KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY, KUMASI, GHANA

Land-based climate change solution options for Sahelian West Africa from land-used and land-cover model

By

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Declaration

I hereby declare that this submission is my work towards the Ph.D. in Climate Change and Land Use and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material that has been accepted for the award of any other degree or diploma at Kwame Nkrumah University of Science and Technology, Kumasi or any other educational institution, except where due acknowledgement is made in the thesis.

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Abstract

Assessing the impacts of anthropogenic land use and land cover change (LULCC) on climate extremes is crucial for understanding the complex interactions between the land surface and the atmosphere, significantly influencing regional climate dynamics. Therefore, the study is essential in Sahelian West Africa, where rapid population growth, desertification, and agricultural expansion intensify environmental changes and amplify climate variability and extremes. Despite numerous studies, there needs to be more consensus on the regional effects of LULCC on climate extremes in West Africa. This research provides the first multidisciplinary systematic review of biophysical LULCC impacts in West Africa. Additionally, high-resolution (15 km) LULCC simulations spanning 2012 to 2022 were performed to investigate these effects in Sahelian West Africa, using a fully coupled Weather Research and Forecasting (WRF-Only) system integrated with the Noah-MP land surface model with dynamic vegetation. Also, the WRF for hydrological forecasting (WRF-Hydro) system was employed, coupled with Noah-MP. These experiments aimed to elucidate the potential impacts of anthropogenic LULCC on regional climate extremes, providing critical insights into land-atmosphere interactions in this vulnerable region. Results indicate that deforestation contributes to regional warming, with significant historical temperature increases of +0.26 ± 0.12 °C and projected increases of +0.88 ±0.25 °C under future scenarios. Conversely, afforestation could significantly cool the climate, reducing temperatures by -0.24 ± 0.14 °C historically and -0.22 ± 0.14 °C in future scenarios, excluding carbon sequestration effects. Deforestation historically decreases regional precipitation by -47.45 ± 29.2 mm/year and -55 ± 102.2 mm/year under future scenarios. In contrast, large-scale afforestation could substantially mitigate droughts, increasing precipitation by +200 ± 124 mm/year historically and +635 ± 521 mm/year in future projections. Analysis of 12 climate indices (mean and extreme) reveals that LULCC negatively affects temperature extremes, with modest average warming. This effect is more pronounced in WRF-Hydro simulations (+2.6%) compared to WRF-Only simulations (+1.88%). Similarly, precipitation increases are more significant in WRF-Hydro (+4.86%) than in WRF-Only (+3.16%). Extreme climate indices demonstrate greater sensitivity to LULCC than mean conditions. The findings emphasize the critical role of hydrological processes in WRF-Hydro, which improves model performance, contributing up to +0.95% for temperature and +2.45%

for precipitation on average. Exceptions are seen in TXn and CCD indices, where hydrological contributions decrease by -0.3%. Land surface temperature shows a maximum increase of up to +0.5 K with WRF-Only and +0.6 K with WRF-Hydro during the wet-to-dry seasonal transition (August to January), primarily driven by reduced plant transpiration (ΔEt) due to decreased canopy foliage. Over the entire year, LULCC induces a slight rise in land surface temperature (<0.3%) in both WRF-Only and WRF-Hydro simulations, with a marginally stronger response in WRF-Hydro. These findings underscore the importance of fully coupled modelling frameworks that integrate the complexities of LULCC and land-atmosphere interactions. Such approaches are essential for effectively evaluating land-based mitigation strategies, enhancing regional climate resilience, and supporting improved livelihoods in Sahelian West Africa.

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ARR: Afforestation, Reforestation, and Revegetation
CC: Climate Change
CDD: Consecutive Dry Days (days)
CH_4: Methane
CI: Confidence Interval
CO_2: Carbon Dioxide
COP: Conference of Parties
COVID: Coronavirus Disease
CTL: Control
ΔDLR: Downward Longwave Radiation
ΔDSR: Downward Shortwave Radiation
DTR: Daily Temperature Range (°C)
ΔEc: Canopy Evaporation
EC: Eddy Covariance
ECMWF: European Centre for Medium-Range Weather Forecasts
EEA: European Environment Agency
ENSO: El Niño-Southern Oscillation
ΔEs: Soil Evaporation
ESM: Earth System Models
ESOM: Earth System Observation and Modeling
ΔEt: Plant Transpiration
ETCCDI: Expert Team on Climate Change Detection and Indices
FAO: Food and Agriculture Organization
ΔG: Ground heat flux
GCM: Global Climate Model
GCOS: Global Climate Observing System
GGW: Great Green Wall
GHG: Greenhouse Gas
GPM: Global Precipitation Measurement
Gt: Gigaton
HPA: Hectopascal
IMERG: Integrated Multi-satellite Retrievals for GPM

IPCC: Intergovernmental Panel on Climate Change

IPCC-SRCCL: Intergovernmental Panel on Climate Change Special Report on Climate Change and Land

ITCZ: Intertropical Convergence Zone

K: Kelvin

$L_{\uparrow}$: The surface upward long-wave radiation

LAI: Leaf Area Index

LE: Latent Heat

LHvap: The latent heat of vaporisation

LSM: Land Surface Model

LST: Land Surface Temperature

LULCC: Land Use and Land Cover

MODIS: Moderate Resolution Imaging Spectroradiometer

MWW: Mann–Whitney–Wilcoxon

N_2O: Nitrous Oxide

NCAR: National Center for Atmospheric Research

Noah-MP: Noah Multi-parameterization, land surface model

NoLCC: No land use and land cover change

NSE: Nash-Sutcliffe Efficiency

Pmean: Mean Precipitation (mm/day)

PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses

R10mm: Heavy precipitation days (days)

R1mm: Wet days (days)

R20mm: Very heavy precipitation days (days)

RCM: Regional Climate Model

RCP: Representative Concentration Pathway

REDD+: Reducing Emissions from Deforestation and Forest Degradation in Developing Countries

RMSE: Root Mean Square Error

SDG: Sustainable Development Goals

SDII: Simple Daily Intensity Index (mm/day)

ΔSH: Sensible Heat

SH: Sensible Heat flux

Tmean: Mean Temperature (°C)

TNn: Annual minima of daily minimum temperature (°C)

TNx: Annual maxima of daily minimum temperature (°C)

TR: Number of tropical nights (days)

TXn: Annual minima of daily maximum temperature (°C)

UNCDD: United Nations Convention to Combat Desertification

UNESCO: United Nations Educational, Scientific and Cultural Organization

UNFCCC: United Nations Framework Convention on Climate Change

USAID: United States Agency for International Development

USGS: United States Geological Survey

WRF: Weather Research and Forecasting

WWR: World Wide Fund for Nature

$\Delta\alpha$: Surface Albedo

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Dedication

This work is dedicated to God, the Most Merciful, whose guidance and blessings
have been my strength throughout this journey,
to my beloved late father, Mr. Yahaya Seydou (of blessed memory), whose wisdom
and advice continue to inspire me,
to my dear mother, Saley Soumana, for her unwavering support and encouragement,
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Grateful to all of you who have been the guiding light on my journey toward every success in life.

CHAPTER 1: GENERAL INTRODUCTION

1.1 Background

Climate change (CC) stands as one of the most pressing challenges confronting the world today, with its effects now surpassing the natural limits of Earth's systems (Gebeyehu & Natural, 2019; Karl & Trenberth, 2003). It is impacting ecosystems globally by altering average conditions and increasing climate variability (Malhi et al., 2020; Underwood et al., 2019). Moreover, CC is anticipated to profoundly impact the Earth's systems and human well-being, particularly by jeopardising food security through rising temperatures, shifting precipitation patterns, and an increased frequency of extreme hydrometeorological events (IPCC-SREX, 2012). Increasing global demand for food and bioenergy, driven by LULCC, has sparked concerns about environmental impact, global warming and climate change (Roy et al., 2022). Human-induced LULCC play a crucial role in the climate system and have garnered considerable attention in recent years for their impact on surface albedo and their influence on the exchange of water, energy, and the carbon cycle (IPCC, 2019b). In addition to the IPCC special report on global warming of 1.5°C, the special report on climate change and land (IPCC-SRCCL et al., 2019) It was recently developed to address greenhouse gas (GHG) fluxes in terrestrial ecosystems, LULCC, and sustainable land management, emphasising their links to climate change adaptation and mitigation, desertification, land degradation, and food security. Land restoration (i.e transformation of an ecosystem type to another) has been highlighted as an essential component of climate mitigation, such as conservation agriculture, agroforestry “climate-smart agriculture” or reforestation/afforestation. LULCC significantly impacts local and regional climates through both biogeochemical and biophysical effects. Biogeochemical effects arise from changes in surface gas emissions, including CO_2, CH_4, and N_2O, while biophysical effects result from alterations in the surface energy budget influenced by factors such as albedo, evapotranspiration, and surface roughness.

Despite advances in land-based management and mitigation options, several modeling uncertainties and limitations persist in accurately representing the regional effects of anthropogenic LULCC on mean climate variables as well as temperature and precipitation and extreme climate indices over West Africa. As a result, Earth System Models (ESMs) are extensively utilised to simulate the effects of LULCC on climate variables. Nevertheless, there remains a lack of integrated models that effectively couple biophysical, hydrological, and ecological processes (Kumar et al., 2021).

The inclusion of LULCC in coupled and vegetation models is relatively partial and recent. At the same time, estimates of their contribution to climate, water and carbon cycle impacts are not fully consensual and need urgent investigation. ESMs and their land modeling components will serve as a guide because they are fundamental in evaluating the impact of LULCC on land surface climate. They provide essential solutions for sustainable land management, adaptation, and inform strategies to mitigate climate change.

