investing in human capital and sustainable natural resource management enhances water, food and energy productivity, which are essential drivers of a green economy transition in West African countries.

D. Structure of the Study

This chapter is organized into four main sections, each serving to achieve the outlined objectives: (1) analyzing the interconnections of water, energy, and food systems in West African countries, particularly in the context of urbanization, and (2) identifying how these interconnections can support the transition to a green economy. The structure is designed to progress from theoretical foundations to empirical analysis, concluding with practical recommendations for urban resilience and policy. The first section introduces the Water-Energy-Food (WEF) nexus, explaining its core components and how these systems are interconnected in the context of urban growth in West African countries. It also explores the role of the nexus in fostering transitions to a green economy, which is crucial for sustainable urban development. The second section provides a critical review of the literature on the WEF nexus, focusing on key theoretical frameworks such as the Environmental Kuznets Curve (EKC). It evaluates their relevance to urban resilience and the theoretical foundations of the nexus. This section also examines existing empirical studies on the WEF nexus in urban contexts, along with critiques, to provide a comprehensive foundation for the study's approach.

The third section outlines the methodological framework, detailing the quantitative models used for analysis. It explains the application of Principal Component Analysis (PCA), the Cobb-Douglas production function, and the Dynamic Panel Generalized Method of Moments (GMM) estimator to assess the interactions and resilience potential of the WEF nexus across selected West African countries.

The fourth and final section presents the results of the empirical analysis and follows with a detailed discussion of the findings. It highlights key policy implications for integrating the WEF nexus into urban governance and resilience strategies. The section concludes by summarizing how the nexus approach can support green economy transitions in West African countries, addressing challenges related to urbanization, resource management, and sustainable development.

SECTION 1: Overview of the Water-Energy-Food (WEF) nexus concept and its significance for sustainable development in urban areas

Over the past decade, urban sustainability and resilience have become key concepts in managing urban resources and addressing challenges associated with urbanization and global environmental change (Romero-Lankao et al., 2016).

Our world has become increasingly urbanized, with cities having unique properties that require specialized study and consideration (Seto & Ramankutty, 2016). Here, global urbanization, along with other macro trends such as population growth and climate change, is reshaping the conditions within which the WEF systems work and interplay (Artioli et al., 2017).

Also, it has been widely promoted as a mechanism for sustainable use of resources and a way for understanding complex socio-technical processes of urban metabolism and infrastructures (Graham, 2000). Although urban areas contribute a significant amount of the gross domestic product (GDP) of a nation, agricultural activities in rural areas consume almost 70% of the available water resources and 30% of the electricity (Fan et al., 2019).

Understanding the Water-Energy-Food (WEF) Nexus is crucial in this context or rapid urbanization. Food, water, and energy are indispensable resources for human survival, and they are the key factors maintaining the balance between human activities and the environment.

The notion of the Water-Energy-Food (WEF) Nexus was initially presented at the World Economic Forum in 2008, subsequently receiving notable attention during the Bonn Conference in 2011 (Bonn2011 Conference, 2012).

The Stockholm Environment Institute (SEI) also played a crucial role in shaping the WEF Nexus concept by highlighting the critical interdependencies between these sectors. These events highlight the importance of an integrated approach to addressing sustainability challenges, particularly in the highly interconnected sectors of water, energy, and food security (Fan et al., 2019). When one of these resources is affected by climatic conditions, human activities, or policy implementation, the WEF nexus is disturbed and becomes even more complicated (Fan et al., 2019).

Achieving water, food, and energy for all will be only possible by considering the interdependencies between the sectors (Davis et al., 2014): water is needed to generate energy, energy is needed to supply water; energy is needed to produce food, food can be used to produce energy; and water is needed to grow food while food is often using energy.

This subsection aims to provide a comprehensive understanding of the Water-Energy-Food (WEF) Nexus by defining its concept, outlining its key components, and exploring the interlinkages between water, energy, and food systems.

1.1 Definition, components and Interactions between WEF nexus

The nexus between water, energy, and food (WEF) first attracted attention in 2011 at the Bonn Nexus Conference during the United Nations Climate Change Colloquium. "Bonn Conference," highlights the imperative to tackle sustainability issues within the highly interconnected sectors of water, energy, and food security (Bonn2011 Conference, 2012). The WEF nexus is usually viewed from the perspective of the decision-maker (Segovia-Hernández et al., 2023). By adopting the water element approach the energy and food sectors become users of the source element (Soleimanian et al., 2022).

From the perspective of the food element, water and energy serve as inputs. And from the perspective of the energy element, water, such as biomass, a biological source, acts as feedstock (Xu et al., 2022).

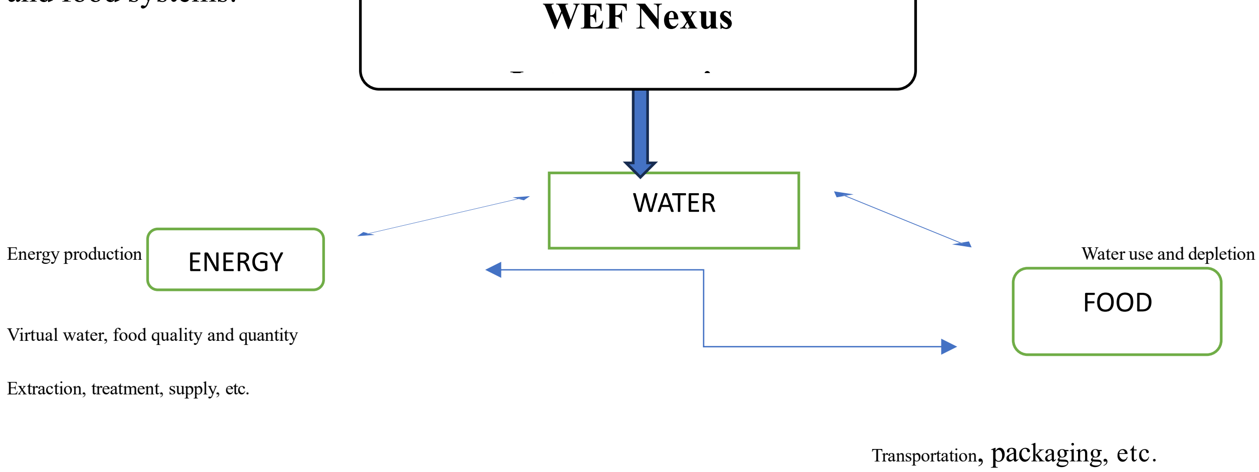
The WEF Nexus refers to the interconnected system where water, energy, and food resources are interdependent and mutually influence each other. Key components of the WEF Nexus include water resources (both surface and groundwater), energy sources (such as fossil fuels, renewable energy), and food production systems (including agriculture and fisheries). Interlinkages between these components highlight the complex relationships and dependencies within the WEF Nexus. For instance, water is essential for energy production (hydroelectric power), while energy is required for water extraction, treatment, and distribution. Similarly, energy is crucial for food production, processing, and transportation.

In their study, (Bazilian et al., 2011) identified several key elements of the water-energy-food (WEF) nexus. They noted the presence of limited resources and rapidly growing global demand. Some areas have populations that lack access to WEF resources, both in terms of quantity and quality. There are interactions between supplies that include local, regional, national, and international trade.

In addition, they observed fluctuations in supply and demand, as well as variable availability of these resources. Yusri visualizes the water -energy–food (WEF) relationship as a strong pillar which generates global security, prosperity, and equity. The interrelationship of the water-energy-food (WEF) system extends beyond merely quantifying the water footprint in food production, estimating CO2 emissions from water supply chains, or analyzing the generation of electricity from alternative sources (Chang et al., 2016).

In other elements such as economics, the environmental and the societal must be considered. Food production necessitates both water and energy (Segovia-Hernández et al., 2023). Energy plays a crucial role in irrigation systems, fertilizer production, livestock rearing, and throughout the entire transformation process, including distribution, packaging, storage, and sales.

Conversely, water extraction, transfer, treatment, and distribution require energy. Moreover, energy generation itself often relies on water resources (Chang et al., 2016). The WEF nexus implies that constraints (or choke points) on one of the resources may limit the availability of the other resources (ZHANG et al., 2022). The Nexus approach recognizes that water, energy, and food are closely linked, through global and local water, carbon and energy cycles (Vanham, 2016). For example, the production of energy requires water, but the provision of food also requires both water and energy. Hence, a systematic and coordinated plan is required to ensure real interaction among water, energy, and food (Pahl-Wostl, 2019). Understanding the dynamics and interdependence of the water-food-energy nexus is imperative for formulating sustainable policies and management practices that can guarantee the availability of these resources in the future (Segovia-Hernández et al., 2023). As we can see in the following graphic, this complex interplay shows the interactions among water, energy, and food systems:



Graph 23: The interrelationship between WEF Nexus (Author)

a) **Water:** As water scarcity intensifies and resources become increasingly strained, its capacity to foster progress in various Sustainable Development Goals (SDGs), particularly those addressing poverty, hunger, sustainability, and environmental preservation, is being reduced. Goal 6 of the Sustainable Development Goals underscores the significance of this aspect ensure availability and sustainable management of water and sanitation for all.

Sustainable Development Goal 6 extends beyond providing access to drinking water, sanitation, and hygiene to also encompass addressing the quality and sustainability of water resources, critical to the survival of people and planet (Rigg, 2024). The 2030 Agenda recognizes the centrality of water resources to sustainable development, and the vital role that improved drinking water, sanitation and hygiene play in progress in other areas, including health, poverty reduction and education (Segovia-Hernández et al., 2023). Most of the energy generation is water intensive, such as its use in coal-fired power plants and in nuclear reactors, and in bio-fuel crop production (Segovia-Hernández et al., 2023).

b) **Energy:** Geothermal energy has great potential as a long-term, climate independent resource that produces little or no green-house gases and does not consume water (World Economic Forum, 2011). The significance of this point is also underscored in Sustainable Development Goal 7: Ensure access to affordable, reliable, sustainable, and modern energy for all(Rigg, 2024).

Access to affordable, reliable, and sustainable energy is crucial to achieving many of the Sustainable Development Goals, from poverty eradication via advancements in health, education, water supply and industrialization to mitigating climate change (Segovia-Hernández et al., 2023). However, access to energy varies significantly among countries, and the current rate of progress is insufficient to achieve the Goal (Segovia-Hernández et al., 2023). Redoubled efforts will be necessary particularly for countries with large energy access deficits and high energy consumption. Governments must prioritize the expansion of renewable energy sources. There is a pressing need for greater support towards the advancement of renewable energy options that are less water-intensive, such as wind and solar power, alongside hydroelectricity (Segovia-Hernández et al., 2023).

c) **Food:** Sustainable agriculture is paramount, as integrated land, soil, and water systems are under immense strain. Sustainable Development Goal (SDG) 2, which focuses on achieving food security and improved nutrition and promoting sustainable agriculture, highlights the critical importance of food production within sustainable development efforts (Rigg, 2024).

Therefore, integrating sustainable practices across the agrifood chain not only conserves resources but also supports global goals for food security and environmental sustainability.

Implementing efficiency measures throughout the entire agrifood chain can contribute to water and energy conservation. For instance, precision irrigation guided by data from water providers can help optimize water usage. Additionally, safeguarding ecosystems alongside agricultural and energy production is essential to uphold environmental integrity (Segovia-Hernández et al., 2023). In the following sub-section, the study will examine the importance of the WEF nexus in enhancing resilience to climate change.

1.2 The Importance of the WEF Nexus in Enhancing Resilience to Climate Change

Indeed, the nexus is a major consideration in countries' sustainable development strategies. The WEF nexus is vulnerable to climate change and environmental impacts, and there are related social security issues. The markets for these resources are regulated, and there are significant implications of explicit risks within this nexus. Factors such as urbanization, environmental issues, and economics intensify the interrelationship of the WEF nexus.

Rapid economic growth, expanding populations and increasing prosperity are driving up demand for energy, water and food, especially in developing countries. According to IRENA report, by 2050, the demand for energy will nearly double globally, with water and food demand estimated to increase by over 50% (IRENA, 2015). Due to climate change, high- intensity rainfall events and long-lasting droughts cause concerning issues, such as water scarcity, agricultural production loss, and extra expenditure for damage recovery (Fan et al., 2019).

Following the Nexus Narrative, these three systems are increasingly under strain as the object of growing and competing demands of changing political-economic conditions, demographic shifts, and technological change (Artioli et al., 2017).

Understanding these interlinkages is critical for developing sustainable strategies in urban areas to ensure efficient resource management, enhance resilience to climate change impacts, and promote economic development. This foundational knowledge sets the stage for further exploration and analysis of the WEF Nexus in subsequent sections of the study.

Addressing the challenge of meeting the growing demand for food while ensuring the sustainable use of natural resources requires a resilient WEF nexus. This involves adopting practices that minimize negative environmental impacts and balance the availability, demand, and costs of water, energy, and food (Raya-Tapia et al., 2023).

Integrating resilience into the WEF nexus is vital for developing a green economy model that can effectively tackle these growing challenges and ensure sustainable development for future generations (Leck et al., 2015). By focusing on resilience, we can better manage the different scales of resource distribution between localities, regions, and countries (Yillia, 2016). This involves not only ensuring the equitable allocation of resources but also implementing policies that promote environmental and social security. In doing so, we can support the economic development of regions and mitigate the multiple effects that energy and water have on the food sector (Segovia-Hernández et al., 2023).