1.2 Problem statement and justification

1.2.1 Problem statement

Over the past few years, numerous studies have explored the impact of human-induced LULCC on the climate system across global, regional, and local scales. These changes expect to be among the most crucial challenges for Earth by, influencing multiple components, such as climate, hydrology, food security, ecosystem services, global biodiversity, and the long-term sustainability of land (Mustard et al., 2012). Among the regions where land surface-atmosphere interactions play a major role, Sub-Saharan Africa has been highlighted as an important hotspot (Koster et al., 2004; Sy et al., 2017; Sy and Quesada, 2020) and it is projected that the highest number of people will be vulnerable to increased land degradation and yield decline (IPCC-SRCCL, 2019). As climate change, variability, and land degradation persist, the region continues to struggle with inadequate land restoration efforts, insufficient supportive policies, and limited financing (Partey et al., 2018). Moreover, activities such as mining, deforestation, land degradation and urbanization exacerbated by population growth in sub-Saharan Africa, they pose a threat to CC (Sy et al., 2017). However, achieving and maintaining land-based mitigation targets, while addressing a growing population and increasing dietary demand, and ensuring biodiversity and sustainable ecosystem use, remains a significant challenge.

1.2.2 Justification

Assessing future climate change, the carbon budget and its associated impacts is crucial. Earth System Observation and Modeling (ESOM) has become a key tool for evaluating the carbon budget and land restoration options (Righi et al., 2020). Nonetheless, the impact of LULCC on extreme events and climate is still largely unexplored or lacks consensus, especially when based on models that use historical data (often relying on a single model), regional studies, or idealised scenarios (Sy & Quesada, 2020). Moreover, the inclusion of LULCC in coupled and vegetation models is relatively partial and recent, while estimates of their climate, water and carbon budget impacts are not fully consensual. Hence, it is critical to increase our understanding of how land-based mitigation options can be achieved sustainably. Such an understanding would allow policies, scientists and mechanisms to be evaluated, making climate targets aimed at limiting global warming to 1.5°C more achievable. Establishment of the regional Earth System Model (ESM) (WRF-Noah-MP-Hydro) involves analysing the GHG emission and mitigation options considering different shares of nature conservation areas, such as forest (afforestation or reforestation), agroforestry, hydrological system, cropland and intensive agriculture.

Thus, the preferred choice of this fully coupled ESM (WRF-Noah-MP-Hydro) provides a comprehensive assessment tool for evaluating land surface properties, including surface heterogeneity, the hydrological cycle, the biogeochemical cycle, anthropogenic contributions, and ecosystem dynamics.

1.3 Aim and Objectives

This study seeks to evaluate land-based mitigation options for climate change in Sahelian West Africa by examining the applicability of a fully integrated (coupled) regional climate-hydrology-vegetation dynamics model (WRF-Noah-MP-Hydro).

Specifically, the study sought to:

i. Evaluate the regional effects of LULCC on mean and extreme climate in Sahelian West Africa using a fully coupled WRF-Noah-MP with dynamic vegetation.

ii. Determine the sensitivity of both WRF-Noah-MP vs. WRF-Noah-MP-Hydro models to LULCC in Sahelian West Africa.
iii. Determine the physical mechanisms driving the surface temperature in response to LULCC.

1.4 Research questions

This study primarily aimed to determine how LULCC impact regional climate variables in Sahelian West Africa, including mean temperature, precipitation, and extreme climate indices. The research focused on addressing the following specific questions:

i. What are the regional effects of LULCC on mean and extreme climate in Sahelian West Africa using a fully coupled WRF-Noah-MP with dynamic vegetation?
ii. What is the sensitivity of both WRF-Noah-MP vs. WRF-Noah-MP-Hydro models to LULCC in Sahelian West Africa?
iii. What physical mechanisms drive the surface temperature in response to LULCC?

1.5 Structure of Thesis

The thesis is organised into **7 Chapters** following the monograph-based format. **Chapter 1** provides a general introduction, offering an overview of the study background, objectives, research questions, and the structure of the thesis. **Chapter 2** continues with a comprehensive literature review, offering definitions of the key concepts used and summarising relevant previous research. The methodology, with a focus on the study area and model experimental set-up, is presented in **Chapter 3**. This chapter also explains the various products and tools used to achieve the desired results for each specific objective.

Chapter 4 specifically reports the regional effects of LULCC on mean and extreme climate in Sahelian West Africa using a fully coupled WRF-Noah-MP. **Chapter 5** addresses the sensitivity of both WRF-Noah-MP vs. WRF-Noah-MP-Hydro models to LULCC in Sahelian West Africa. **Chapter 6** focuses on determining the physical mechanisms driving the surface temperature in response to LULCC in Sahelian West Africa. Finally, **Chapter 7** provides the conclusions and recommendations.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This section focuses on describing and understanding key concepts and theories from various scientific studies that have been used and developed in these research areas to examine land-based solutions for CC through land use and land cover models. Particular attention is given to anthropogenic LULCC and their biophysical impacts on regional climate variables, extreme indices, and the interactions between land ecosystems and the carbon cycle in the West African Sahelian region. More importantly, land-based solution options are vital for climate change mitigation and adaptation because they harness natural systems to capture carbon, preserve biodiversity, and maintain essential ecosystem services. A fully coupled Land use and land cover models and climate models, play a crucial role by providing data-driven insights to guide effective land management and policy decisions. They help identify opportunities for carbon sequestration, assess the impacts of different LULCCs on climate, and balance trade-offs to ensure sustainable development. By integrating these elements, these models support strategies that address the effects of CC while enhancing environmental resilience and promoting sustainable land management.

2.2 Definitions of Key Concepts

- **Climate change**: The United Nations Framework Convention on Climate Change (UNFCCC, 2011) defines CC as a change directly or indirectly caused by human activities that alter the composition of the global atmosphere, in addition to natural climate variability observed over similar time periods. According to (IPCC, 2021) summary for all, climate change is how the conditions of our atmosphere change over minutes, hours, days and weeks. Rising temperatures, changes in rainfall patterns, and an increase in extreme weather events are all examples of CC.
- **Climate system**: Is an interactive framework comprising five major components: the atmosphere, hydrosphere, cryosphere, land surface, and biosphere. It is driven or influenced by various external forcing mechanisms (Baede et al., 2001; Goosse, 2010).

- **Greenhouse gases**: A greenhouse gas (GHG) is a type of gas in the atmosphere that absorbs and re-emits heat, helping to maintain a warmer planetary atmosphere than would exist without them. The main GHGs in Earth's atmosphere include water vapour, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone. While GHGs naturally occur in the atmosphere, human activities such as burning fossil fuels have led to higher concentrations. This increase is contributing to global warming and driving CC (Brander & Davis, 2023).

- **Carbon cycle**: It refers to the series of processes that regulate the movement of carbon in various forms through living organisms and the environment, detailing how carbon is stored and released in different ways. It can be understood in terms of carbon reservoirs and the processes that control the exchanges between them (WWF, 2008).

- **Carbon sink**: A carbon sink is the natural process, activity, or mechanism by which carbon dioxide is absorbed and stored in the atmosphere (Chen et al., 2021). It is the equilibrium of carbon transfer between an ecosystem and the land atmosphere over a specific period (Keenan & Williams, 2018).

- **CC mitigation**: CC mitigation involves implementing actions to reduce and limit GHG emissions (UNESCO, 2019). Mitigation strategies can be divided into four key areas: decreasing emissions from deforestation, cutting emissions from forest degradation, boosting forest carbon sinks, and substituting products. Substitution includes using wood as an alternative to fossil fuels for energy and replacing materials like cement, steel, and aluminium with wood fibre, as their production releases significant amounts of greenhouse gases (FAO, 2014).

- **Carbon sequestration:** Carbon sequestration involves capturing carbon from the land atmosphere and storing it in soil. It can help offset some human-induced GHG emissions, making it a crucial component of global CC mitigation efforts (Don et al., 2024)**.** It is crucial in combating climate change by capturing and storing carbon dioxide (CO_2) from the atmosphere, which helps lower greenhouse gas emissions (Prajapati, 2023).

- **Land use and land cover change:** The terms LULCC are often used together. It refers to changes in the biophysics, biogeochemistry, and biogeography of the terrestrial surface and their effects on atmospheric characteristics, which are primarily driven by human activities (Nedd et al., 2021; Pielke et al., 2011).

- **Climate change adaptation:** Adaptation involves modifying management practices to reduce the ecosystem's vulnerability to climate change, along with actions aimed at lowering people's susceptibility to its impacts (FAO, 2014). Adaptation to climate change can significantly reduce many harmful effects and enhance positive outcomes, though it involves costs and may still result in some lasting damage (Burton et al., 2001).

- **Earth System Models (ESM)**: ESM are advanced global climate models enhanced to explicitly represent biogeochemical processes that interact with the physical climate, influencing its response to human-induced forces. These models provide insights into the dynamics of the Earth's climate dynamics and its future changes (Flato, 2011). In simple terms, ESM are vital tools for forecasting climate behavior under diverse human and natural forcing scenarios (Heinze et al., 2019).

- **Land surface modeling:** It is the process of simulating the land surface dynamics and its role in interacting with the Earth's system, particularly in the context of global change (Fisher & Koven, 2020). It refers to the simulation of the Earth's interconnected components, involving the complex interaction of various physical, biological, and chemical processes, all explicitly represented to better understand and predict the planet's behavior over time (Flato, 2011).

- **Climate feedback**: Climate feedbacks are systemic processes that might either intensify or weaken the reaction of the climate to a disturbance from without. Still, temperature is the most basic input in the climate system. The feedback parameter, whether positive or negative, amplifies (or dampens) the temperature response of the climate system. (Bony et al., 2006). In the Earth system, climate feedbacks are defined as processes that affect climate sensitivity and stability (Heinze et al., 2019). For example, reductions in rainfall on a regional level could influence the surviving forests. Deforestation over 30–50% of the Amazon might lower rainfall by 40% over non-deforested areas, therefore affecting the resilience of the remaining forest (Spracklen et al., 2018). Positive feedback increases the change or output, while negative feedback reduces it.

- **Land surface albedo:** Since it helps to control the Earth's energy budget, this is defined as the ratio of reflected to incident solar radiation on its surface and is among the most crucial climatic determinant. It is an essential parameter in local, regional, and global climate models, and is significantly influenced by LULCC (Li Qiuping et al., 2018; Pang et al., 2022). It is the fraction of the global mean incident shortwave radiative flux that is reflected back into space (Liang et al., 2019).

- **Surface roughness**: Surface roughness refers to the small-scale irregularities in a surface's texture, which can be categorised into three components: roughness, waviness, and form. This measure is commonly used to describe the variation in soil surface elevation across a field and plays a significant role in influencing surface temperature, hydrological processes, and erosion dynamics under various conditions. (Zhu et al., 2020).

- **Soil moisture:** Generally speaking, soil moisture is the water content of a top layer of a field soil. This state variable underlies the control of a wide spectrum of biological, hydrological, geotechnical, and meteorological activities (Romano, 2014). Moreover, Soil moisture is a key variable of the climate system. It is a component that stores abnormalities in radiation and precipitation and causes persistence in the climate system (Corti et al., 2010).

- **Leaf area index**: Divided by the ground surface area, the total one-sided area of leaf tissue is the Leaf Area Index (LAI). Especially for scaling gas exchange from the leaf to the canopy level, it is a fundamental parameter in ecophysiology, agro-climatology, modelling, forestry, and agroforestry. LAI explains the canopy-atmosphere interface, whereby most energy (Breda, 2003; Watson, 1947).
- **Sensible heat fluxes**: Sensible heat is the energy responsible for changing the temperature of a substance. It can be directly felt as it increases the temperature of an object without changing its phase (Mechcontent, 2022).

- **Latent heat fluxes**: In contrast to sensible heat, latent heat is the energy responsible for changing the phase of a substance, such as from solid to liquid or liquid to gas. Fusion, melting, and evaporation are typical examples of latent heat (Mechcontent, 2022).

2.3 Land-use/land-cover change interaction with the climate system

2.3.1 Land use/land cover change over West Africa

LULCC over West Africa has significantly impacted the environment and climate. Rapid urbanisation, agricultural expansion, and deforestation have been major drivers of these changes. A growing population, particularly in coastal and urban areas, has led to increased demand for agricultural land, converting forests and savannahs into farmlands and settlements (Tiando et al., 2021). This transformation has caused a reduction in biodiversity and ecosystem services while increasing the region's vulnerability to climate change (Sage, 2020). Climate variability also plays a crucially important in determining LULCC in West Africa extreme weather occurrences including floods and drenches abound in the area, which impact agricultural productivity and land-use patterns. In the Sahel, for example, recurrent droughts have led to shifts in farming practices and land management strategies (Yira et al., 2016). These changes, coupled with human activities, create feedback loops where degraded landscapes exacerbate CC's effects include changed rainfall patterns and rising temperatures (Gonzalez et al., 2012). Agricultural expansion has also led to unsustainable land management practices, including overgrazing and the excessive use of chemical fertilizers. These activities contribute to soil degradation and desertification, posing a serious threat to the region's subsistence farming systems (USAID, 2017). As soil fertility declines, farmers often clear new land for cultivation, further perpetuating a cycle of land degradation. The socio-economic consequences of LULCC are profound, as reduced agricultural productivity threatens food security and livelihoods in West Africa (Ofori et al., 2021).

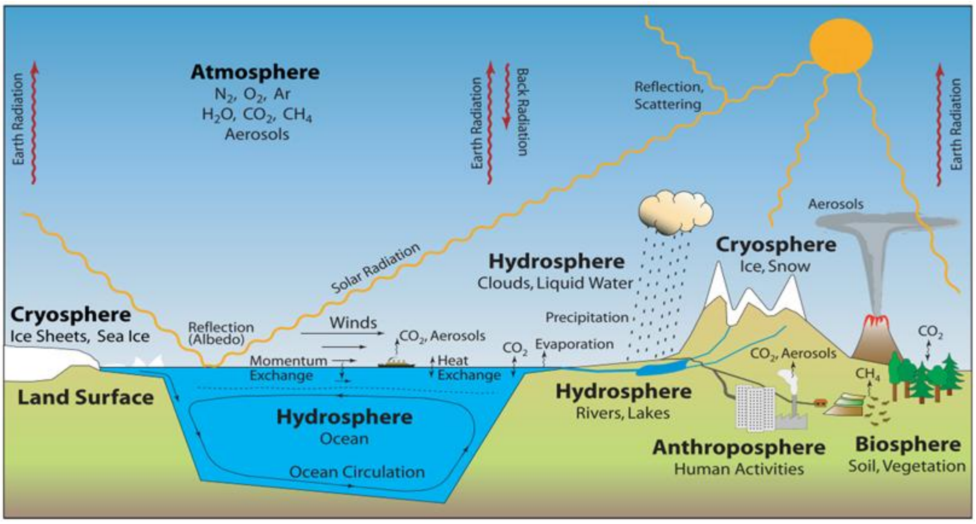


Figure 2.1: The key components and associated processes of the climate system at both global and regional scale (Stocker, 2016).

2.3.2 West Africa land use and land cover categories

A sub-continental scale investigation of past land use/land cover transitions in West Africa revealed spatial reallocation, characterized by simultaneous land use/land cover categories' losses and improvements across several sites. This analysis represents one of the most effective approaches for quantifying and understanding the interactions between land surface categories and the climate system (Asenso Barnieh et al., 2022).

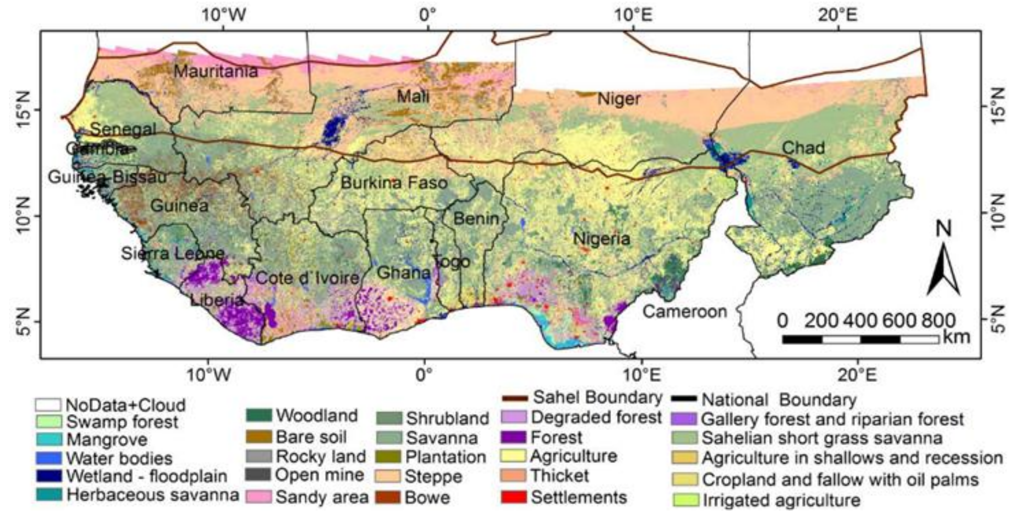


Figure 2.2: The USGS original land use/land cover maps of West Africa (Barnieh et al., 2020).

Covering Sub-Saharan West Africa, from 4°N-18°W to 18°N-24°E, this land use/ land cover map as such, the terrain of West Africa might be characterised as a multifarious ecosystem covering several environments (Barnieh et al., 2020).

Table 2.1: The land use/land cover reclassification scheme developed for the United States Geological Survey (USGS) datasets in 1975, 2000, and 2013 at 2 km spatial resolution (Barnieh et al., 2020).

USGS Original LULC Types	Reclassified LULC Types Developed by This Research
Rain-fed agricultural land, plantation, agricultural land in recession, irrigated agricultural land, cropland in shallows with oil palm.	Cropland
Forest, gallery forest, degraded forest, swamp forest, woodland, mangrove.	Forestland
Savannah, steppe, bowe, thicket, herbaceous, Sahelian short grasses.	Other vegetation
Wetland	Wetland
Water	Water
Settlement	Settlement
Rocky land, sandy areas, bar soil, open mines	Other LULC
Cloud cover, no data	No data-cloud cover

2.3.3 Relevant land surface properties within the climate system

Various studies reveal that land cover, such as chlorophyll-rich vegetation changes fundamental characteristics of the land surface, thereby either favourably or negatively influencing the fluxes of energy, moisture, momentum, trace gases, and particles between the surface and the atmosphere (Dong & Shi, 2022; M. He et al., 2022; Nzabarinda et al., 2021; Spracklen et al., 2018).

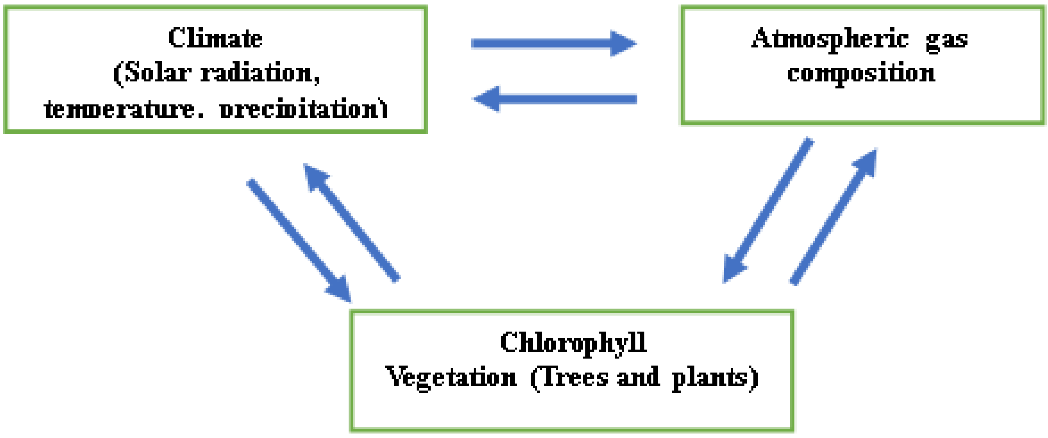


Figure 2.3: Interactions and interlinkages between climate and vegetation (Harrison et al., 2005).