1.3 The role of the WEF nexus in advancing the green economy transition

The green economy is defined as an economy that enhances human well-being and social equity while significantly reducing environmental risks and ecological scarcities (Brears, 2017). At its core, a green economy is low-carbon, resource-efficient and socially inclusive. In such an economy, income and employment growth is driven by public and private investments that reduce carbon emissions, improve resource efficiency, and protect biodiversity and ecosystem services.

A fundamental aspect of this economy is the recognition of natural capital as a vital economic asset and source of public benefits (Brears, 2017).

The primary goal of the transition to a green economy is to achieve economic growth and investment while improving environmental quality and promoting social inclusion. Also, according to (Brears, 2017), the main overall objectives of the green economy include: << *Improving resource-use efficiency*: a green economy is one that is efficient in its use of energy, water, and other material inputs, *ensuring ecosystem resilience*: it also protects the natural environment, its ecosystems, and ecosystem flows and *enhancing social equity*: it promotes human well-being and a fair burden sharing across societies **>>.**

With rising demand for water, energy, and food, managing the water-energy-food nexus is a key aspect of developing the green economy as the nexus approach recognizes the need to use resources more efficiently while seeking policy coherence across the nexus sectors in support of green growth (Brears, 2017).

The green economy offers an innovative way forward those balances economic growth with environmental sustainability and social equity (Brears, 2017). This approach aims to minimize environmental risks and ecological scarcities by valuing natural capital and prioritizing resource efficiency.

It purposes a sustainable future in which economic activities support the health of our planet and the well-being of its inhabitants. This framework is critical to relieve pressure on the interconnected water, energy and food systems (Brears, 2017).

The WEF nexus aims to achieve a balance with the green economy development model to tackle the growing challenge of WEF security and its management approach to address this challenge (Leck et al., 2015). The Water Energy Food (WEF) nexus is indeed essential in driving the transition to a green economy.

Several studies have attempted to analyze the link between the WEF nexus and the economy in general. Recent research has been developed by analyzing the trajectory of natural resource governance from the state-national to the supranational level by exploring the financialization of water, food and energy systems, and their links to the global economy (Schmidt & Matthews, 2018). Water, which has only very recently received attention in the Green Economy debate, is an essential input for all biomass growth and hence for all ecosystem services and associated jobs and livelihoods (Hoff, 2011).

Hence the Green Economy itself is the nexus approach by excellence (Hoff, 2011). To succeed, a Green Economy must go beyond sectoral solutions and actively address the water, energy and food security nexus, in-line with human rights-based approaches (Hoff, 2011).

The next section presents the literature review of the WEF nexus by developing both theoretical and empirical approaches, as well as exploring the connection between the WEF nexus and the green economy transition.

SECTION 2: Literature Review of the WEF Nexus

In the literature on the Water-Energy-Food (WEF) nexus, various theoretical frameworks provide foundational insights into the interconnectedness of water, energy, and food systems.

2.1 Theoretical review of the WEF nexus

2.1.1 Theoretical Foundations of the WEF Nexus and Green Economy

The Water-Energy-Food (WEF) Nexus is an integrated framework that explores the interconnectedness of water, energy, and food systems, and how these systems can be managed in a sustainable way to ensure long-term resource security. The theory behind the WEF Nexus emphasizes that these three critical resources are interdependent and any intervention in one area can have profound effects on the others.

A comprehensive understanding of the WEF Nexus is crucial to addressing global challenges such as climate change, urbanization, and population growth, all of which have a direct impact on resource management and security. According to LO (David, 2024) in his paper "*theoretical synthesis for WEF security and sustainability*" explains different theories such as Securitization Theory, Malthusian Theory of population, Game theory, Institutional theory, Technology Acceptance Model (TAM) and Innovation Diffusion theory (IDT).

1) **Securitization Theory**: This theory suggests that issues of resource scarcity, particularly water, energy, and food, should be treated as security threats requiring urgent intervention. According to the theory, framing resource issues as matters of national security can mobilize resources, policies, and institutional actions to address pressing challenges. The theory emphasizes the importance of identifying security threats related to water, energy, and food systems, and advocates for robust planning to mitigate such risks. It also raises questions about resource management, such as the capacity of institutions to respond to these threats and the effectiveness of current governance systems.

2) Malthusian Theory of Population: Malthus' theory predicts that population growth will outpace the availability of resources, leading to a crisis of resource depletion. This theory, when applied to the WEF Nexus, highlights the importance of preventive checks and resource planning to avoid the so-called "Malthusian catastrophe," where the inability to meet the growing demand for resources leads to widespread crises. The Malthusian perspective highlights the need for strategies that can manage the balance between resource consumption and population growth, such as sustainable resource management, technological innovation, and policy interventions.

3) Game Theory: Game Theory applies strategic decision-making models to understand how individuals or entities interact within the context of resource management. In the WEF Nexus, game theory helps analyze both cooperative and non-cooperative interactions between stakeholders, such as governments, private sectors, and communities, in managing shared resources. The theory emphasizes the role of information sharing and the interests of different players, stressing that the success of resource management depends on cooperation and effective communication among stakeholders. Then by applying this theory, decision-makers can design more efficient and equitable resource allocation strategies, considering the interests and strategies of all relevant actors.

4) Institutional Theory: Institutional theory focuses on the role of institutions in shaping behaviors, decision-making, and policies. In the WEF Nexus context, the theory highlights the need for strong institutional frameworks that promote sectoral policy coherence, human resource capacity development for nexus thinking, and effective stakeholder management. The theory suggests that institutions should facilitate global collaboration while ensuring local implementation of policies tailored to specific contexts. It also advocates for the adaptation of successful international practices to local settings, emphasizing the importance of governance systems that support sustainability and resilience across water, energy, and food sectors.

5) Technology Acceptance Model (TAM): This model explains how users come to accept and use new technologies. In the context of the WEF Nexus, TAM helps assess the perceived ease of use (PEU) and perceived usefulness (PU) of new technologies aimed at enhancing resource management. For example, the adoption of renewable energy technologies, water-saving devices, and sustainable agricultural practices depends on how users perceive the benefits and usability of these innovations. The model suggests that improving the acceptance of these technologies will require understanding user needs, providing adequate training, and ensuring that these technologies align with social and economic realities.

6) Innovation Diffusion Theory (IDT): This theory examines how new technologies and innovations spread within a society. When applied to the WEF Nexus, IDT focuses on how innovations in water, energy, and food systems are adopted by different groups, ranging from local communities to large-scale industries. The theory identifies five key characteristics that influence adoption: relative advantage, compatibility, complexity, trialability, and observability.

For the WEF Nexus to be successful, innovations must be compatible with local needs, easy to adopt, and demonstrate clear advantages over existing practices. The theory also emphasizes the importance of social sustainability, ensuring that innovations contribute not only to environmental sustainability but also to social and economic well-being.

7) Theories for a Green Economy: we have environmental economics and ecological economics

Firstly, Environmental economics attributes environmental issues to inefficient use of natural resources and the undervaluation of natural capital (Borel-Saladin and Turok, 2013)(Loiseau et al., 2016). It assumes that man-made and natural capitals are interchangeable(Bina & La Camera, 2011). The Porter hypothesis suggests that environmental regulation can drive innovation and improve both economic and environmental performance(Porter, 1995). The theory focuses on internalizing externalities, using tools like taxes, subsidies, and ecosystem service payments, to promote optimal decision-making(Pigou, 1920). It assumes that by setting correct prices, unsustainable resource use can be halted(Williamson, 1994), supporting a weak sustainability model where natural capital can be substituted by man-made and human capital (Pelenc and Ballet, 2015).

On the other hand, Ecological economics sees the economy as a subsystem of the natural world, bound by Earth's biophysical limits(Bina & La Camera, 2011). This perspective emphasizes integrated approaches to understanding environmental issues and advocates for structural changes to reduce ecological damage(Williams & Millington, 2004). It focuses on physical indicators, such as ecological footprints, to promote dematerialization and the conservation of critical natural capital (Ekins et al., 2003). Dematerialization aims to reduce material and energy use, though technological advances alone may not prevent rebound effects (Loiseau et al., 2016). Ecological economics supports strong sustainability, where critical natural capital must be preserved for long-term sustainability(Lorek & Spangenberg, 2014).

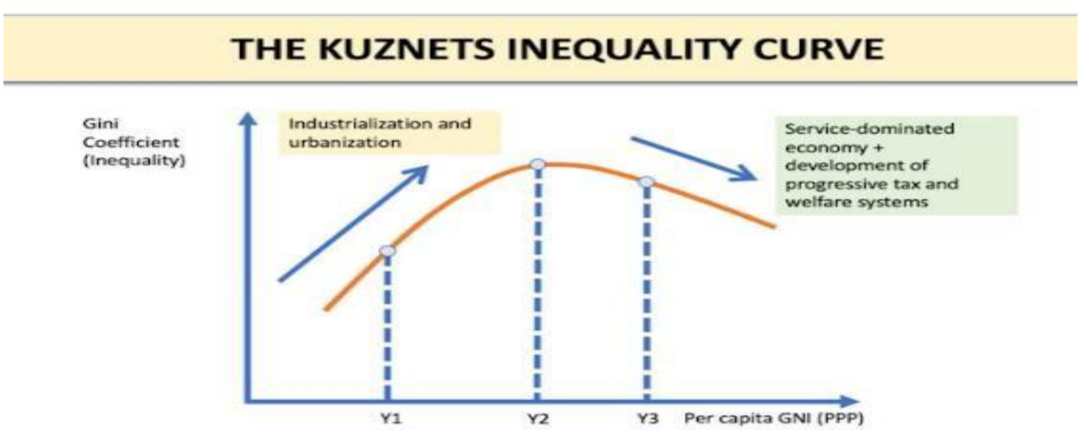
These theories provide a comprehensive framework for understanding the WEF Nexus and its potential to foster advancing green economy transitions.

2.1.2 Exploring the Environmental Kuznets Curve in the Context of the Water-Energy-Food Nexus: Theoretical Insights and Critiques

In the scope of our study, we propose the Environmental Kuznets Curve theory (Kuznets, 1955) (Kaufmann et al., 1998). This hypothesis suggests that there exists a relationship between economic development and environmental quality, wherein environmental degradation initially worsens as a country experiences economic growth (Kuznets, 1955).

Indeed, Kuznets (1955) claims an inverted U-shaped relationship between economic development and environmental degradation. The inverted U-shaped curve signifies that environmental conditions deteriorate in the early stages of economic growth and improve in the later stages of economic growth (Kuznets, 1955). This implies that environmental degradation initially increases and decreases as the economy grows. (Ozturk, 2015) conducted a sustainability assessment of the WEF nexus, using dynamic panel modeling with the EKC hypothesis among BRICS countries (Brazil, the Russian Federation, India, China, and South Africa) (Ozturk, 2015).

Moreover, (Zaman et al., 2017) confirmed the carbon fossil-methane EKC of West African (SSA) countries by analyzing the non-linear relationship between WEF resources and air pollutants. Additionally, the results showed that energy efficiency improves air quality indicators while industry value added increases CO2 emissions, fossil fuel energy, and GHG emissions. (Nassani et al., 2019) used the simultaneous generalized method of moments and investigated the relationships between WEF resources, carbon fossil-GHG emissions, and growth-specific factors to verify the EKC in Pakistan (Nassani et al., 2019). (Xu et al., 2022) examined the link between economic growth and the WEF footprint by exploring the existence of the EKC in China's economic zones and regions. The results showed that the LOWESS model may be more conducive to reflect the real relationship between economic growth and WEF footprint. According to the analysis, the policy suggestions are put forward to promote the sustainable development of the water-energy-food system (Xu et al., 2022). The graph below shows the environmental Kuznets curve according to the (Tutor2u.net/ economics,2023).



Graph 24: Tutor2u.net/economics, 2023

Following the theoretical foundations, this section delves into the growing pressures on the WEF nexus and its implications for green economy transitions.

2.1.4 Pressures on the WEF Nexus and Implications for Green Economy Transitions

Pressure on the nexus is being driven by a rising global population, rapid urbanization, changing diets and economic growth and these Pressure on the water–energy-food nexus threatens the Sustainable Development Goals (SDGs) (Segovia-Hernández et al., 2023). According to (Segovia-Hernández et al., 2023) the water, energy, and food sectors should be consolidated under one umbrella to initiate symbiotic benefits that enhance the cross-sector integration of resources. Also, Also, in this context of urbanization, (Heard et al., 2017) demonstrated that urban systems rely on water, energy, and food, which are often scarce resources, and the consumption of these resources leads to significant environmental challenges.

They emphasized that the three spheres of the WEF nexus face growing demands and constraints that are crucial for conserving a sustainable world. Their study revealed that as urbanization expands, the necessity for large-scale sustainable solutions becomes more pressing.

Furthermore, they highlighted that studying the interactions and interconnections of the WEF nexus can facilitate addressing the complex challenge of sustainability.

Moreover, always in the context of urbanization, (Zhang et al., 2019) presented a paper aimed at providing a comprehensive literature review of the water-energy-food (WEF) nexus, particularly focusing on the urban WEF nexus. Their objective was to develop a conceptual framework for scientific analysis and policymaking related to the urban WEF nexus. Their investigation led to the proposal of a three-dimensional conceptual framework of the urban WEF nexus. This framework offered insights into resource interdependency, resource provision, and system integration, which proved valuable for systematically modeling and interactively managing the complex nexus issues of urban systems.