A visual comparison of global climate patterns and vegetation reveals a strong connection between climatic and vegetation zones. This correlation, however, is not coincidental but rather reflects underlying interactions between climate and vegetation. (Harrison et al., 2005).

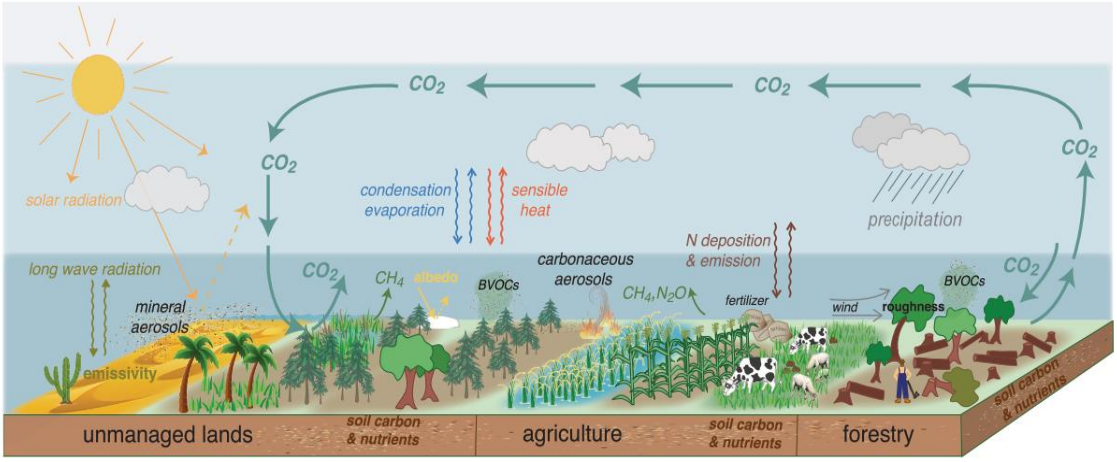


Figure 2.4: The structure, functioning and interactions of land use/land cover that affect local, regional and global climate (IPCC., 2019).

2.3.4 Exploring how land use and land cover changes affect climate patterns and processes

The influence of LULCC on regional and global climates through biochemical and biophysical processes is essential for understanding historical climate changes and projecting future scenarios (Bounoua et al., 2002; J. Liu et al., 2016). Furthermore, understanding and managing LULCC is essential for tackling environmental challenges, ensuring the effective application of natural resources and preservation of ecological systems for the advantage of present and next generations (Blay & Abunyuwah, 2024). Thus, Human activities have been shaping the environment for thousands of years. Over recent centuries, rapid population growth, migration, and intensified socioeconomic activities have further accelerated these environmental changes. The resulting climate impacts are evident in local, regional, and global trends observed in modern temperature records and other climate indicators (Deng et al., 2013; Mahmood et al., 2010). Anthropogenic LULCC influences regional climate by altering the water balance and energy budget. These effects are often seen in changes to precipitation patterns and surface temperatures (Salazar et al., 2015). Additionally, it can affect the ecosystem's ability to deliver vital services to humans, such as maintaining biodiversity and supplying resources like food, fiber, and water (Barati et al., 2023). Influences regional and global climate through Driven by fluctuations in albedo, evapotranspiration, and surface roughness, biophysical adjustments in the surface energy budget (Perugini et al., 2017). As well as by the emission of long-wave radiation, the terrestrial surface warms by absorbing solar and long-wave radiation and cools through the transfer of sensible heat (by conduction and convection) and latent heat (energy from water evapotranspiration) to the atmosphere. Land surface features including shortwave radiation reflectance (albedo), long-wave radiation emissivity by vegetation and soils, surface roughness, and soil water accessibility for vegetation, which depends on soil properties and root distribution, affect these land-atmosphere interactions (IPCC-SRCCL, 2019).

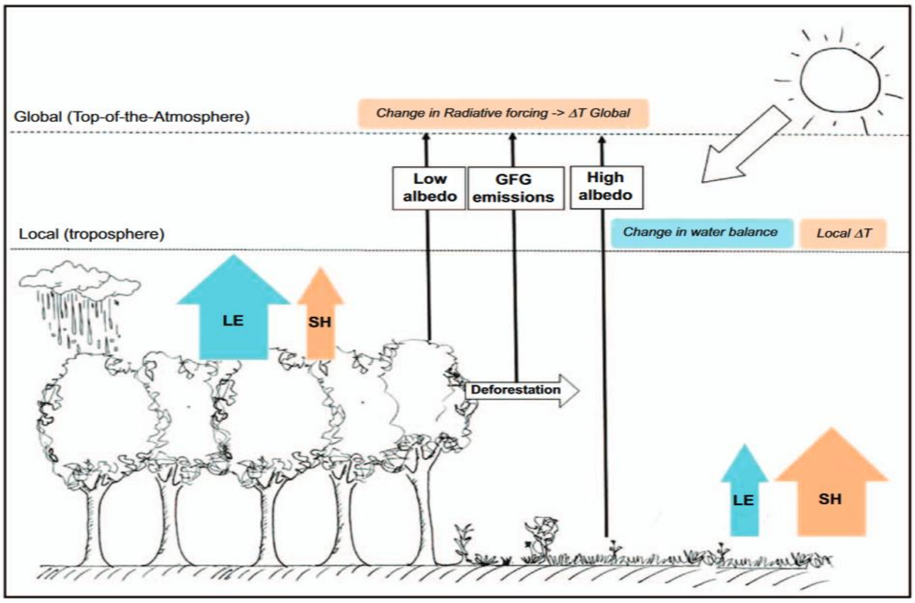


Figure 2.5: A schematic representation that illustrates the biophysical and biogeochemical effects of LULCC. LE: latent heat; SH: sensible heat; GHG: greenhouse gas (Perugini et al., 2017).

2.3.5 Atmospheric carbon dioxide removal

The carbon cycle and Earth's climate are tightly interconnected. Key greenhouse gases in the atmosphere are carbon-containing gases like methane (CH_4) and carbon dioxide (CO_2), together with water vapour. These GHGs trap heat by absorbing portions of the long-wavelength radiation emitted by the Earth. Notably, CO_2 is a long-lived GHGs (Keller, 2018). CO_2 is temporarily removed from the atmosphere through carbon (C) sequestration by plants during photosynthesis. However, this sequestration is reversible and time-limited, typically lasting up to a few decades. (Terlouw et al., 2021). Large living trees store disproportionately large amounts of carbon and play a significant role in driving carbon cycle dynamics in forests globally (Mildrexler et al., 2020). Furthermore, intact forests, which are largely undisturbed by human activities, are highly carbon-dense and have the potential to remove atmospheric CO_2 at much faster rates (Moomaw et al., 2019). According to WWF, (2018), enhancing forest carbon stocks through restoration and natural regeneration, as well as increasing soil carbon through agricultural carbon sequestration and biochar production, can significantly boost carbon sequestration in natural systems, offering benefits that outweigh the associated costs.

2.3.6 Role of land use/land cover within the climate system

Nature-based solutions and enhanced green infrastructure are being progressively proposed in recent years as more affordable and sustainable means of adaptation and mitigating CC impact (EEA, 2011). Many studies show LULCC's great capacity, including for afforestation, reforestation and agroforestry, to ameliorate microclimate conditions by decreasing air temperature and solar radiation, regulating humidity, and sequestering CO_2 (Vranic et al., 2016). Furthermore, land use/land cover are a key driver in strength mitigation measures (regulating carbon and energy budget) and preventing irreversible declines in soil fertility and ecosystem services (Zhou et al., 2021). Forests, agroforests and trees are also fundamental because it reduce harmful air pollutants and enable the achievement of Sustainable Development Goals (SDG3), SDG11 and SDG13 (Dagnachew & Hof, 2022).

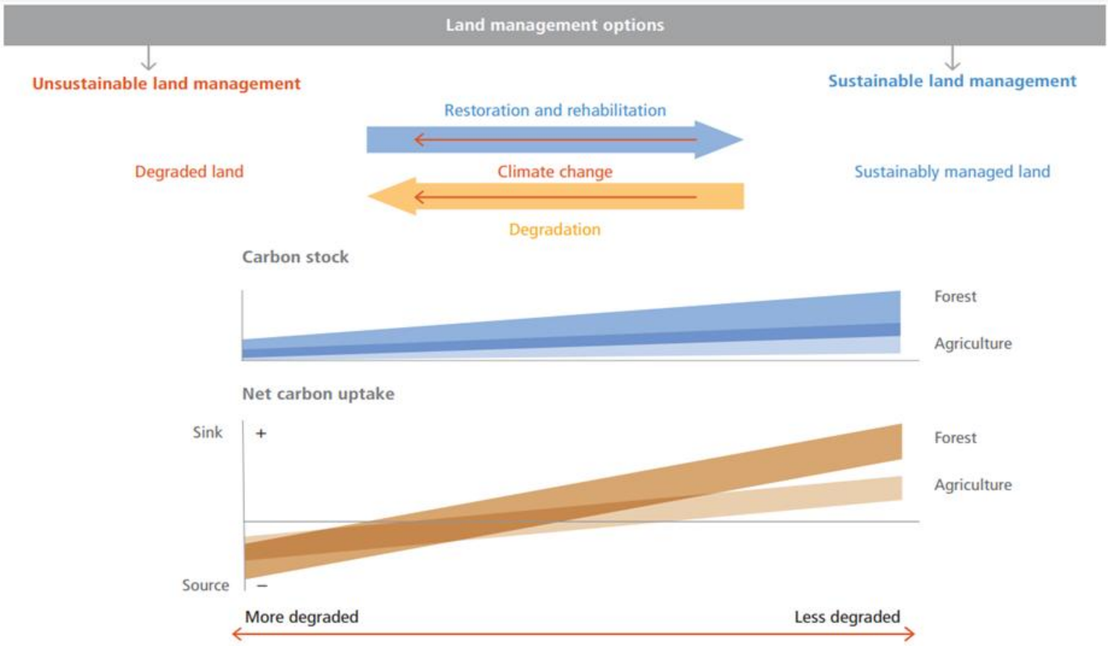


Figure 2.6: Conceptual figure illustrating that climate change impacts interact with land management to determine sustainable or degraded outcome (IPCC, 2019).