The paper identified future directions for urban nexus research, including systematic characterization, cross-region teleconnection mechanisms, co- decision model development, and governance transition.

The authors stressed the importance of quantitative and integrated models at different levels to achieve collaborative management and advance WEF governance practices.

Therefore, (Al-Saidi & Elagib, 2017) conducted an extensive literature search to uncover two primary aspects: firstly, the rationale behind the WEF nexus debate, and secondly, the diverse tools utilized in analyzing the interrelationships within the WEF nexus framework in both scientific and policy contexts. Their study identified three key factors that promote the WEF nexus concept. The first factor pertains to the uncertainty surrounding interrelationships; the second factor addresses the crisis in resource supply; and the third factor involves strategies for managing these resources. Their work initiates a debate on nexus governance and opens the pathway to discussions on sustainability.

Additionally, (Trabucco et al., 2018) delved into the water-energy-food nexus concept through a case study focused on Sardinia, an Italian region grappling with various challenges including water scarcity, food security, energy management, and the impacts of climate change.

The study identified interactions with other nexus sectors, incorporating feedback processes, and engaged stakeholders to inform the development of policies, goals, and tools tailored to the Sardinian case study. From the point of view of (Bazilian et al., 2011) it becomes evident that the spheres of energy, water, and food significantly impact each other, and neglecting the effects in one sphere can have substantial repercussions on the others.

However, research such as that conducted by (Weitz et al., 2017) has popularized the concept of the Water-Energy-Food (WEF) nexus in environmental impact research and policy discussions. The study conducted by (Sarkodie & Owusu, 2020) underscores the intricate relationship between the water-energy-food nexus and environmental sustainability, emphasizing the influence of various socioeconomic factors. It suggests that structural adjustments in economic development will play a crucial role in determining how the water-energy-food nexus contributes to environmental sustainability. This highlights the importance of addressing socioeconomic considerations to effectively manage the nexus and achieve sustainable outcomes.

Building on the theoretical foundations, the following section provides an overview of empirical literature, focusing on practical applications and case studies that explore the Water-Energy-Food Nexus and its implications for the transition to a green economy.

2.2 Empirical review of the WEF nexus

(Yang et al., 2016) demonstrate the critical importance of collectively addressing the challenges of Water-Energy- Food (WEF) security. They conducted an evaluation of Pakistan's Indus River WEF nexus using the Indus Basin Model Revised-Multi Year.

Their study involved modeling the impact of WEF within a spectrum of climate change scenarios, alongside various alternative water allocation and water infrastructure development mechanisms. Their findings indicate that leveraging WEF nexus interactions appropriately can help alleviate the adverse impacts of climate change on agricultural water and energy use, while also establishing a framework for sustainability.

(Weitz et al., 2017) also suggested that proponents of the WEF nexus approach advocate for governance agreements. They identified obstacles in achieving coherence within the WEF nexus approach as particularly significant.

West African (SSA) countries are no exception that majorly hit by the recent global financial crisis, which affected the country's natural environment through the channel of unsustainable energy-water-food production. In this context, (Zaman et al., 2017) clearly demonstrate the commitment of the environmental sustainability agenda to managing water, energy, and food resources. Their study explores various perturbations in WEF resource variables alongside the generation of atmospheric pollutants in different African countries.

The results reaffirm a strong relationship between WEF resources and atmospheric emissions, highlighting the necessity of designing optimal WEF nexus models for each specific region to achieve a sustainable future.

Trabucco et al. (2018) analyzed Sardinia's WEF nexus, highlighting its reliance on tourism (17% of GDP) and agriculture (4% of GDP). With water resources meeting only 53% of demand, agriculture consumes the most (69.4%). Water security risks are rising due to growing agricultural, tourism, and energy needs under climate change. To address these challenges, a nexus model integrating water supply and demand, energy use, climate factors, and land use has been developed to assess sustainability challenges.

Walker et al., 2014) delved into the sustainability issues and the impact of human behavior on urban metabolism. They employed the WEF nexus as a research tool to assist in investment and policy decision-making processes.

Through a multi-sectoral analysis, they derived resource estimates, elucidated the synergy and interactions among water, energy, and food systems, and evaluated the economic and environmental benefits. Their findings indicated that adopting improved technologies, food, and waste collection, along with algae cultivation, could foster sustainability in the city of London.

(El Gafy et al., 2017) employed system dynamics models to develop a novel approach for analyzing dynamic behavior, with a focus on interactions within the Water-Energy-Food (WEF) nexus. Their model initially establishes energy and water footprints in crop production and consumption. Secondly, it examines virtual water and energy export and import.

Thirdly, it evaluates the balance of energy and water savings in agricultural production. Lastly, it calculates the WEF nexus index.

The case study, conducted in Egypt, demonstrated that the WEF nexus generates an intersection of issues related to human welfare, poverty reduction, and sustainable development. Fabiani et al. (2020) conducted a study that examined the environmental sustainability of durum wheat production in central Italy under Mediterranean conditions using a Water-Energy-Food (WEF) nexus framework. The study compared the effects of mineral and organic fertilization strategies on marketable yields, emphasizing the significance of reducing energy consumption, utilizing renewable energy, and minimizing non-renewable energy use.

The study's findings suggest that the WEF nexus approach holds potential in enhancing agricultural sustainability, promoting farm competitiveness, and supporting environmentally friendly production practices, a development that is expected to benefit both farmers and policymakers.

The framework developed by Yue et al. (2021) has been shown to balance efficiency and equity in resource allocation using a social welfare function, thereby enabling sustainable water and land resource allocation by resolving conflicts across socioeconomic, resource, and eco-environmental domains. This framework optimizes resource use across sectors, crops, and time, providing insights for decision-makers.

Zaman et al. (2017) conducted an analysis of the WEF nexus and economic sustainability in SSA from 1990 to 2014. Their findings indicate positive food production growth in most countries, with Zambia, Ethiopia, and Tanzania exceeding 100%, while Mauritius and Zimbabwe demonstrated negative growth.

Energy production from conventional sources experienced significant growth in Ghana, Mozambique, Namibia, and Tanzania, while it declined in several other countries. The analysis further reveals that water resources demonstrated a general increase, with the notable exceptions of Sudan and Zimbabwe. (Prasad et al., 2012) presented a planning and modeling project that recognized the utility of WEF nexus tools in enhancing resource utilization and policy coherence in South Africa.

Their analysis and conception highlighted how the WEF nexus presents opportunities to enhance resource efficiency by ensuring sustainable access to water, energy, and food, thereby improving policy coherence. According to (De Laurentiis et al., 2014) the core of nexus thinking is that no good results can be achieved from considering these resources independently, which means that food security cannot be achieved in a context of either/both water or/and energy insecurity. All three elements have to be assured to foster sustainability, resilience, prosperity and peace (De Laurentiis et al., 2014).

In the context of the BRICS countries (Brazil, the Russian Federation, India, China, and South Africa), (Ozturk, 2015) examined the food-energy-water nexus and investigated the dynamic links between energy, food, water, public health, economic growth, and the environment. Employing three models and panel data spanning from 1980 to 2013, (Ozturk, 2015) analyzed the relationships and identified policy implications. The aim of this research was to explore the interconnectedness of health, wealth, and the environment and derive lessons for policy development.

Furthermore, (Ozturk, 2015) developed a food security index using principal component analysis, which integrated factors such as agricultural machinery, cereal production land, and agricultural value added. These variables were assigned individual weights, and the food security index served as the primary variable in the food model.

Additionally, the study investigated the potential relevance of the Environmental Kuznets Curve (EKC) hypothesis among BRICS nations. The findings revealed that energy shortages and inadequate water resources have a negative impact on food security in the BRICS countries. Economic growth contributes to increased energy demand and environmental degradation.

Moreover, the depletion of forests and natural resources poses challenges to economic sustainability. (Ozturk, 2015) emphasizes the necessity of adopting a diverse energy mix in BRICS countries to enhance health infrastructure, drive economic growth, and reduce carbon emissions.

Additionally, the Environmental Kuznets Curve (EKC) hypothesis can provide potential solutions for sustainability and food security in these nations. In our study, we will use the same approach as Ozturk (2015) for Sub-Saharan African countries, analyzing data from 2000 to 2022.

Review of the WEF nexus literature revealed several challenges in connecting the theoretical nexus constructs to empirical research and practical applications (Tye et al., 2022). In the following section, we present the methodology used and the data employed in this study.

SECTION 3: Materials and Methods

Since the interpretations and centrality of the WEF nexus vary, numerous and diverse methods and tools have been used in different contexts (Zhang et al., 2019). Generally, these methods and tools have been adopted or derived from traditional disciplinary approaches, which can be broadly classified into three categories: quantification of resource-environmental footprints, assessment and systematic simulation, and optimal management methods.

(Zhang et al., 2019) conducted a study that provides a comprehensive literature review to debate the current concepts and methods of the WEF nexus at different scales, aiming to develop a conceptual knowledge base framework for scientific analysis and policymaking associated with the urban WEF nexus (Fan et al., 2019). Monitoring the various linkages within the water-energy-food (WEF) nexus is crucial to better understanding the potential synergies and trade-offs between these three sectors (Mentor, n.d.). Quantification is essential to provide a clearer understanding of these numerous linkages and to improve decision-making processes. Excellent reviews of the methodologies developed in recent years can be found in the works of (Soleimanian et al., 2022), (Fan et al., 2019), (ZHANG et al., 2022), (Wen et al., 2022), (Wang et al., 2023) , (Endo, 2017), (Kurian, 2017), (Endo, 2017), (Chang et al., 2016) and (Kurian, 2017).

It is important to recognize that each case of WEF nexus is unique, and there is no one-size-fits-all approach to modeling and quantifying these linkages according to the work of Aboelngan, Khalifa, McNamara, Ribbe and Sycz (2018). The complexity and type of model required will always depend on the specific nexus situation being examined. Therefore, despite the variety of modeling options available, the choice of the appropriate model must be tailored to the particular characteristics and needs of the nexus case (Mentor, n.d.).

3.1. Identification of Key Variables and Data Sources

To effectively analyze the enhancement of climate resilience in the context of urbanization and leverage the WEF nexus for a green economy transition, it is essential to examine a range of variables that capture the multifaceted interactions between water, energy, and food systems, and their implications for economic growth, environmental sustainability, and social well-being.

Despite the growing importance of urbanization in shaping these dynamics, there is a notable lack of detailed and consistent data at the city level in Sub-Saharan African cities. This limitation poses significant challenges to conducting a thorough and accurate analysis specific to urban contexts. Consequently, to overcome these constraints, country-level data from selected West African countries have been used as a proxy for urban-level analysis.

The data used in this study are sourced from reputable international organizations such as the World Development Indicators (WDI) database, which provide comprehensive and standardized datasets on economic, environmental, and social indicators. Based on data availability, the following Sub-Saharan African countries were selected for the analysis: Benin, Burkina Faso, Côte d'Ivoire, The Gambia, Ghana, Guinea, Guinea-Bissau, Mali, Niger, Nigeria, Senegal, Sierra Leone, and Togo. Mauritania and Cape Verde were excluded due to the unavailability of relevant data.

Based on the identification of key variables and data sources, the next part of this section outlines the specific methodological approach adopted for modeling the WEF nexus and assessing its potential to support the transition toward green and resilient economies.

Table 46: List of Variables and data sources

List of Variables	**Names**	**DATA SOURCES**
Response Variables or Dependent Variables		
Energy_final_consump_million_kwh	ENERGY	WDI
Food Index Comprises	FINDEX	WDI
Agricultural machinery, tractors	AGRIMAC	WDI
Agriculture, forestry, and fishing, value added (% of GDP)	AGRIVAL	WDI
Agricultural land (% of land area)	AGRILAND	WDI
Land under cereal production (hectares)	LANDCER	WDI
Water productivity, total (constant 2015 US$ GDP per cubic meter of total freshwater	WATPROD	WDI
Regressors or Independent Variables		
Current health expenditure per capita (current US$)	HEXP	WDI

Economic Growth GDP (constant 2015 US$)	GDP	WDI
CO2 emissions (kg per 2015 US$ of GDP)	CO2	WDI
Miscellaneous variables		
People using at least basic drinking water services (% of population)	BDRINK	WDI
Gross fixed capital formation (current US$)	GFCF	WDI
Industry (including construction), value added (current US$)	IND	WDI
Labor force participation rate, total (% of total population ages 15+) (modeled ILO estimate)	LFPR	WDI
Adjusted savings: net forest depletion (% of GNI)	NFD	WDI
Adjusted savings: natural resources depletion (% of GNI)	NRD	WDI

3.2 Analytical Framework and Methodological Approach

Following the framework used to analyze the BRICS countries by (Ozturk, 2015), this study focuses on the West African countries selected. The study of (Ozturk, 2015) examines environmental indicators relevant to long-term sustainability through the food-energy-water nexus in the BRICS countries. It highlights the sustainability issues arising from the Environmental Kuznets Curve (EKC) hypothesis and biodiversity considerations, emphasizing the need for proper resource allocation to ensure food security. In this context, our study aims to explore the dynamic linkages between energy, food, water, public health, economic growth and the environment in the West African countries selected.

In order to examine the enhancement of climate resilience in the context of urbanization and to leverage the WEF nexus for a green economy transition, this research uses principal component analysis to construct a food security index that includes agricultural machinery, land under cereal production, and agricultural value added.