2.3.7 Land use/land cover change impact on climate and Human wellbeing

LULCC dynamics are a growing global concern due to their significant impacts, both beneficial and harmful, on terrestrial and aquatic ecosystems as well as on climate systems (Sibanda & Ahmed, 2021). Urban sprawl has led to the loss of surface water bodies, green areas, and viable agricultural land. Driven by the search of greater employment prospects and improved living conditions, urban population growth and development are accelerating as major migration from rural areas and smaller towns moves to bigger cities (Bhat et al., 2017). The growing human demand for land, driven by population growth and economic development, has intensified daily. These changes to landscapes have added pressure on environmental sustainability of natural resources, biogeochemical cycles, and hydrological cycles (Nath et al., 2021). Indeed, LULCC has closely aligned with the evolution of human societies and civilizations, particularly over the past 300 years (Mal & Singh, 2014). Therefore, a study conducted by Hussain & Karuppannan. (2021) in in district Khanewal, Punjab Pakistan analysed LULCC and their effects on Land Surface Temperature (LST). The findings revealed an increase in LST from 1980 to 2020 due to the expansion of built-up areas. The eastern region of the study area exhibited lower temperatures due to greater vegetation and agricultural land. Additionally, changes in LST were primarily associated with variations in urban building materials and the extent of vegetation in both urban and rural areas. Vegetation played a dual role in influencing temperatures across different LULCC types. In urban or built-up areas, it mitigated warming trends, while in colder weather, it contributed to maintaining warmth in other types of land (Xiao & Weng, 2007). Furthermore, rapid population growth and intensified economic activities drive LULCC, leading to environmental disturbances such as soil erosion. While soil loss has increased in agricultural and built-up areas, it has significantly decreased in forests, mixed forest areas, paddy fields, and grasslands or shrublands (Nut et al., 2021). The rapid transformation of LULCC affects biodiversity, ecosystem services, and functions, as well as local and regional climates (Choudhury et al., 2019).

In Sub-Saharan Africa, particularly in West Africa, LULCC, especially the conversion of natural vegetation into agricultural land, are ongoing process driven primarily by human activities and further intensified by population growth (Guzha et al., 2018). Despite the growing focus on CC, the effect of land use conversions on natural ecosystems and the water cycle both crucial for agricultural production and climate mitigation are often overlooked. This neglect threatens the sustainability of the socio-ecological system in West Africa (Näschen et al., 2019). The transition from dense semi-deciduous forests to open forests in West Africa is primarily driven by human activities, which amplify the effects of CC (Kingbo et al., 2022). The expansion of cropland to meet the growing demand for fuel, food, and fiber is a key driver of natural ecosystem degradation (Manzoor et al., 2022). In the coming decades, nearly a million hectares of forest and land are at risk of being lost, particularly in tropical regions. This loss will significantly impact the climate system and land-atmosphere interactions (Sy et al., 2017).

2.3.8 Effect of land use/land cover change on climate

Several research highlight that LULCC influences regional climate as well as land surface temperature (Hua & Chen, 2013; J. Jiang & Tian, 2010; Pal & Ziaul, 2017; Tran et al., 2017). In contrast to temperature, the changes in rainfall are much more complicated, not only in the spatial patterns but also in the amounts and distributions (Shi et al., 2013). Thus, LULCC is among the most harmful effects on the land ecosystem and disturbs it function, which has direct and indirect interaction with climate. These are exacerbated by rising temperatures and radiation (C. Huang et al., 2020). On the other hand, future climate forecast goes beyond merely the estimate of greenhouse gas emissions and their corresponding climatic reaction. LULCC (both natural and manmade sources) by their impacts on surface albedo, Bowen ratio, surface roughness, aerosol emission, surface mass, energy, and momentum fluxes provide still another crucial forcing for regional and global climates (Guiling et al., 2017).

2.3.9 Climate and extreme weather indices responses to LULCC over West Africa

LULCC in West Africa significantly influences local and regional climate patterns, particularly extreme climate events. Deforestation in the region (mostly in Sahelian West Africa) has been linked to shifts in rainfall patterns, reducing precipitation and intensifying droughts. Studies using Earth System Models (ESMs) suggest that deforestation reduces local evapotranspiration, which disrupts the West African monsoon system, leading to drier conditions, especially in the Sahel region (Pongratz et al., 2021; M. Zhang, Gao, Zhang, et al., 2024). Taylor et al, (2022) demonstrated that the loss of forest cover over time contributed to significant increases in temperature extremes across West Africa, discussed the effects of global warming on regional temperature. Additionally aggravating severe temperature episodes in the area is LULCC. Urbanisation and agricultural development have been proven to contribute to the urban heat island effect, hence raising the frequency and intensity of heat waves in West African citiess. The replacement of natural vegetation with crops and urban infrastructure leads to higher land surface temperatures, which in turn drive more frequent hot and dry summers (Findell et al., 2017). In the other hand, LULCC is also responsible for altering extreme rainfall patterns. As forested areas are replaced with farmland and urban infrastructure, the increased runoff and reduced infiltration rates lead to more frequent and severe flooding in some parts of West Africa (Tazen et al., 2019; M. Zhang, Gao, Zhang, et al., 2024). Given CC, this is especially important since the mix of changed land cover and global warming is predicted to intensify the frequency of heavy rainfall events, therefore taxing the water management systems of the area (Findell et al., 2017).

2.4 Carbon budget and regulation of land surface temperature

With the Paris Agreement, the international community has committed to hold the global average temperature rise well below 2 °C and pursue measures to limit it to below 1.5 °C which suggests severe carbon budgets and unprecedented mitigating worldwide (Pan et al., 2022). With fossil CO_2 emissions of 36.5 Gt CO_2 and LULCC emissions of 6.6 Gt CO_2, world CO_2 emissions still kept rising up to a record high of 43.1 Gt CO_2 in 2019. In such situation, the world carbon emissions must decrease 32 Gt CO2 (7.6% per year) from 2020 to 2030 for the 1.5 °C warming limit, which is even more bigger than the COVID-induced reduction (6.4%) in global CO_2 emissions during 2020 (Huang & Zhai, 2021). The carbon cycle feedback parameters amplify after the CO_2 concentration and temperature peaks, allowing land and ocean absorption of more carbon per unit change in atmospheric CO_2 change (stronger negative feedback) and loss of more carbon per unit temperature change (stronger positive feedback) than if the feedbacks remained unchanged due of the inertia of the Earth system (Melnikova et al., 2021). Originally adopted at the 13th Conference of Parties (COP) of the UNFCCC, Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (REDD+) is an international program for protecting, conserving and enhancing the carbon stocks of tropical forest regions and reducing anthropogenic emissions of greenhouse gases which was first adopted

(Albers & Robinson, 2013). Similarly, the Africa sub-Sahelian becomes a fascinating area for win-win vision Afforestation, Reforestation, and Revegetation (ARR) projects like the Great Green Wall (GGW). The target is far beyond improving rural livelihoods or increases in ecological resiliency (Turner et al., 2021) but also, has also been advocated as a means of reducing desertification and enhancing carbon storage at a large scale, precious to preserve life on earth (O'Connor & Ford, 2014).

2.4.1 Carbon cycle

The carbon cycle is the interaction of carbon among 4 main reservoirs: the atmosphere, terrestrial biosphere, oceans, and sediments. In essence, it involves the transfer of carbon between the lithosphere and hydrosphere. Notably, scientists estimate that 99.9% of all life forms on Earth are carbon-based (Balasubramanian, 2017). An evaluation of the carbon cycle in Sahelian West Africa in response to LULCC was initially planned but could not be conducted due to the limited timeframe of the program.

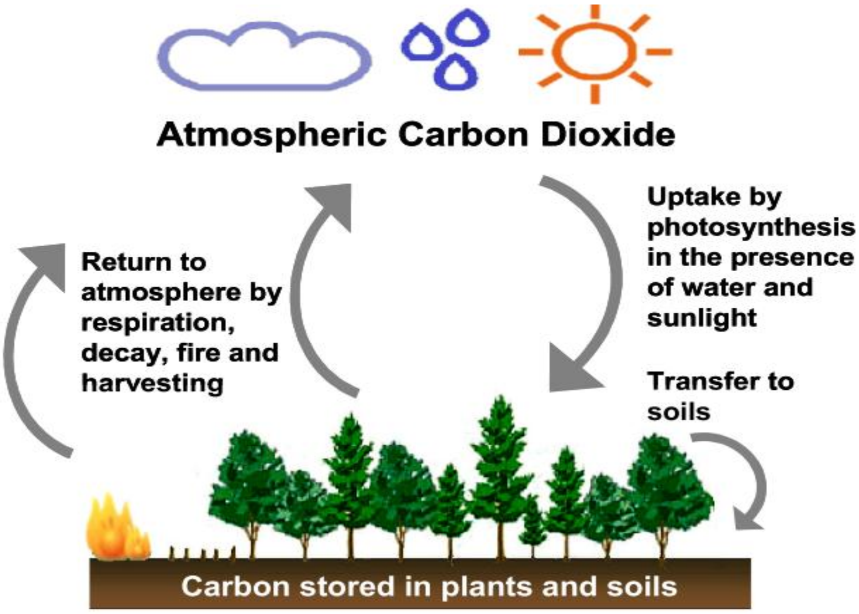


Figure 2.7: A sub-cycle within the global carbon cycle; source (University of New Hampshire, 2014).