In addition, dynamic panel modeling in a generalized method of moments (GMM) system is used to obtain reliable parameter estimates.

3.2.1 First Method: PCA (Principle Component Analysis) Model

Principal component analysis (PCA) is used to construct a food security index that includes agricultural machinery, land under cereal production, and agricultural value added. This approach provides a comprehensive measure of food security by capturing the multifaceted nature of agricultural productivity and resource use.

In our study, Data covers annual time series spanning 2002-2022 for three dependent variables. In this study, it used PCA (Principal component analysis) to construct a weighted food index for the West African countries selected.

PCA is among the multivariate statistical procedures that confine the number of variables in a smaller dimension (Ozturk, 2015). Mathematically, PCA is a procedure for correlating 'n' variables, where each factor is a linear weighting of the initial variables. For example, there is a set of variables X_1 to X_n such that.

$$PC_1 = \alpha_{11}X_1 + \alpha_{12}\alpha_{11}X_2 + \cdots .. + \alpha_{1n}X_n \quad \textbf{(1)}$$

$$PC_m = \alpha_{m1}X_1 + \alpha_{m2}X_2 + \cdots .. + \alpha_{mn}X_n \quad \textbf{(2)}$$

Where α_{m1} represents them_{th} weighted Principal component of the nth variable. The weight of each factor encompasses the respective eigenvalue that reveals the variance across each variable. An index constructed using PCA encompasses all the relevant information of different variables into one variable.

3.2.2 Second method: Cobb Douglas Model

The study employed the Cobb Douglas production function to analyze the dynamics among energy-food-water, health, wealth, and environment including labor and capital as factors of production, in the panel of the Sub-Saharan countries selected. The Cobb-Douglas production function will be used to analyze the relationship between inputs (such as labor, capital, and natural resources) and outputs (such as food, water, and energy production). This model will provide an understanding of how different factors contribute to overall productivity and efficiency within the WEF nexus. It takes the following form:

$$Y = A^{\alpha 0} H^{\alpha 1} W^{\alpha 2} L^{\alpha 3} K^{\alpha 4} M^{\alpha 5} e^{u} \quad \textbf{(3)}$$

Y' is the summation of a technology variable, five energy-food-water variables, and the error term. 'A' denotes the level of technology used in the respective countries.

H, W, L, K, and M denote per capita health expenditures, wealth (GDP in constant 2000 US$), the labor force participation rate, gross capital formation as a percentage of GDP, and miscellaneous variables (e.g., improved water sources, industry value added, natural resource depletion, and net forest depletion), respectively, e denotes white noise. Superscripts α_0 to α_5 show the respective variables' returns to scale. This study decomposed the series for all variables into natural logarithms that present results as elasticities. The log-log form of the Cobb Douglas production function i is:

$$Ln(Y)_t = \alpha_0 + \alpha_1 Ln(H)_t + \alpha_2 Ln(W)_t + \alpha_3 Ln(L)_t + \alpha_4 Ln(K)_t + \alpha_5 Ln(M)_t + u_t \quad \textbf{(4)}$$

In this study, we used three simultaneous models/equations that estimate dynamics between energy-food-water and health-wealth-environment are as follows:

MODEL 1: Energy Demand:

$$Ln(ENERGY)_{i,t} = \alpha_0 + \alpha_1 Ln(HEXP)_{i,t} + \alpha_2 Ln(GDP)_{i,t-1} + \alpha_3 Ln(GDP)_{i,t} + \alpha_4 Ln(CO2)_{i,t} + \alpha_5 Ln(BDRINK)_{i,t} + \alpha_6 Ln(GFCF)_{i,t} + \alpha_7 Ln(IND)_{i,t} + \alpha_8 Ln(LFPR)_{i,t} + \alpha_9 (NRD)_{i,t} + \alpha_{10} Ln(NFD)_{i,t} + ui_{,t} \quad \textbf{(5)}$$

Model 2: Food Index

$$Ln(FINDEX)_{i,t} = \alpha_0 + \alpha_1 Ln(HEXP)_{i,t} + \alpha_2 Ln(GDP)_{i,t-1} + \alpha_3 Ln(GDP)_{i,t} + \alpha_4 Ln(CO2)_{i,t} + \alpha_5 Ln(BDRINK)_{i,t} + \alpha_6 Ln(GFCF)_{i,t} + \alpha_7 Ln(IND)_{i,t} + \alpha_8 Ln(LFPR)_{i,t} + \alpha_9 (NRD)_{i,t} + \alpha_{10} Ln(NFD)_{i,t} + ui_{,t} \quad \textbf{(6)}$$

Model 3: Water Productivity

$$Ln(WATPRO)_{i,t} = \alpha_0 + \alpha_1 Ln(HEXP)_{i,t} + \alpha_2 Ln(GDP)_{i,t-1} + \alpha_3 Ln(GDP)_{i,t} + \alpha_4 Ln(CO2)_{i,t} + \alpha_5 Ln(BDRINK)_{i,t} + \alpha_6 Ln(GFCF)_{i,t} + \alpha_7 Ln(IND)_{i,t} + \alpha_8 Ln(LFPR)_{i,t} + \alpha_9 (NRD)_{i,t} + \alpha_{10} Ln(NFD)_{i,t} + ui_{,t} \quad \textbf{(7)}$$

<u>This study sought confirmation of the EKC hypothesis by rearranging the EKC equation as follows:</u>

Environmental Kuznets Curve Equation:

$$(CO2)_{i,} = \alpha_0 + \alpha_1 (HEXP)_{i,t} + \alpha_2 Ln(GDP)_{i,t-1} + \alpha_3 Ln(GDP)_{i,t} + \alpha_4 Ln(BDRINK)_{i,t} + \alpha_5 Ln(GCF)_{i,t} + \alpha_6 Ln(IND)_{i,t} + \alpha_7 Ln(LFPR)_{i,t} + \alpha_8 (NRD)_{i,t} + \alpha_9 Ln(NFD)_{i,t} + ui_{,t} \quad \textbf{(8)}$$

This equation confirms or rejects the EKC hypothesis by identifying or finding no inverted U-shaped relation between carbon emissions and economic growth among West African countries.

3.2.3 Third method: Dynamic panel of the generalized moment estimator

In addition, dynamic panel modeling using the Generalized Method of Moments (GMM) system is used to obtain reliable parameter estimates and to estimate the dynamic relationships among the variables of interest, considering potential endogeneity issues. This technique is particularly useful in addressing potential endogeneity issues and providing robust insights into the dynamic relationships within food security. This model will provide insights into how changes in one sector affect others over time and help formulate policies that enhance resilience and sustainability.

Econometricians have tested the above equations/models using panel modeling techniques, including unit root tests, cointegration tests, and heterogeneous dynamic modeling di.e., GMM (generalized method of moments) system equations. This study will employ the Fisher-PP panel unit root test to evaluate the null hypothesis of no unit root in the series of variables.

After analyzing the order of integration between the variables, this study will employ the Johansen Fisher PP. The Fisher procedure is similar to the traditional time series Johansen cointegration technique, which requires lag length and evaluates the cointegration vector between the variables.

Finally, this study will use dynamic panel model that includes first lagged dependent variable coupled with the explanatory variables. Doing so allows adjustments in the traditional OLS (ordinary least squares) assumptions to minimize heterogeneity. That is:

$$y_{i,} = \alpha_0 + \alpha_1 X_{it} + u_{it} \quad \textbf{(9)}$$

$$y_{i,} - y_{i,-1} = \lambda\,(y_{i,t} - y_{i,t-1}) \quad \textbf{(10)}$$

where y* is the desired level of y.

Substituting y* into the second equation, we obtain the following estimating equation

$$y_{i,} = \alpha_0\lambda + (1-\lambda)_{,-1} + \lambda\alpha_1 X_{it} + \lambda U_{it} \quad \textbf{(11)}$$

This study used an instrumental variable technique, i.e., GMM, where instruments can be lagged values of variables in the original models. The previous equations are prescribed for the GMM technique. The model will be used under the assumption of the environmental Kuznets Curve (Ozturk,2015) on the sustqinqbility in the WEF nexus: Evidence from BRICS Countries.

Section 4: Results and discussions

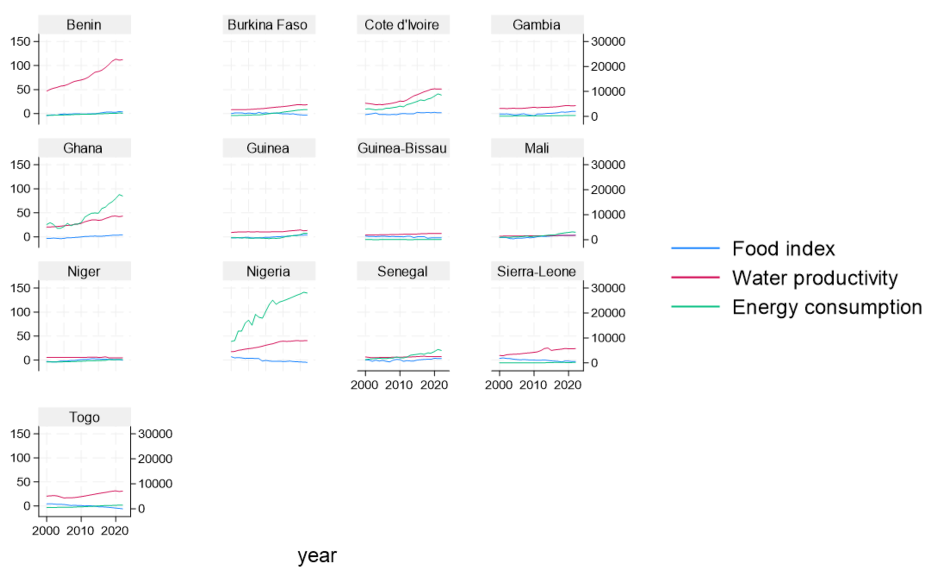
In this section, we analyze the model's results. We begin by presenting graphs related to the food index, water productivity, and energy consumption, followed by a discussion of the key findings.

4.1 Graphs presentation

4.1.1 Trends in Food Index, Water Productivity, and Energy Consumption in West African countries (2000-2020)

The graph presents trends from 2000 to 2020 for three indicators: the Food Index, Water Productivity, and Energy Consumption across various Sub-Saharan African countries.

Most countries demonstrate an increasing Food Index, indicating improved food availability or agricultural output. Water Productivity remains stable in most countries, suggesting limited improvements or challenges in efficiency. Energy Consumption increases significantly in some countries, such as Nigeria and Niger, possibly reflecting industrialization or greater access to energy. While the trends vary across countries, Benin, Ghana, Mali, and Nigeria show notable growth in key indicators. As demonstrated in the graph below:



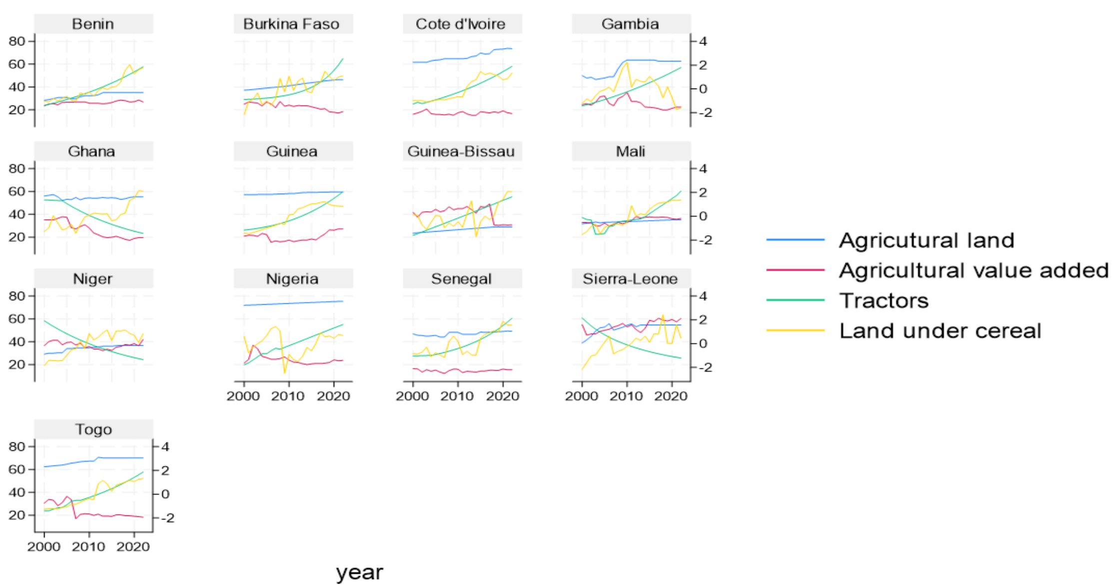
Graph 25: Trend in Food index, Water productivity and energy consumption

Finally, the graph provides a comprehensive overview of trends in food availability, water productivity, and energy consumption in various Sub-Saharan African countries from 2000 to 2020. It highlights general improvements in food availability across the region, with varying levels of changes in water productivity and energy consumption. This information is valuable for policymakers to understand areas needing more focus, such as improving water use efficiency and managing energy consumption sustainably.

4.1.2 Trends in Agricultural Development in West African Countries (2000-2020)

The graph below presents trends from 2000 to 2020 for key agricultural indicators in Sub-Saharan African countries, including Agricultural Land, Agricultural Value Added, Tractors, and Land under Cereal production.