2.5 Model-based LULCC studies in West Africa

Figure 2.8a (see below) shows that most of the selected articles were published after 2017, with the earliest study identified being Charney (1975). Approximately 60% of these publications published over the past six years, show a growing emphasis on LULCC's local and regional biophysical effects in West Africa. Several factors likely contribute to this increased interest: (i) West Africa is particularly vulnerable to climate impacts due to its high exposure and limited adaptive capacity (Barros et al., 2014), and has experienced significant multidecadal rainfall variability and severe droughts, particularly in the 1970s and 1980s (Masih et al., 2014; Nicholson, 2013a). Additionally, since the mid-1970s, mean annual and seasonal temperatures have increased by 1-3°C, with the largest increases observed in the Sahara and Sahel regions (Cook and Vizy, 2015; Lelieveld et al., 2016; Trisos et al., 2022); (ii) The region also faces critical land-use challenges, such as deforestation, overgrazing, and land degradation due to agricultural expansion and urbanization, which have significantly altered the landscape (Bliefernicht et al., 2018; Boone et al., 2016; Potapov et al., 2022; Sy et al., 2017). These changes strongly influence land-atmosphere interactions, intensifying climate extremes and altering local and regional climate systems (Barry et al., 2018; Russo et al., 2016; Sy and Quesada, 2020); (iii) Since Charney's (1975) seminal work on the link between desertification and drought in the Sahel, West Africa has been at the centre of discussions on the biophysical impacts of deforestation and desertification (Fuller and Ottke, 2002; Zheng and Eltahir, 1997); (iv) over the past 50 years, the region's population has practically doubled; by mid-century, it is predicted to double once again, resulting in growing strain on land resources and faster land-use change (Sy et al., 2017; Van Bavel, 2013); and (v) In response to these challenges, initiatives such as the Great Green Wall have emerged to combat climate impacts and land degradation through large-scale reforestation and afforestation efforts (Ingrosso and Pausata, 2024; Smiatek and Kunstmann, 2023).

2.6 Simulated temperature responses

Surface air temperature responses (°C) to LULCC scenarios, including deforestation and afforestation, over the simulation periods are summarized in Figure 2.8b and Table 2.2. Boxplots display the temperature responses from individual models (represented by different cross symbols), while the triangle represents the multi-model ensemble mean (i.e., the average result from all models). On average, deforestation scenarios lead to regional warming, with simulated values of +0.26 ± 0.12 °C during the historical period and +0.88 ± 0.25 °C in future scenarios (95% confidence interval). In contrast, afforestation produces a cooling effect, with values of –0.24 ± 0.14 °C in the historical period and –0.22 ± 0.14 °C in future projections (see Table 2.2 and Figure 2.8b). As expected, the warming due to deforestation is more pronounced in the future, although the range of change in temperature is large and could include negative values (–0.3°C to +2.0°C). For afforestation, the largest cooling effect occurs during the historical period, with temperature changes ranging from –0.2°C to +1.0°C. This suggests that afforestation had a more significant cooling impact historically, likely due to greater vegetation cover. By contrast, in future scenarios, elevated levels of atmospheric CO_2 and altered radiation balances may diminish the cooling effects of afforestation.

Table 2.2: Regional averages of surface air temperature (°C) and precipitation (mm/day) responses under different LULCC scenarios based on model outputs. The table shows the regional average, 95% Confidence Interval (95% CI), and maximum and minimum responses calculated from different individual model simulations. The regional mean significance at the 0.05 level was calculated using the rank-based non-parametric Mann–Whitney–Wilcoxon (MWW) test.

Temperature response (°C)							
Period	**LCC scenarios**	**Mean**	**(95% CI)**	**p-value**	**Max**	**Min**	**Entries**
Historical	Deforestation	0.26	0.12	< 0.05	2	–0.3	14 [1,3 -7,11,19,20,21,24]
	Afforestation	–0.24	0.14	< 0.05	0.18	–3	6 [1,4,14,15,17,23]
Future	Deforestation	0.88	0.25	< 0.05	3.4	–0.3	4 [2,12,16,22]
	Afforestation	–0.22	0.14	< 0.05	0.4	–1.48	3 [8,10,13]
Precipitation response (mm/day)							
Historical	Deforestation	–0.13	0.08	< 0.05	0.5	–2.5	16 [1,3-7,11,18-21,24,25]
	Afforestation	0.55	0.34	< 0.05	4.1	–0.05	6 [1,4,14,15,17,23]
Future	Deforestation	–0.15	0.28	> 0.05	2.1	–5	4 [2,12,16,22]
	Afforestation	0.22	0.16	< 0.05	1.8	–0.18	4 [8,9,10,13]

[1] (Glotfelty et al., 2021); [2] (Abiodun et al., 2007); [3] (G. Wang et al., 2015); [4] (A. Chukwudi et al., 2021); [5] (Boone et al., 2016); [6] (Achugbu et al., 2022); [7] (Sy et al., 2017); [8] (Oguntunde et al., 2012); [9] (Odoulami et al., 2018); [10] (Babatunde et al., 2012) ; [11] (Zheng & Eltahir, 1997) ; [12] (Abiodun et al., 2013); [13] (Diasso & Abiodun, 2017), [14] (Diba et al., 2018); [15] (Diba et al., 2016); [16] (Ji et al., 2018); [17] (A. Bamba et al., 2019); [18] (Charney, 1975); [19] (Sylla, Pal, et al., 2015); [20] (Chilukoti & Xue, 2020); [21] (Mortey et al., 2023); [22] (Sy and Quesada, 2020); [23] (Smiatek & Kunstmann, 2023); [24] (Crook et al., 2023); [25] (Duku & Hein, 2021)

2.7 Simulated precipitation responses

Figure 2.8c shows the responses of precipitation (mm/year) to deforestation and afforestation scenarios, comparable to the temperature patterns observed in Figure 2.8b. Deforestation consistently led to regional decreases in precipitation in both the historical and future periods. Specifically, historical deforestation reduced precipitation by -0.13 ± 0.08 mm/day (–47.45 ± 29.2 mm/year), while future projections show a slightly larger reduction of –0.15 ± 0.28 mm/day (–54.75 ± 102.2 mm/year) (see Table 2.2 and Figure 2c). Conversely, afforestation led to regional increases in precipitation of +0.55 ± 0.34 mm/day (200 ± 124 mm/year) in the historical period and +1.74 ± 1.43 mm/day (635 ± 521 mm/year) in the future scenarios. As expected, both deforestation and afforestation impacts increased in the future projections, but with considerable variability between model results.

Deforestation projections included potential wetting effects, albeit with a large range in precipitation changes from –450 to +500 mm/year, while afforestation results included potential drying effects, again with a large model response's spread from –75 to +250 mm/year (Figure 2c).

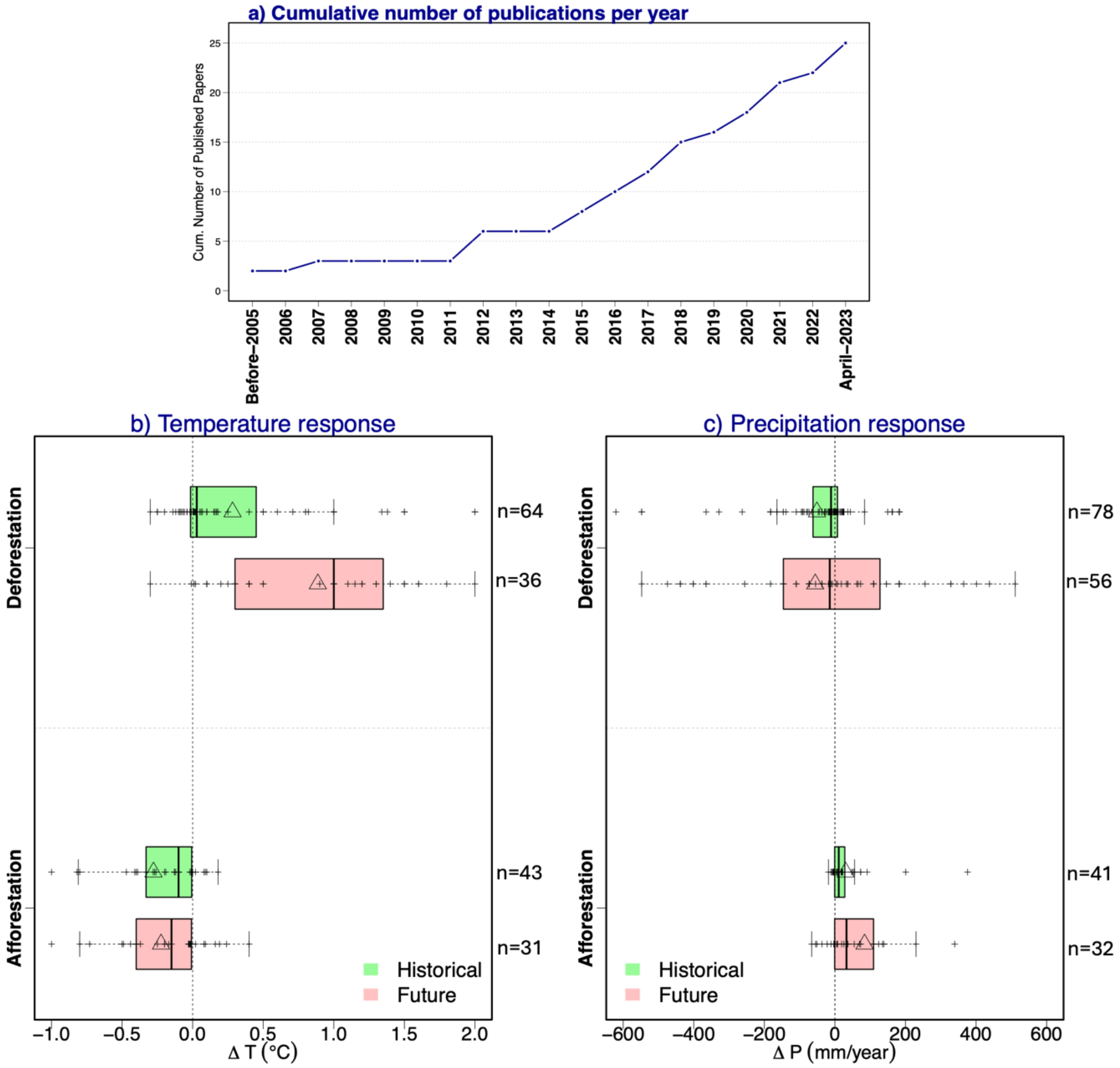


Figure 2.8: a) Cumulative number of publications per year (from January 1975 to April 2023) focusing on LULCC impact in West Africa. b) Biophysical effects of LULCC (deforestation and afforestation scenarios) on surface air temperature (°C) b) and precipitation (mm/day) (c). The boxplots show the distribution of individual model temperature and precipitation responses to LULCC scenarios. The triangle indicates the multi-model ensemble mean (i.e., the average of results from different individual models), and (n) represents the number of model simulations. The median of the multi-

model ensemble is marked with a black line; the lower hinge of each box represents the first quartile (Q1, 25th percentile), and the upper hinge represents the third quartile (Q3). The bars indicate the maximum and minimum values, with individual model responses beyond the whiskers plotted as black circles. Green and red boxplots represent model responses over different simulation periods (historical and future).