The majority of countries, such as Benin, Ghana, Mali, and Nigeria, show increases in Agricultural Land and Agricultural Value Added, reflecting growth in agriculture. Tractors exhibit significant growth in countries like Mali and Ghana, indicating mechanization, while others show stable or fluctuating trends. A general increase in the area dedicated to cereal cultivation is observed, indicating an expansion in cereal crop production across the region. As demonstrated in the graph below:



Graph 26: Trend in Agricultural development

Finally, the graph highlights an expansion in agricultural land, increased economic value from agriculture, and varying levels of mechanization. This information is valuable for policymakers to understand agricultural development and to identify areas needing more focus, such as improving mechanization and managing the expansion of agricultural land sustainably.

4.1.3 Agricultural Trends in West African Countries (2000-2020): Land Use, Value Added, tractors and Cereal Production

The graph provides a comprehensive overview of agricultural trends from 2000 to 2020 for West African countries, with a particular focus on the following metrics: tractors, agricultural land, land under cereal cultivation, and agricultural value added. Most of the countries examined, including Benin, Burkina Faso, Ghana, Mali, and Nigeria, have demonstrated a notable increase in agricultural land and agricultural value added, signifying an advancement in the agricultural sector. Tractors have shown a substantial increase in utilization in countries such as Mali and Ghana, while other countries have experienced either fluctuating or stable trends in their tractor usage. A similar trend is observed in Land under Cereal, which also demonstrates an upward trajectory across most countries, reflecting the expansion of cereal crop production. As demonstrated in the graph below:

Graph 27: Agricultural Trends in Sub-Saharan Africa countries

The graph highlights the expansion of agricultural land, increased economic value from agriculture, and varying levels of mechanization. This information is valuable for policymakers to understand agricultural development and to identify areas needing more focus, such as improving mechanization and managing the expansion of agricultural land sustainably. After presenting these graphs, we construct the food index from the three previously indicated proxy variables and adopted the PCA approach to encompass all three in one Sub-Saharan African Countries index. Table shows the results of PCA for the Sub-Saharan African Countries studied.

4.2 Construction of the Food Index across Countries

The construction of a food index is challenging due to the difficulty in determining the logical sequence of variables that would make the index meaningful (Ozturk, 2015). This study used three variables for constructing the food index: agricultural machinery, agricultural land (for cereal production), and agriculture, forestry and fishing value added. To construct the food index, we utilized the standardized variance of the first principal component (PC1) for each country.

The components included LANDCER (Land under Cereal Production), AGRIVAL (Agricultural Value Added), and AGRIMAC (Agricultural Machinery, tractors). The weights assigned to each component varied according to their individual contributions to the standardized variance. As shown in the table below:

Table 47: Construction of Principle Component Matrix (PCA) for Food Index in Sub-West African Countries

PC1	***Benin***	***Burkina Faso***	***Côte d'Ivoire***	***Gambia***	***Ghana***	***Guinea***	***Guinea-Bissau***	***Mali***	***Niger***	***Nigeria***	***Senegal***	***Sierra-Leone***	***Togo***
Eigenvalue	*2.488*	*2.431*	*1.934*	*1.810*	*2.640*	*2.121*	*2.117*	*2.554*	*2.199*	*1.547*	*2.079*	*2.343*	*2.609*
Prop. Variance	*0.829*	*0.810*	*0.645*	*0.603*	*0.880*	*0.707*	*0.706*	*0.851*	*0.733*	*0.516*	*0.693*	*0.781*	*0.870*
FINDEX Variables													
LANDCER	*0.611*	*0.615*	*0.697*	*-0.546*	*0.605*	*0.677*	*0.546*	*0.575*	*0.622*	*0.705*	*0.603*	*-0.625*	*0.593*
AGRIVAL	*0.600*	*0.523*	*0.695*	*0.483*	*-0.544*	*0.593*	*0.609*	*0.592*	*- 0.644*	*0.194*	*0.674*	*0.564*	*0.593*
AGRIMAC	*0.517*	*-0.590*	*0.180*	*0.685*	*0.581*	*0.436*	*-0.575*	*0.565*	*0.444*	*-0.682*	*0.427*	*0.541*	*- 0.545*

*Note: **PC 1** represents the principal component 1*

In the table, Ghana constitutes the largest proportion of standardized variance Ghana (88%), followed by Togo (87%), Mali (85,10%), Benin (82,90%), Burkina Faso (81%), Sierra-Leone (78,10%), Niger (73,3%), Guinea (70,70%), Guinea-Bissau (70,60%), Senegal(69,30%), Ivory-Coast (64,50%), Gambia(60,30%) and Nigeria(51,16%).

We only extracted the first principal component (PC 1) for all countries in the region because it accounts for the greatest variance. We used the individual contributions of LAND (Land under Cereal Production), AGRIVAL (Agriculture, forest and fishing Value Added), and AGRIMAC (Agricultural Machinery, tractors) to the standardized variance of the first principal components as weights to construct the food index. To construct the food index, the weights for each variable (LANDCER, AGRIVAL, AGRIMAC) are derived from their contributions to the standardized variance of the first principal components in each country. Following this, we have:

Principle Component Analysis (PCA): PCA is performed on the variables (LANDCER, AGRIVAL, AGRIMAC) to extract the principal components. The first principal component (PC1) is the linear combination of the original variables that captures the maximum variance in the data.
Standardized Variance Contribution: The contribution of each variable to the standardized variance of the first principal component is calculated. These contributions reflect how much each variable contributes to explaining the total variance captured by PC1.
Weights Calculation: The contributions of each variable (as percentages) are used as weights for constructing the food index. These weights are obtained by dividing the contribution of each variable by the sum of contributions of all variables.
The weights used in constructing the food index for Benin is shown in the table below (table 3). Also, we pooled individual countries food indexes into a (Sub-Saharan countries except Mauritania, Liberia, and Cape Verde) regional index (FINDEX) and calculate the total FINDEX (and ∑FINDEX represents the simulation of food index). As shown in the table below:

Table 48: Weights calculation

	PC1		FINDEX VARIABLES (PC1)						
	Eigenvalue	**Prop. Variance**	**AGRLAND**	**AGRVAL**	**AGRMAC**	**Total FINDEX**	**W AGRLAND**	**W AGRVAL**	**W AGRMAC**

Benin	2.488	0.829	0.611	0.6	0.517	1.728	0.74	0.98	0.86
Burkina Faso	2.431	0.81	0.615	0.523	-0.59	0.548	0.76	0.85	-1.13
Côte d'Ivoire	1.934	0.645	0.697	0.695	0.18	1.572	1.08	1.00	0.26
Gambia	1.81	0.603	-0.546	0.483	0.685	0.622	-0.91	-0.88	1.42
Ghana	2.64	0.88	0.605	-0.544	0.581	0.642	0.69	-0.90	-1.07
Guinea	2.121	0.707	0.677	0.593	0.436	1.706	0.96	0.88	0.74
Guinea-Bissau	2.117	0.706	0.546	0.609	-0.575	0.58	0.77	1.12	-0.94
Mali	2.554	0.851	0.575	0.592	0.565	1.732	0.68	1.03	0.95
Niger	2.199	0.733	0.622	-0.644	0.444	0.422	0.85	-1.04	-0.69
Nigeria	1.547	0.516	0.705	0.194	-0.682	0.217	1.37	0.28	-3.52
Senegal	2.079	0.693	0.603	0.674	0.427	1.704	0.87	1.12	0.63
Sierra-Leone	2.343	0.781	-0.625	0.564	0.541	0.48	-0.80	-0.90	0.96
Togo	2.609	0.87	0.593	0.593	-0.545	0.641	0.68	1.00	-0.92

4.3 Stationarity and Integration order

In line with the methodological framework developed by Hurlin and Mignon (2007), this study employs panel data techniques that account for cross-sectional heterogeneity among cities.

Their approach is particularly well-suited to dynamic panels with a relatively small-time dimension, which corresponds to the characteristics of the dataset used in this research. Due to the unavailability of consistent and comprehensive city-level data, national-level data from the World Development Indicators (WDI) database were used as proxies.

To examine the stationarity of the variables, the Augmented Dickey-Fuller (ADF) test was conducted. Furthermore, Johansen's cointegration test was employed to explore potential long-run relationships among the variables.

4.3.1 Stationarity

The following table presents the results of stationarity tests for various economic and agricultural variables across different countries. We used the Dickey-Fully Augmented stationarity test following (Hurlin & Mignon, 2007). All variables, including GDP, healthcare expenditures, CO2 emissions, labor force, industrial output, and agricultural-related variables, are stationary at level (I(0)). The constants and trends show varying degrees of significance, indicating the stability of these variables over time.

Table 49: Stationarity test: ADF test

		Level		
Variables	**Constant**	**Tendance**	**Ho: Stationary**	**Order**
GDP	46.82**	24.62	Accepted	I(0)
GDP2	44.39**	23.97	Accepted	I(0)
HEXP	74.97***	32.27	Accepted	I(0)
CO2	104.97***	41.94**	Accepted	I(0)
BDRINKS	303.01***	212.76***	Accepted	I(0)
LABOR	60.02***	16.90	Accepted	I(0)
GFCF	31.07	103.42***	Accepted	I(0)
IND	92.01***	37.29*	Accepted	I(0)
NFD	103.00***	84.09***	Accepted	I(0)
NRD	131.24***	96.81***	Accepted	I(0)
WATPROD	35.99*	28.35	Accepted	I(0)
AGRILAND	82.77***	42.83**	Accepted	I(0)
AGRIMAC	77.50***	78.63***	Accepted	I(0)
AGRIVA	86.87***	53.30**	Accepted	I(0)
LANDCER	71.08***	53.40**	Accepted	I(0)
ENERGY	19.37	57.34***	Accepted	I(0)

All variables in the table are stationary at level (I (0)), as indicated by the accepted stationarity tests. This implies that these variables do not require differencing to achieve stationarity, which is crucial for further econometric analyses such as regression models and forecasting. The high significance levels (denoted by ** and ***) for many constants and trends suggest robust underlying data trends.

These findings provide a solid foundation for analyzing economic and agricultural dynamics within the given countries. The conclusion drawn from this analysis is that all variables are integrated of order zero, indicating their stationarity, a prerequisite for accurate economic and agricultural modeling.

4.3.2 Cointegration Analysis

The 3 tables below present the results of Johansen Fisher Panel Cointegration Tests for three different models: ENERGY Model, FINDEX Model, and WATER Model.

Each model examines the relationship between a set of economic and environmental variables over the period from 2000 to 2022.

1) Energy Model

The ENERGY Model includes variables such as ENERGY, HEXP, GDP, CO2 emissions, BDRINK, IND, NFD, NRD, and LABOR, spanning the test period from 2000 to 2022 with 299 observations. The analysis assumes a linear deterministic trend and uses a lag interval of 1 in the first differences.

The Unrestricted Cointegration Rank Test results indicate the presence of cointegration among the variables. Specifically, for the number of Cointegrating Equations (CEs), the Fisher Statistic is 12.48 with a probability (Prob.) of 0.8217 for none.

For at most 1 to at most 2, the probabilities remain high, indicating no significant cointegration. However, from at most 3 to at most 8, there is cointegration, at most 8, the Fisher Statistic is 69.49 with a probability of 0.0000, indicating significant cointegration. As shown in the table below:

Table 50: Johansen Fisher Panel Cointegration Test Results for the ENERGY Model (2000-2022)

ENERGY MODEL				
Johansen Fisher Panel Cointegration Test Series: **ENERGY HEXP GDP CO2 BDRINK IND NATRESS** FDEP LABOR Date: 06/04/24 Time: 09:38 Sample: 2000 2022 Included observations: 299 Trend assumption: Linear deterministic trend Lags interval (in first differences): 1 1 Unrestricted Cointegration Rank Test (Trace and Maximum Eigenvalue				
Hypothesized	Fisher Stat.*		Fisher Stat.*	
No. of CE(s)	(from trace test)	Prob.	(from max-eigen test)	Prob
None	12.48	0.8217	12.48	0.8217
At most 1	12.48	0.82	12.48	0.822
At most 2	11.09	0.89	29.51	0.042
At most 3	2.77	1.0000	131.7	0.0000
At most 4	1.39	1.0000	148.8	0.0000
At most 5	0.000	0.0000	165.8	0.0000
At most 6	165.8	0.0000	165.8	0.0000
At most 7	181.3	0.0000	156.2	0.0000
At most 8	69.49	0.0000	69.49	0.0000
* Probabilities are computed using asymptotic Chi-square distribution. Présence de cointégration entre les 9 variables				

2) FINDEX Model

Similarly, the FINDEX Model examines variables such as FINDEX, HEXP, NFD, GDP, NRD, CO2 emissions, BDRINK, IND, and LFPR over the same period and number of observations. This model also assumes a linear deterministic trend and uses a lag interval of 1 in first differences.