2.8 Comparison with other tropical studies

According to the Special Report on CC and Land (IPCC-SRCCL, 2019), there is *a high confidence* that large-scale tropical deforested areas are warmer than surrounding non-deforested zones. After a pantropical deforestation experiment, a significant mean biophysical warming of +0.61 ±0.48°C is found when averaged over the entire tropics (n=18 simulations across 15 studies). Perugini et al., (2017), integrating more tropical subregional studies, found a very similar significant biophysical warming of 0.60 ±0.26°C over the tropical zones (n=34 simulations across 12 studies). In West Africa, our quantitative review indicates a smaller warming response of +0.26 ± 0.12°C likely due to the relatively small extent of deforestation simulated in this region, as discussed by Sy et al. (2017). However, projected future deforestation shows a much larger warming response of +0.88 ± 0.25°C, probably due to more drastic land-cover changes and more sensitive models. We found that the evapotranspiration reduction is the leading driver (see Figure 2.9), largely outdoing the albedo-cooling effect in response to tropical deforestation, as commonly reported in the literature both for models and observation-based outputs (Jia et al., 2019; Perugini et al., 2017).

Moreover, large-scale tropical deforestation results in a significant mean rainfall decrease, as confirmed by the overwhelming majority of studies, both observational and modeling results (Lawrence and Vandecar, 2015; Perugini et al., 2017; Spracklen et al., 2018; Sy and Quesada, 2020). This is consistent with our West African study: West African deforestation results in a rainfall decrease on average (Table 2.2 and Figure 2.8c). Perugini et al. (2017) reported a mean simulated decrease of –288 ± 110 mm/year (95% confidence interval) for tropical studies (n=42 simulations), while our results indicate a –47 to –55 mm/year, a much lower number than most tropical modelling studies. Furthermore, based on observational satellite-based methodology, local reductions in precipitation ranged from -115 ± 86 mm/year in South East Asia to -55 ± 28 mm/year in the Amazon and -50 ± 45 mm/year in the Congo for a comparable

20% historical deforestation (Smith et al., 2023). This last value in Africa is coherent with the modelling studies found in West Africa (Figure 2c). Given a 2200 mm/year annual mean rainfall/precipitation over the Amazon basin, across all simulations (n=96), the average change in annual mean Amazon basin rainfall/precipitation induced by historical deforestation was −264 ± 242 mm/year (Spracklen and Garcia-Carreras, 2015), a much higher estimate than the observational-based estimates. However, it is worth noting that observation-based estimates account for fewer deforestation impacts than model-based ones: the space-for-time assumption does not consider remote impacts of deforested pixels, trends in global climate change partly induced by land cover changes, or slight hydroclimatic dynamic differences between neighbouring pixels (though the assumption of a common background climate is made for distance) (Chen and Dirmeyer, 2020; Quesada et al., 2017; Sy and Quesada, 2020).

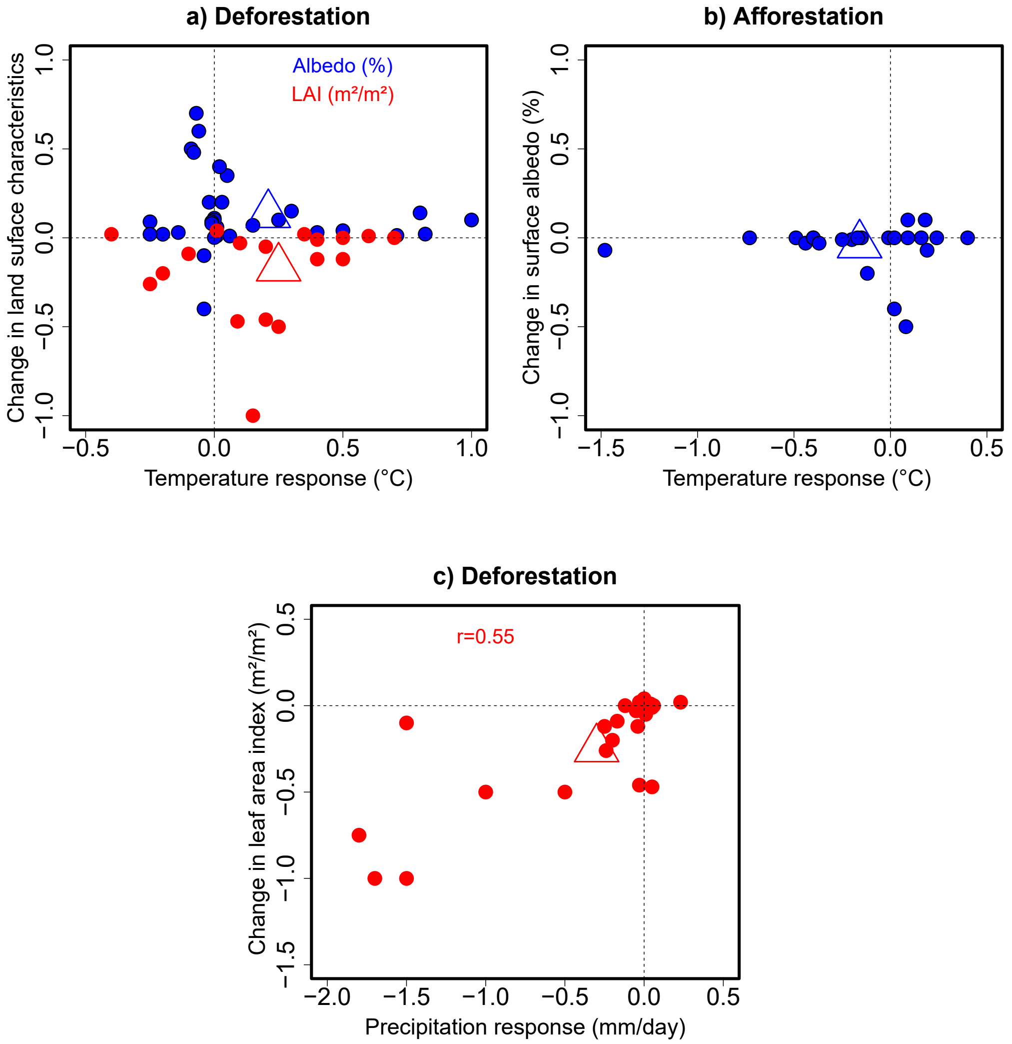


Figure 2.9: LULCC-induced changes in the simulated leaf area index (m²/m², in red) and surface albedo (%, in blue) plotted against changes in temperature (°C; top panels) and precipitation (mm/day; bottom panel) under different LULCC scenarios. Symbols represent individual model simulation results. The Mann-Kendall rank correlation (r) between changes in LAI and changes in precipitation (mm/day; bottom panel) is provided. The triangle symbols indicate the multi-model ensemble mean (i.e., the average of results from different individual models).

2.9 Land-based solution options for climate change in West Africa

2.9.1 Integrating agriculture, forestry, and carbon sequestration

Integrating agriculture, forestry, and carbon sequestration in West Africa offers promising solutions for climate mitigation and sustainable LULCC management. Agroforestry practices, which combine crops with tree planting, are particularly effective for enhancing soil health and sequestering carbon. Agroforestry can capture up to 3 tons of carbon per hectare annually while improving biodiversity and agricultural productivity (Lal, 2019; Nair et al., 2022). These practices are vital in West Africa, where land degradation and food security remain critical concerns. Sustainable forestry integrated with agriculture also boosts carbon sequestration. For example, afforestation and reforestation initiatives have been shown to increase carbon sinks while preventing soil erosion and conserving water resources (Mercer & Gregg, 2024; Nave et al., 2018). In West Africa, these initiatives not only capture carbon but also protect against desertification, particularly in the Sahel region, which is highly vulnerable to land degradation (Diop et al., 2022). Policy frameworks like the GGW and REDD+ are essential for promoting the integration of forestry, agriculture, and carbon sequestration. These initiatives provide financial incentives for sustainable land management, helping to sequester millions of tons of CO_2 while restoring degraded lands (Pancholi et al., 2023; The World Bank et al., 2011; Turner et al., 2021). However, achieving widespread adoption of these practices in West Africa requires greater support in terms of funding, monitoring, and capacity building.

2.9.2 Planting trees as key helpers to help mitigate regional warming and drying

Simulation results due to large-scale afforestation, albeit few (less or equal to 6 outputs per scenario, see Figure 2bc), indicate substantial cooling and wetting. The biophysical cooling found approx. -0.2°C in response to large-scale afforestation can moderately mitigate the regional West African warming of 0.2°C per decade approximately (1970-2014, Iyakaremye et al., 2021)), without even accounting for the biogeochemical effect (Bonan, 2008). Moreover, our results indicate that the regional rainfall increase by 80-200 mm/year in response to large-scale reforestation or afforestation may compensate for the rainfall amount loss from significant recent drying trends in countries of West Africa like Guinea, Liberia, Ghana, or Ivory (Tano et al., 2023).