The Unrestricted Cointegration Rank Test shows that for the number of Cointegrating Equations (CEs), the Fisher Statistic is 12.48 with a probability of 0.8217 for none. For at most 1 to at most 2, the high probability suggests no significant cointegration. For at most 8, the Fisher Statistic is 101.5 with a probability of 0.0000, indicating significant cointegration. However, for at most 3 to at most 8, the probabilities are 0.0002 for at most 3 and 0.0000 for the rest, indicating very strong cointegration among the variables. As shown in the table below:

Table 51: Johansen Fisher Panel Cointegration Test Results for the FINDEX Model (2000-2022)

	FINDEX Model			
Johansen Fisher Panel Cointegration Test Series: FINDEXB HEXP NFD GDP NRD CO2 BDRINK IND LFPR Date: 06/04/24 Time: 10:35 Sample: 2000 2022 Included observations: 299 Trend assumption: Linear deterministic trend Lags interval (in first differences): 1 1 Unrestricted Cointegration Rank Test (Trace and Maximum Eigenvalue)				
Hypothesized No. of CE(s)	Fisher Stat.* (from trace test)	Prob.	Fisher Stat.* (from max-eigen test)	Prob.
None	12.48	0.8217	12.48	0.8217
At most 1	12.48	0.8217	12.48	0.8217
At most 2	12.48	0.8217	12.48	0.8217
At most 3	9.704	0.9411	46.55	0.0002
At most 4	0.000	0.0000	165.8	0.0000
At most 5	0.000	0.0000	165.8	0.0000
At most 6	165.8	0.0000	165.8	0.0000
At most 7	203.7	0.0000	157.4	0.0000
At most 8	101.5	0.0000	101.5	0.0000
* Probabilities are computed using asymptotic Chi-square distribution.				

3) Water Model

The WATER Model includes variables such as WATPROD, CO_2 emissions, BDRINK, HEXP, NFD, IND, LFPR, NRD, and GDP, with a similar trend assumption and lag interval as the previous models. The Unrestricted Cointegration Rank Test results show that for the number of Cointegrating Equations (CEs), the Fisher Statistic is 12.48 with a probability of 0.8217 for none. For at most 1, the high probabilities continue, indicating no significant cointegration. However, for at most 2, the Fisher Statistic is 46.55 with a probability of 0.0002, and for at most 3 to at most 8, the probabilities are 0.0000, indicating very strong cointegration among the variables. As shown in the table below:

Table 52: Johansen Fisher Panel Cointegration Test Results for the WATER Model (2000-2022)

WATER Model
Johansen Fisher Panel Cointegration Test
Series: WATPROD CO2 BDRINK HEXP NFD IND LFPR NRD GDP
Date: 06/04/24 Time: 10:38
Sample: 2000 2022
Included observations: 299
Trend assumption: Linear deterministic trend
Lags interval (in first differences): 1 1

Unrestricted Cointegration Rank Test (Trace and Maximum Eigenvalue)

Hypothesized No. of CE(s)	Fisher Stat.* (from trace test)	Prob.	Fisher Stat.* (from max-eigen test)	Prob.
None	12.48	0.8217	12.48	0.8217
At most 1	12.48	0.8217	12.48	0.8217
At most 2	9.704	0.9411	46.55	0.0002
At most 3	4.159	0.9997	114.7	0.0000
At most 4	0.000	0.0000	165.8	0.0000
At most 5	0.000	0.0000	165.8	0.0000
At most 6	165.8	0.0000	165.8	0.0000
At most 7	230.6	0.0000	181.1	0.0000
At most 8	125.0	0.0000	125.0	0.0000

* Probabilities are computed using asymptotic Chi-square distribution.

The cointegration tests across the three models (ENERGY, FINDEX, WATER) reveal significant long-term relationships among the variables in the respective models. The ENERGY and FINDEX models show significant cointegration at the highest number of cointegrating equations, indicating robust long-term equilibrium relationships.

The WATER model also demonstrates strong cointegration at multiple levels, confirming the interconnectedness of the included variables. These results suggest that the variables within each model move together over time, providing valuable insights for policymakers and researchers analyzing the economic and environmental dynamics within these regions.

Following the cointegration analysis, we will use the Generalized Method of Moments (GMM) model to further investigate the relationship between the variables, as suggested by Ozturk (2015). The GMM approach is particularly suitable for addressing potential issues of endogeneity and heteroscedasticity, providing more robust and consistent estimators when dealing with dynamic panel data models.

4.4 Method: Panel Generalized Method of Moments

This study uses a heterogeneous dynamic panel model estimated using the Generalized Method of Moments (GMM) approach to examine the relationships among key variables over the period 2002-2022. The data set consists of 21 time periods and 13 cross-sectional units that are likely to represent different countries, resulting in a total of 273 balanced observations.

The regression analyses presented in the table use the panel GMM framework to examine three different dependent variables: WATPROD, ENERGY, and FINDEX. WATPROD is assumed to represent water production or productivity, ENERGY represents energy production or consumption, and FINDEXB represents the food index or a related measure.

These analyses explore the dynamics and interdependencies within the dataset, providing insights into how these variables evolve over time across different entities. Using the GMM methodology, which addresses issues such as endogeneity and unobserved heterogeneity through instrumental variables, the study provides robust estimates that contribute to a deeper understanding of the factors influencing water production, energy dynamics, and food index fluctuations over the period analyzed.

4.4.1 Water Production (WATPROD): Examines trends and drivers of water production or productivity

The following table presents the results of the Panel Generalized Method of Moments (GMM) regression, which were used to identify the key determinants of water production (WATPROD) over the period 2002–2022.

Table 53: Panel Generalized Method of Moments Regression Results for Determinants of water Production (2002-2022)

DependentVariable
:WATPROD
Method: Panel Generalized Method of Moments
Date: 06/04/24 Time: 19:52
Sample (adjusted): 2002 2022
Periods included: 21
Cross-sections included: 13
Total panel (balanced) observations: 273
2SLS instrument weighting matrix
Instrument specification: C HEXP (-1) NFD (-1) IND(-1)
LFPR (-1) NRD (-1) BDRINK (-1) GDP(-2) CO2(-1)
Constant added to instrument list

Variable	Coefficient	Std. Error	t-Statistic	Prob.
HEXP	**0.15**	**0.072**	**2.113**	**0.036**
NFD	-7.09E-07	3.32E-07	-2.131	0.034
IND	-11.59354	2.936473	-3.948	0.0001
LFPR	**3.61E-10**	**1.75E-10**	**2.059**	**0.040**
NRD	-0.241000	0.052374	-4.601	0.0000
BDRINK	-0.420557	0.127020	-3.310	0.0011
GDP (-1)	**19.20428**	**3.659054**	**5.248**	**0.0000**
CO2	**95.62**	**10.96081**	**8.724**	**0.0000**
C	-173.67	30.29195	-5.733	0.0000
R-squared	0.40	Mean dependent var		21.30
Adjusted R-squared	0.38	S.D. dependent var		21.41
S.E. of regression	16.90	Sum squared resid		75395.16
Durbin-Watson stat	0.06	J-statistic		1.52E-17
Instrument rank	9			

The panel data regression analysis using the Generalized Method of Moments (GMM) was conducted to assess the determinants of water production (WATPROD) across West African countries over the period 2002–2022. The results reveal that health expenditure (HEXP) has a positive and statistically significant effect on water production, suggesting that improvements in the health sector may support better access to clean water and water system management.

Conversely, net forest depletion (NFD) shows a small but significant negative impact, indicating that environmental degradation undermines water productivity. Industrial activity (IND) exerts a strong and significant negative influence on water production, possibly due to competition over water resources or pollution-related challenges. Labor force participation (LFPR), although with a very small magnitude, contributes positively and significantly, hinting at the role of human capital in supporting water-related infrastructure.

In contrast, natural resource depletion (NRD) significantly and negatively affects water production, reflecting the pressure placed on ecosystems and water systems by overexploitation.

Notably, access to basic drinking water (BDRINK) has a negative and significant coefficient, which may reflect inefficiencies in water management or the overuse of existing supply systems. Lagged GDP appears to have a strong and positive impact on water production, suggesting that economic growth is associated with increased investment in water infrastructure. CO_2 emissions also show a significant and positive relationship with water production, potentially serving as a proxy for industrial development and energy-intensive infrastructure linked to water services. The model explains about 40% of the variation in water production (R-squared = 0.40; Adjusted R-squared = 0.38).

4.4.2 Energy Consumption (ENERGY): Analysis of patterns and factors that influence the dynamics of energy consumption.

The panel data regression analysis using the Generalized Method of Moments (GMM) was conducted to identify the main determinants of energy production (ENERGY) across West African countries over the period 2002–2022.

The results indicate that health expenditure (HEXP) has a strong and statistically significant positive effect on energy production, suggesting that improved healthcare systems may support energy access and infrastructure through better labor productivity and human development. Net forest depletion (NFD) also shows a positive and highly significant influence, possibly reflecting the role of biomass and forest-based energy in the region's energy mix.

In contrast, industrial activity (IND) presents a negative but statistically insignificant coefficient, indicating that its impact on energy production may be limited or context dependent. Labor force participation (LFPR) exerts a positive effect, marginally significant at the 10% level, pointing to the contribution of human capital to energy output.

However, natural resource depletion (NRD) significantly and negatively affects energy production, highlighting the unsustainable exploitation of resources as a barrier to long-term energy availability. Access to basic drinking water (BDRINK) displays a strong and positive influence, which could reflect broader infrastructural development that supports both water and energy services. Lagged GDP has a large and statistically significant positive impact, underscoring the role of economic growth in driving energy investments and production.

Conversely, CO_2 emissions are negatively and significantly associated with energy production, suggesting that emissions-intensive activities may not necessarily translate into productive energy outputs or that the region relies on low-carbon sources. The model demonstrates excellent explanatory power, with R-squared and adjusted R-squared values of 0.92, meaning that 92% of the variation in energy production is explained by the included variables, and j-statistic near to zero as demonstrated in the table below:

Table 54: Panel Generalized Method of Moments Regression Results for Determinants of Energy Production (2002-2022)

Dependent Variable: ENERGY

Method: Panel Generalized Method of Moments

Date: 06/04/24 Time: 19:50

Sample (adjusted): 2002 2022

Periods included: 21

Cross-sections included: 13

Total panel (balanced) observations: 273

2SLS instrument weighting matrix

Instrument specification: C HEXP (-1) FDEP (-1) IND (-1) LABOR (-1) NATRESS (-1) BDRINK (-1) GDP (-2) CO2(-1)

Constant added to instrument list

Variable	Coefficient	Std. Error	t-Statistic	Prob.
HEXP	35.24	7.70	4.59	0.0000
NFD	0.0001	3.55E-05	5.22	0.0000
IND	-234.38	313.43	-0.75	0.4553
LFPR	3.33E-08	1.87E-08	1.78	0.0763
NRD	-13.75	5.60	-2.46	0.0146
BDRINK	86.89	13.56	6.41	0.0000
GDP (-1)	1706.53	390.56	4.37	0.0000
CO2	-3775.21	1169.93	-3.23	0.0014
C	-37518.89	3233.30	-11.60	0.0000
R-squared	0.92	Mean dependent var		3633.34
Adjusted R- squared	0.92	S.D. dependent var		6235.56
S.E. of regression	1803.80	Sum squared resid		8.59E+08
Durbin-Watson stat	0.14	J-statistic		9.93E-17
Instrument rank	9			

4.4.3 Food Index (FINDEXB): Examine fluctuations and determinants of the food index or related metrics over the study period.

The panel data regression analysis using the Generalized Method of Moments (GMM) explores the determinants of the financial index (FINDEXB) across 13 countries over the period 2002–2022. The results reveal that net forest depletion (NFD) and industrial activity (IND) positively and significantly affect the financial index, suggesting that natural capital and industrial expansion play a role in enhancing financial development. Basic access to drinking water (BDRINK) also shows a positive and marginally significant effect, pointing to the importance of infrastructure and public services in supporting financial inclusion.

Conversely, labor force participation (LFPR) exerts a strong and statistically significant negative influence on the financial index, which may indicate labor market inefficiencies or mismatches with financial sector growth. Health expenditure (HEXP), CO_2 emissions (CO2), and natural resource depletion (NRD) all have statistically insignificant effects, while lagged GDP has a significant negative impact, implying that previous economic performance might not directly support current financial development or could reflect macroeconomic instability.

The validity of the instruments used in the model is confirmed by a J-statistic close to zero and an appropriate instrument rank, supporting the robustness of the results and ensuring a well-identified specification. Additionally, the model explains 16% of the variation in FINDEXB, as indicated by the R-squared value, reflecting modest explanatory power, as shown in the table below.

Table 55: Panel Generalized Method of Moments Regression Results for Determinants of Food Production (2002-2022)

Dependent Variable: FINDEXB
Method: Panel Generalized Method of Moments
Date: 06/04/24 Time: 19:48
Sample (adjusted): 2002 2022
Periods included: 21
Cross-sections included: 13
Total panel (balanced) observations: 273
2SLS instrument weighting matrix
Instrument specification: C HEXP (-1) NFD (-1) IND (-1)
LFPR (-1) NRD (-1) BDRINK (-1) GDP (-2) CO2 (-1)

Constant added to instrument list				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
HEXP	-0.01	0.008968	-1.58	0.11
NFD	1.79E-07	4.13E-08	4.32	0.00
IND	1.17	0.365144	3.22	0.00
LFPR	-1.16E-10	2.18E-11	-5.33	0.00
NRD	-0.00	0.0065	-0.67	0.50
BDRINK	0.03	0.016	1.94	0.05
GDP (-1)	-1.11	0.454	-2.45	0.01
CO2	1.92	1.363	1.41	0.16
C	-1.38	3.767	-0.37	0.71
R-squared	0.16	Mean dependent var		0.00
Adjusted R-squared	0.14	S.D. dependent var		2.26
S.E. of regression	2.10	Sum squared resid		1165.80
Durbin-Watson stat	0.36	J-statistic		4.65E-18
Instrument rank	9			

4.4.4 Kuznets Curve: Analysis of CO2 Emissions in Sub-Saharan Africa: A Panel GMM Approach

This study utilizes a panel data regression analysis to explore the determinants of CO2 emissions across 13 sub-Saharan African countries from 2002 to 2022. Employing the Generalized Method of Moments (GMM) approach, the analysis addresses potential endogeneity issues and provides robust parameter estimates.

The dataset includes 21 periods and a total of 273 balanced observations. Key independent variables in the model include expenditure on health (HEXP), net forest depletion (NFD), industrial development (IND), labor force participation (LABOR), natural resource depletion (NRD), access to basic drinking water (BDRINK), lagged GDP per capita (GDP (-1)), and a quadratic term of GDP (GDP2) to capture the Environmental Kuznets Curve (EKC) hypothesis. The results reveal several significant relationships and supporting the EKC hypothesis as shown in the table below:

Table 56: Panel Generalized Method of Moments Regression Results for Determinants of C02 Emissions (2002-2022)

Dependent Variable: CO2
Method: Panel Generalized Method of Moments
Date: 06/04/24 Time: 20:06
Sample (adjusted): 2002 2022
Periods included: 21
Cross-sections included: 13
Total panel (balanced) observations: 273
2SLS instrument weighting matrix
Instrument specification: C HEXP (-1) NFD (-1) IND (-1)
LFPR (-1) NRD (-1) BDRINK (-1) GDP(-2) GDP2(-1)
Constant added to instrument list

Variable	Coefficient	Std. Error	t-Statistic	Prob.
HEXP	-0.001545	0.000413	-3.745375	0.0002
NFD	3.40E-09	1.97E-09	1.730098	0.0848
IND	0.039441	0.017255	2.285857	0.0231
LFPR	1.81E-12	1.56E-12	1.161349	0.2465
NRD	0.000424	0.000312	1.359084	0.1753
BDRINK	0.004916	0.000685	7.179995	0.0000
GDP (-1)	-0.047420	0.021473	-2.208301	0.0281
GDP2	-1.98E-24	6.67E-25	-2.966612	0.0033
C	0.285020	0.178213	1.599318	0.1109
R-squared	0.204638	Mean dependent var		0.301550
Adjusted R-squared	0.180536	S.D. dependent var		0.110378
S.E. of regression	0.099919	Sum squared resid		2.635711
Durbin-Watson stat	0.131327	J-statistic		2.28E-16
Instrument rank	9			

The regression analysis indicates several relationships between various factors and CO2 emissions. Health expenditure (HEXP) has a negative and significant impact on CO2 emissions, suggesting that higher investments in health could lead to reduced emissions through improved efficiency and environmental management. In contrast, forest depletion (NFD) shows a positive relationship with CO2 emissions, as deforestation reduces the planet's ability to absorb carbon dioxide, releasing stored carbon into the atmosphere. This highlights the need for sustainable forest management practices to mitigate CO2 emissions. Industrial development (IND) also demonstrates a positive and significant relationship with CO2 emissions, emphasizing that industrialization, without the adoption of green technologies, tends to exacerbate environmental pollution.

The labor force participation rate (LFPR) has a negative coefficient, indicating that higher participation in the labor force could theoretically reduce CO2 emissions.

However, this relationship lacks statistical significance, suggesting that any observed effect might be attributable to random variation rather than a substantial underlying trend. Natural resource depletion (NRD) has a positive and significant association with CO2 emissions, highlighting the deleterious effects of extracting natural resources on the environment. This reaffirms the imperative for implementing resource-efficient and sustainable practices. While access to basic drinking water (BDRINK) is recognized as a crucial aspect of human development, it does not demonstrate a significant effect on CO2 emissions within the model, as evidenced by the positive but non-statistically significant coefficient.

The lagged GDP per capita (GDP (-1)) exhibits a negative and significant impact on current CO2 emissions, suggesting that enhancements in economic productivity in the past may result in a decline in emissions over time. This phenomenon is likely attributable to increased efficiency and technological advancements within the economy.

Negative Quadratic GDP (GDP2): The significant negative coefficient for the quadratic term of GDP confirms the presence of an inverted U-shaped relationship, which is a key feature of the EKC. This supports the EKC hypothesis, showing that CO2 emissions initially increase with economic growth, but eventually decrease as economies mature and prioritize more environmental sustainability or sustainable practices. As shown in the table below:

The study validates the Environmental Kuznets Curve (EKC) hypothesis for sub-Saharan Africa, demonstrating that while economic growth initially increases CO_2 emissions, they may decrease with sustainable development. Policy recommendations include increasing health expenditure, promoting green industrialization, enforcing stricter environmental regulations, and adopting sustainable forestry and resource-efficient practices.

The integration of green economy principles, particularly within the Water-Energy-Food (WEF) nexus, is imperative for achieving a sustainable balance between urbanization, economic growth, and environmental sustainability.

4.4 Integrating Green Economy Transitions into the Food-Energy-Water Nexus Model: Insights from Sub-Saharan Africa

To integrate the transition to a green economy into the model exploring the food-energy-water nexus in Sub-Saharan African countries, this study integrates green economy variables to examine the interrelationship between the water-energy-food (WEF) nexus and sustainable development in the context of urbanization. Key variables such as energy consumption, agricultural productivity, and agricultural contribution to GDP, agricultural land use, and water productivity are analyzed.

In addition, indicators such as health expenditure per capita, CO2 emission intensity, and access to drinking water services are considered to assess their impact on economic growth and environmental sustainability. The study aims to show how these variables interact in urban environments, highlighting this importance of transitioning to a green economy to manage resource efficiency, enhance resilience to urban challenges, and promote long-term sustainable development.

Transitioning to a green economy in African urban context involves adopting sustainable development practices that promote economic growth, environmental protection, and social inclusion. This transition is crucial for mitigating the impacts of climate change, reducing urban poverty, and ensuring long-term urban sustainability.

Policymakers can develop comprehensive strategies that optimize resource use, reduce environmental degradation, and improve the quality of life for urban populations by leveraging the WEF Nexus. The following table presents key aspects of integrating green economy principles into WEF nexus.

Table 57: Integrating Green Economy Principles into the Water-Energy-Food Nexus

Key Aspect	Description	Application in Senegal
Investments in Renewable Energy	Adoption of renewable energy sources (e.g., solar-powered irrigation) to increase agricultural productivity and reduce environmental impact (Ashfaq et al., 2024).	In Senegal, solar-powered irrigation systems can reduce reliance on fossil fuels and enhance agricultural productivity. Implementation of WEF Nexus strategies, including efficient irrigation, solar energy, agroforestry, and urban agriculture to enhance urban resilience and

		sustainability (Goodarzi et al., 2022)
Natural Resource Conservation & Sustainable Agriculture	Implementation of the WEF Nexus principles, such as sustainable agriculture, soil and water conservation, and agroforestry	Senegal can adopt precision agriculture, drip irrigation, and integrate agroforestry to improve food security and conserve natural resources.
Technological Innovation & Green Jobs	Development of clean technologies and green jobs to stimulate economic growth and reduce environmental impact (Houssam et al., 2023).	Senegal can develop clean technologies, create green jobs, and enhance water and food security through innovative solutions.
Environmental Policies	Adoption of carbon emissions regulations, habitat protection, and sustainable policies to preserve biodiversity (Hoff, 2011).	Senegal can implement policies on carbon emissions, resource conservation, and sustainable urban planning to strengthen resilience. Senegal can apply WEF strategies in water management, renewable energy, sustainable agriculture, and urban planning to achieve sustainable development goals.

Although the transition to a green economy was not tested directly through econometric or statistical methods, the results of the chapter provide indirect evidence of this potential. The analysis highlights how key factors such as health expenditure, human capital, and sustainable resource use influence water, energy, and food production core pillars of the green economy.

These findings suggest that policies focusing on improving public health, reducing environmental degradation, and promoting sustainable infrastructure may enhance resource productivity and resilience. Therefore, we hypothesize that strengthening these intersectoral linkages can support West African's transition to a green economy.

Hypothesis for further research: Integrated investments in human capital, environmental sustainability, and infrastructure development contribute to the water-energy-food nexus performance and can act as drivers of the green economy transition in West African countries.

4.5.2. Policy Implications WEF nexus and green economy transition

This study analyzes the integration of the Water-Energy-Food (WEF) Nexus and green economy strategies to enhance resilience in West African countries, considering the challenges posed by urbanization, climate change, and resource scarcity. It emphasizes the interconnectedness of water, energy, and food systems, advocating for coordinated policies to improve resilience.

Short-term: In the immediate future, West African countries should concentrate on addressing climatic variability by promoting renewable energy sources (such as solar) and enhancing land and water management to mitigate adverse impacts on agricultural productivity.

Medium-term: Countries should prioritize sustainable water management strategies to address agricultural water scarcity and improve land fertility, which is crucial for long-term food security.

Long-term: The adoption of integrated frameworks for the food-energy-water nexus is imperative to cultivate resilience, with a focus on environmental stewardship and long-term economic growth. The Environmental Kuznets Curve (EKC) theory postulates that while economic growth initially leads to environmental degradation (e.g., increased CO2 emissions), a point of inflection occurs, and emissions may decline as development progresses and cleaner technologies are implemented.

Conclusion: Based on the analysis of the Water-Energy-Food (WEF) nexus for West African countries from 2002 to 2022, several key insights emerge that inform the need for integrated and holistic policies addressing the challenges faced by urban areas. The study highlights the interconnections between health, wealth, and environmental factors, emphasizing their combined impact on achieving sustainable development goals in the region.

First, the findings highlight the significant role of health expenditure in reducing environmental degradation, with increased investments in health potentially fostering more efficient resource management and improving urban resilience.

However, forest depletion and natural resource extraction remain critical challenges that exacerbate carbon emissions, demonstrating the importance of implementing sustainable resource management practices and strengthening environmental regulations. Industrial development, while contributing to economic growth, has a detrimental effect on CO2 emissions, suggesting that industrialization must be coupled with green technologies to minimize its environmental footprint.

The relationship between labor force participation and CO2 emissions, though not statistically significant, suggests potential opportunities for optimizing the labor market in a way that aligns with environmental goals, such as promoting green jobs and sustainable practices. Moreover, the lagged effect of GDP per capita on CO2 emissions suggests that improvements in economic productivity, driven by technological advancements and increased efficiency, can reduce emissions over time.

However, the analysis also reveals that urban agriculture and water access do not significantly contribute to CO2 emissions, although these factors are critical for ensuring food security and water conservation in urban settings. In conclusion, this study advocates for a strategic and integrated approach to addressing the WEF nexus in West African countries.

Governments should adopt policies that foster the efficient use of resources, promote renewable energy, and encourage sustainable agricultural practices. Strong environmental regulations and the adoption of green economy principles are crucial for mitigating climate change impacts, reducing carbon emissions, and enhancing urban resilience. By focusing on these interconnected factors, urban centers can be better equipped to navigate future challenges and contribute to sustainable development for generations to come. Some African countries, such as Ghana and Kenya, illustrate the early stages of this trend, suggesting the possibility of achieving sustainability through the implementation of suitable environmental reforms.

General Conclusion: Towards Resilient, Green, and Sustainable Cities in Senegal and West Africa

The three essays presented in this thesis make a significant contribution to understanding the key drivers of urban resilience and the transition to a green economy in Senegalese cities and, more broadly, in West African countries.

Through a multidimensional approach combining socio-economic, spatial, and econometric analyses, this research highlights the fundamental role of urban green spaces, urban agriculture, and the integration of the Water-Energy-Food (WEF) nexus in addressing the growing challenges of urbanization, food insecurity, and climate change. This thesis has explored the multifaceted pathways through which African cities particularly in Senegal can build resilience to climate change and advance the transition toward a green economy.

In the context of rapid urbanization, increasing environmental vulnerabilities, and socio-economic disparities, the research offers empirical insights and analytical reflections across three critical pillars: public knowledge, satisfaction and willingness to pay for urban green spaces, the role of urban agriculture in enhancing food security and climate resilience, and the dynamics of the Water-Energy-Food (WEF) Nexus in Sub-Saharan African countries. Collectively, these three essays provide a coherent and complementary perspective that advances the understanding of how cities can achieve the transition toward a green economy through integrated, inclusive, and sustainable urban strategies.

The first part of the study examined urban residents' **knowledge, satisfaction, and willingness to pay** for the improvement of green spaces in Senegal. The findings highlight the importance of education, income, and environmental awareness in shaping public attitudes toward urban sustainability. They also reveal disparities in satisfaction with green space management, reflecting challenges such as poor maintenance, limited accessibility, and weak integration into urban planning.

Notably, individuals with higher awareness and satisfaction levels are more willing to financially support the improvement of green spaces. These insights emphasize the need for inclusive urban policies that promote environmental education, participatory governance, and innovative financing mechanisms such as public-private partnerships to ensure equitable and sustainable access to urban green infrastructure.

The second essay focused on **urban agriculture** as a transformative tool for building climate-resilient cities and advancing the green economy transition. Empirical findings from six Senegalese cities highlight the role of urban agriculture in enhancing food security, promoting biodiversity, and generating green employment, particularly for marginalized groups such as women and youth.

Climate-smart practices such as agroecology, water-saving technologies, and circular resource use emerge as critical tools for adapting to and mitigating climate change impacts. Spatial analyses revealed that cities with higher vegetation cover and better access to water resources benefit from stronger ecosystem services and greater climate resilience.

Urban agriculture not only reduces the carbon footprint of urban food systems but also stimulates local economies and supports the regeneration of degraded urban ecosystems. Municipal governments play a pivotal role in leveraging this potential by integrating urban agriculture into land-use planning, infrastructure development, and policy frameworks that prioritize equity and sustainability.

The third essay of the thesis analyzed the **Water-Energy-Food (WEF) nexus** across West African countries over two decades. The results emphasize the importance of integrated policy approaches to manage the interdependencies between environmental, economic, and social systems. Health expenditures were found to reduce environmental degradation, while industrial development, in the absence of green technologies, contributed to rising CO_2 emissions. The findings call for the adoption of low-carbon development strategies, the promotion of renewable energy, and sustainable resource use to reduce climate vulnerability and environmental damage. While urban agriculture and water access were not directly linked to CO_2 emissions in the model, they remain critical tools for sustainable urban development, food security, and social well-being.

Taken together, the three essays converge on a powerful message: **building climate-resilient and sustainable cities in Africa requires a paradigm shift that place green infrastructure, inclusive governance, and integrated resource management at the center of urban development strategies**.

Urban green spaces, urban agriculture, and the WEF nexus are not isolated solutions but interlinked components of a broader urban transformation agenda. Achieving this transformation requires coordinated efforts across sectors, levels of government, and stakeholders including local communities, civil society, and the private sector. For Senegal and, more broadly, for Africa, this thesis recommends a holistic and inclusive urban policy agenda that:

- Strengthens public awareness and participation in the management of urban green spaces through community engagement and education, fostering environmental stewardship and promoting behavioral change and civic engagement.
- Integrates and invests in nature-based solutions and green infrastructure into urban planning to enhance climate resilience and environmental quality, especially in vulnerable and underserved neighborhoods.
- Promotes urban agriculture as a key driver of food security, employment, and low-carbon development in rapidly urbanizing areas;
- Supports urban agriculture through land access, training, and green technology adoption, thereby linking climate resilience with food sovereignty and local economic development.
- Supports the adoption of Water-Energy-Food (WEF) nexus-based approaches and implements cross-sectoral policies that align water, energy, and food strategies to ensure resource efficiency, reduce urban vulnerability, and promote sustainable development while reinforcing synergies and minimizing resource-related conflicts
- Strengthens institutional capacity at the municipal level, enabling cities to plan, finance, and manage sustainable urban development more effectively.
- Encourages innovation and investment in green technologies and inclusive business models, particularly those that empower women, youth, and marginalized urban populations;
- Enhances coordination between municipal authorities, national governments, and development partners to institutionalize the green economy transition within local governance frameworks.
- "*The future of Africa lies in the resilience of its cities, where sustainability and equity must thrive together to overcome the challenges of climate change and socio-economic pressures*."

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APPENDIX

Node number 2: 146 observations
complexity param=0.04242424 predicted class= Very low expected loss=0.760274 P(node) =0.705314 class counts: 35 29 33 32 17 probabilities: 0.240 0.199 0.226 0.219 0.116 left son=4 (129 obs) right son=5 (17 obs) Primary splits: UA_Years_practices< 3.5 to the right, improve=2.264565, (0 missing) Annual_contribution_of maintenance_< 1100000 to the left, improve=2.063927, (0 missing) Main_constraint_splits as R-RL-, improve=2.023775, (0 missing) Main_crop_ splits as LRLR, improve=1.776103, (0 missing) Type_of space_used_ splits as LLRR, improve=1.744696, (0 missing)

Node number 3: 61 observations,
complexity param=0.01818182 predicted class= Very high expected loss=0.5901639 P(node) =0.294686 class counts: 7 12 8 9 25 probabilities: 0.115 0.197 0.131 0.148 0.410 left son=6 (8 obs) right son=7 (53 obs) Primary splits: Field_distance_km < 23.5 to the right, improve=2.618775, (0 missing) Extension_servies_ splits as RL, improve=1.925379, (0 missing) Type _of_space used_splits as RLLR, improve=1.520807, (0 missing) Main_constraint_splits as -R--L, improve=1.277188, (0 missing) UA_Years_practices_ < 14.5 to the left, improve=1.110358, (0 missing)

Node number 4: 129 observations,
complexity param=0.04242424 predicted class= Very low expected loss=0.7364341 P(node) =0.6231884 class counts: 34 28 25 27 15 probabilities: 0.264 0.217 0.194 0.209 0.116 left son=8 (79 obs) right son=9 (50 obs) Primary splits: UA_Years_practices < 14.5 to the left, improve=3.490550, (0 missing) Type _of_space used_splits as LLRR, improve=2.209025, (0 missing)

Annual_contribution_of maintenance < 1250000 to the left, improve=2.169312, (0 missing)
Main_constraint_ splits as R-RL-, improve=1.764962, (0 missing)
Crop_production_splits as LLLR, improve=1.674040, (0 missing)
Surrogate splits:
Source_of_funding_splits as RLL-L, agree=0.659, adj=0.12, (0 split)
Type of_space_used_splits as RLLL, agree=0.643, adj=0.08, (0 split)
Main_constraint_splits as L-RL-, agree=0.628, adj=0.04, (0 split)
Field_distance_km< 3.5 to the left, agree=0.620, adj=0.02, (0 split)
Annual_contribution_of maintenance < 1750000 to the left, agree=0.620, adj=0.02, (0 split)

Node number 5: 17 observations

predicted class=Medium
expected loss=0.5294118
P(node) =0.0821256
class counts: 1 1 8 5 2
probabilities: 0.059 0.059 0.471 0.294 0.118

Node number 6: 8 observations

predicted class=Medium
expected loss=0.625
P(node) =0.03864734
class counts: 1 1 3 3 0
probabilities: 0.125 0.125 0.375 0.375 0.000

Node number 7: 53 observations,

complexity param=0.01818182
predicted class= Very high
expected loss=0.5283019
P(node) =0.2560386
class counts: 6 11 5 6 25
probabilities: 0.113 0.208 0.094 0.113 0.472
left son=14 (8 obs)
right son=15 (45 obs)
Primary splits:
Extension_services_splits as RL, improve=2.1998950, (0 missing)
Main_constraint_splits as -R--L, improve=1.7580300, (0 missing)
UA_training_ splits as RL, improve=1.2862590, (0 missing)
Main_production__splits as -LRL, improve=1.2556300, (0 missing)
type _of_space used_ splits as RLRL, improve=0.8219819, (0 missing)
Surrogate splits:
UA_training_splits as RL, agree=0.906, adj=0.375, (0 split)
Method of_funding_splits as LR-, agree=0.887, adj=0.250, (0 split)
Source of_funding_splits as RRRLR, agree=0.868, adj=0.125, (0 split)

Node number 8: 79 observations,
complexity param=0.02424242 predicted class=Low expected loss=0.7088608 P(node) =0.3816425 class counts: 22 23 7 18 9 probabilities: 0.278 0.291 0.089 0.228 0.114 left son=16 (71 obs) right son=17 (8 obs) Primary splits: Annual_contribution for maintenance_< 950000 to the left, improve=2.726154, (0 missing) type of_space_used_splits as LLRR, improve=2.383116, (0 missing) Use of_pesticides_splits as RLR, improve=2.128792, (0 missing) Main_constraint_splits as R--L-, improve=1.480573, (0 missing) UA_Years_practices < 8.5 to the left, improve=1.434369, (0 missing) Surrogate splits: Main_crop_ splits as LRLL, agree=0.911, adj=0.125, (0 split)

Node number 9: 50 observations
predicted class=Medium expected loss=0.64 P(node) =0.2415459 class counts: 12 5 18 9 6 probabilities: 0.240 0.100 0.360 0.180 0.120

Node number 14: 8 observations
predicted class=Low expected loss=0.5 P(node) =0.03864734 class counts: 2 4 0 1 1 probabilities: 0.250 0.500 0.000 0.125 0.125

Node number 15: 45 observations
predicted class=Very high expected loss=0.4666667 P(node) =0.2173913 class counts: 4 7 5 5 24 probabilities: 0.089 0.156 0.111 0.111 0.533

Node number 16: 71 observations,

complexity param=0.02424242
predicted class= Very low
expected loss=0.6901408
P(node) =0.3429952
class counts: 22 21 5 18 5
probabilities: 0.310 0.296 0.070 0.254 0.070
left son=32 (59 obs)
right son=33 (12 obs)
Primary splits:
Type_of space used_splits as LLRR, improve=3.147728, (0 missing)
Use of_pesticides_splits as RLR, improve=2.561368, (0 missing)
UA_Years_practices_ < 8.5 to the left, improve=1.680970, (0 missing)
source_of_funding_splits as LLL-R, improve=1.092618, (0 missing)
Mian_constraint_ splits as R--L-, improve=1.083590, (0 missing)
Surrogate splits:
Main_crop_ splits as R-LL, agree=0.859, adj=0.167, (0 split)
Production_method_splits as RL, agree=0.845, adj=0.083, (0 split)

Node number 17: 8 observations

predicted class= Very high
expected loss=0.5
P(node) =0.03864734
class counts: 0 2 2 0 4
probabilities: 0.000 0.250 0.250 0.000 0.500

Node number 32: 59 observations,

complexity param=0.01010101
predicted class= Very low
expected loss=0.6271186
P(node) =0.2850242
class counts: 22 16 3 17 1
probabilities: 0.373 0.271 0.051 0.288 0.017
left son=64 (39 obs) right son=65 (20 obs)
Primary splits:
UA_Years_practices_ < 9.5 to the left, improve=1.3206000, (0 missing)
Field_distance_km_ < 4 to the left, improve=0.9295130, (0 missing)
Funding_method_splits as -LR, improve=0.8064972, (0 missing)
Annual_contribution for maintenance < 8750 to the left, improve=0.7231638, (0 missing)
UA_Training _splits as LR, improve=0.7155881, (0 missing)
Surrogate splits:
Annual_contribution for maintenance_< 275000 to the left, agree=0.729, adj=0.20, (0 split)
Field_distance_km < 45 to the left, agree=0.678, adj=0.05, (0 split)
UA_Training_ splits as LR, agree=0.678, adj=0.05, (0 split)

Node number 33: 12 observations

predicted class=Low
expected loss=0.5833333
P(node) =0.05797101
class counts: 0 5 2 1 4
probabilities: 0.000 0.417 0.167 0.083 0.333

Node number 64: 39 observations,

complexity param=0.01010101
predicted class=Very low
expected loss=0.
P(node) =0.1884058
class counts: 14 14 2 9 0
probabilities: 0.359 0.359 0.051 0.231 0.000
left son=128 (30 obs)
right son=129 (9 obs)
Primary splits:
UA_Years_practices_< 4.5 to the right, improve=1.3025640, (0 missing)
Field_distance_km < 6 to the left, improve=0.9950372, (0 missing)
Annual_contribution for maintenance_< 6250 to the left, improve=0.5927602, (0 missing)
Main_constraint_splits as L--R-, improve=0.5820650, (0 missing)
Source_of_funding_splits as RLL-R, improve=0.1805211, (0 missing)
Surrogate splits:
Annual_contribution for maintenance_ < 225000 to the left, agree=0.821, adj=0.222, (0 split)
Main_crop_splits as R-LL, agree=0.795, adj=0.111, (0 split)

Node number 65: 20 observations,

complexity param=0.01010101
predicted class=Very low
expected loss=0.6
P(node) =0.09661836
class counts: 8 2 1 8 1
probabilities: 0.400 0.100 0.050 0.400 0.050
left son=130 (11 obs) right son=131 (9 obs)
Primary splits:
UA_Years_practices_< 11.5 to the right, improve=0.5525253, (0 missing)
Annual_contribution for maintenance_< 6000 to the left, improve=0.5500000, (0 missing)
Field_distance_champ_km < 2.5 to the left, improve=0.4428571, (0 missing)
Main_constraint_splits as R--L-, improve=0.3000000, (0 missing)
Surrogate splits:

UA_Training_as RL, agree=0.75, adj=0.444, (0 split)
field_distance__km < 2.5 to the right, agree=0.70, adj=0.333, (0 split)
Annual_contribution for maintenance_< < 6000 to the left, agree=0.65, adj=0.222, (0 split)
source_of_funding_ splits as LL--R, agree=0.60, adj=0.111, (0 split)

Node number 128: 30 observations

predicted class= Very low
expected loss=0.5666667
P(node) =0.1449275
class counts: 13 11 1 5 0
probabilities: 0.433 0.367 0.033 0.167 0.000

Node number 129: 9 observations

predicted class= High
expected loss=0.5555556
P(node) =0.04347826
class counts: 1 3 1 4 0
probabilities: 0.111 0.333 0.111 0.444 0.000

Node number 130: 11 observations

predicted class= Very low
expected loss=0.5454545
P(node) =0.0531401
class counts: 5 1 1 3 1
probabilities: 0.455 0.091 0.091 0.273 0.091

Node number 131: 9 observations

predicted class= High
expected loss=0.4444444
P(node) =0.04347826
class counts: 3 1 0 5 0
probabilities: 0.333 0.111 0.000 0.556 0.000

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