2.9.3 Restoring ecosystems, enhancing adaptation and resilience in West Africa

Ecosystem restoration can help address the degradation of arid lands and deforestation, particularly in the Sahel region. Initiatives like the Great GGW aim to restore 100 million hectares of degraded land across the continent by 2030, boosting biodiversity, microclimate creation and food security (Bado et al., 2016; UNCCD, 2020). By enhancing soil fertility and water retention, these efforts can increase agricultural productivity, contributing to the livelihoods of millions of people (Chomba et al., 2020; Larbi et al., 2020). Enhancing climate adaptation through ecosystem restoration is critical for improving resilience, adaptation and mitigation against extreme weather events. Restored ecosystems provide essential services such as regulating local climates and acting as natural buffers against floods and droughts, which are becoming more frequent due to CC (IPCC, 2018). For example, mangrove restoration along West Africa's coastal regions helps to protect communities from storm surges and rising sea levels while supporting fish populations that many depend on for their livelihoods (Blankespoor et al., 2017). Ecosystem restoration also plays a role in enhancing long-term resilience by fostering biodiversity and strengthening communities' capacity to adapt to climate fluctuation. Diverse ecosystems are more resilient to external shocks, helping to reduce vulnerability to natural disasters (Nsikani et al., 2023; Sinare & Gordon, 2015). In West Africa, initiatives combining reforestation, agroforestry, and sustainable land management practices can significantly contribute to adaptation strategies, allowing local communities to maintain sustainable livelihoods even in changing environmental conditions (Bado et al., 2016; Weston et al., 2015).

2.10 Model-based LULCC studies in West Africa

The earliest study found in the literature review was from Charney (1975). The recent interest is likely driven by several factors, including: (i) the region becoming a focal point in debates over the biophysical impacts of desertification and deforestation since Charney's (1975) theory on the dynamics of deserts and droughts in the Sahel (Charney, 1975; Fuller & Ottke, 2002; Zheng & Eltahir, 1997); (ii) the rapidly growing population, which has approximately doubled in the past 50 years and is projected to double again by the mid-21st century (Van Bavel, 2013), leading to significant landscape pressure, intensive anthropogenic LULCC, and agricultural intensification (Bliefernicht et al., 2018; Potapov et al., 2022; Sy et al., 2017); and (iii) regional reforestation/afforestation projects implemented over the last decade, such as the large-scale GGW initiative proposed and initiated in West Africa to mitigate regional climate impacts (Ingrosso & Pausata, 2024; Smiatek & Kunstmann, 2023).

Land-based modeling in West Africa has become increasingly sophisticated, with recent advances improving our understanding of regional climate dynamics. For instance, high-resolution satellite data have enhanced the accuracy of vegetation and soil moisture simulations, crucial for predicting agricultural outcomes, climate change assessment and water availability (Camara et al., 2022; Hipt et al., 2018). Additionally, updated land surface models now incorporate more detailed topographic and land use and land cover data, offering finer-scale insights into environmental changes and their impacts (Ifeanyi C. Achugbu et al., 2020). Recent advancements in land surface modeling have provided new insights into the impact of climate variability on West African ecosystems (Glotfelty et al., 2021). The integration of dynamic vegetation models with high-resolution climate projections has revealed significant shifts in vegetation zones and seasonal patterns (Mehboob et al., 2020). Furthermore, enhanced modeling techniques are now better at capturing the interplay between LULCC and hydrological cycles, which is important for managing water resources and mitigating climate impacts (Camara et al., 2022; A. I. Chukwudi et al., 2024). The focus of these modeling (fully coupled land surface and climate models) in West Africa is increasingly addressing the challenges posed by CC effects, extreme climate events and land degradation. Recent studies emphasize the need for improved model parameterisation to better capture the effects of droughts and floods on land surface processes (Silué et al., 2024). Integrating socio-economic factors into Earth system models is proving vital for developing adaptive strategies that enhance resilience to CC and support sustainable land management practices (Palazzo et al., 2016).

2.11 Challenges, uncertainties and limitations in land-based modeling studies in West Africa

2.11.1 Challenges

Land-based modeling in West Africa faces significant challenges due to the region's complex and variable climate, vegetation and land use/land cover. One critical issue is the accurate representation of soil moisture and heat flux, which is essential for predicting rainfall and drought patterns. Recent studies show that current models struggle with capturing soil-atmosphere interactions due to heterogeneity in soil types and vegetation cover, leading to discrepancies in simulating extreme weather events (Ifeanyi C. Achugbu et al., 2020; Dembele et al., 2020; Poan et al., 2016; Prestele et al., 2017). Moreover, the lack of high-resolution climate data exacerbates this issue, as models rely on coarse datasets that fail to determine the spatial variability of land surface properties across West Africa (Oluwagbemi et al., 2022).

Additionally, the performance of Land Surface Models (LSMs) in West Africa is hampered by the limitations of climate models, in modeling land cover (canopy structures) and their impact on water, carbon, and energy exchanges (Mortey et al., 2023). Traditional models, which often use simplified two-layer schemes, inadequately capture the complex dynamics within dense tropical forests, leading to errors in simulating evapotranspiration rates and carbon cycling (Jung et al., 2019). Improved approaches, such as multi-layer schemes, are emerging but require enhanced datasets and computational resources, which are not yet widely available across the region (Ifeanyi C. Achugbu et al., 2020). This highlights the need for continued refinement of LSMs and increased investment in data collection infrastructure across West Africa.

2.11.2 Uncertainties and limitations in simulated temperature responses to LULCC

Various LULCC-induced compensating phenomena simulated differently across model simulations can influence the magnitude and direction of temperature responses. These include the following.

i) Local/regional physical mechanisms, such as changes driven by albedo-induced cooling effects versus evapotranspiration-induced warming effects (Sy et al., 2024; Sy & Quesada, 2020). Also, there are regional responses, like local/regional deforestation, compared to LULCC in other regions.

ii) Variability in how models handle non-local effects (L. Chen & Dirmeyer, 2016; Hirsch et al., 2014; Pang et al., 2022; Winckler et al., 2017). For instance, deforestation in one region can influence climate patterns in another, but the extent and nature of these influences can differ significantly between models.

iii) Model resolution can affect the simulation of temperature changes, with Regional Climate Models (RCMs) often showing more pronounced effects compared to Global Climate Models (GCMs) (Lenderink et al., 2007). This difference is likely due to RCMs' ability to capture finer-scale biophysical effects of LULCC that GCMs may miss. However, this increased resolution can also introduce additional uncertainties related to local processes that are less critical at the global scale.

Noteworthy is that each model incorporates its own set of assumptions, parameterizations, and simplifications (Rounsevell et al., 2014). These include how LULCC information and crop phenology are represented in LSMs (Boisier et al., 2012; Pitman et al., 2009; Sy et al., 2017; Sy & Quesada, 2020), the methods used to integrate LULCC into the background land cover, and the datasets employed to characterize current or potential natural vegetation (De Noblet-Ducoudré et al., 2012). These can influence both the magnitude and effectiveness of the energy fluxes exchanged between the surface and the atmosphere (Rounsevell et al., 2014; Sy et al., 2017). Glotfelty et al., (2021) highlighted that uncertainties in temperature responses to LULCC could arise from inaccuracies in the default LSMs, leading to inconsistent localized temperature changes influenced by the sensitivity of evapotranspiration to LULCC. According to Boone et al., (2016), the magnitude of LULCC impacts may also depend on model-dependent coupling strength between the surface and the overlying atmosphere, the extent of surface biophysical changes (e.g., surface albedo, leaf area index, roughness), and how key processes linking the surface with the atmosphere are parameterized within a particular model framework. Sy et al., (2017) found similar results. They emphasized that the magnitude of LULCC effects can also depend on the prescribed LULCC extent, the representation of coupling strength between climate and LAI, and the lack of interactive LAI in some models.

On the other hand, temperature responses to afforestation are also influenced by various physical mechanisms (Ingrosso & Pausata, 2024; Smiatek & Kunstmann, 2023; Sy et al., 2024), which may be simulated differently across models. These mechanisms include: i) forest transpiration-driven cooling effects. Afforestation increases canopy foliage, which boosts plant transpiration. This process involves water uptake by plant roots and its release as water vapor through the leaves (Bonan, 2008). The enhanced transpiration can lead to significant cooling effects, although the extent of cooling can vary depending on the type of forest; for instance, evergreen forests may exhibit different transpiration rates compared to savannas (Sy et al., 2024); ii) albedo-driven warming effects, forested areas typically have a lower albedo than open land or grasslands, meaning they absorb more solar radiation (Bonan, 2008). This absorption can result in daytime warming. Additionally, increased canopy cover can lead to higher relative humidity, which may trap more heat during the night, reducing nocturnal cooling (Ingrosso and Pausata, 2024). This dual effect - i.e., more heat absorption during the day and less heat release at night - can lead to an overall warming effect; iii) afforestation can also be associated with soil evaporation reduction due to the increased canopy foliage (Sy et al., 2024). The dense forest cover shields the soil from direct sunlight and reduces surface wind speeds, both of which contribute to lower evaporation rates from the soil. While this reduction in soil evaporation can lead to less cooling from the soil surface, it is often compensated by the cooling effects of enhanced forest transpiration (Sy et al., 2024). This balance between reduced soil evaporation and increased transpiration can vary across different model simulations depending on the afforestation experiment (Ingrosso and Pausata, 2024). Different climate models may emphasize these mechanisms to varying degrees based on their parameterizations and assumptions, leading to different simulated temperature responses (Boone et al., 2016; Glotfelty et al., 2021; Sy et al., 2017). Finally, recent simulations from studies published after 2018 generally show lower climate sensitivity than those from studies published before 2017 (Figure 2.10).

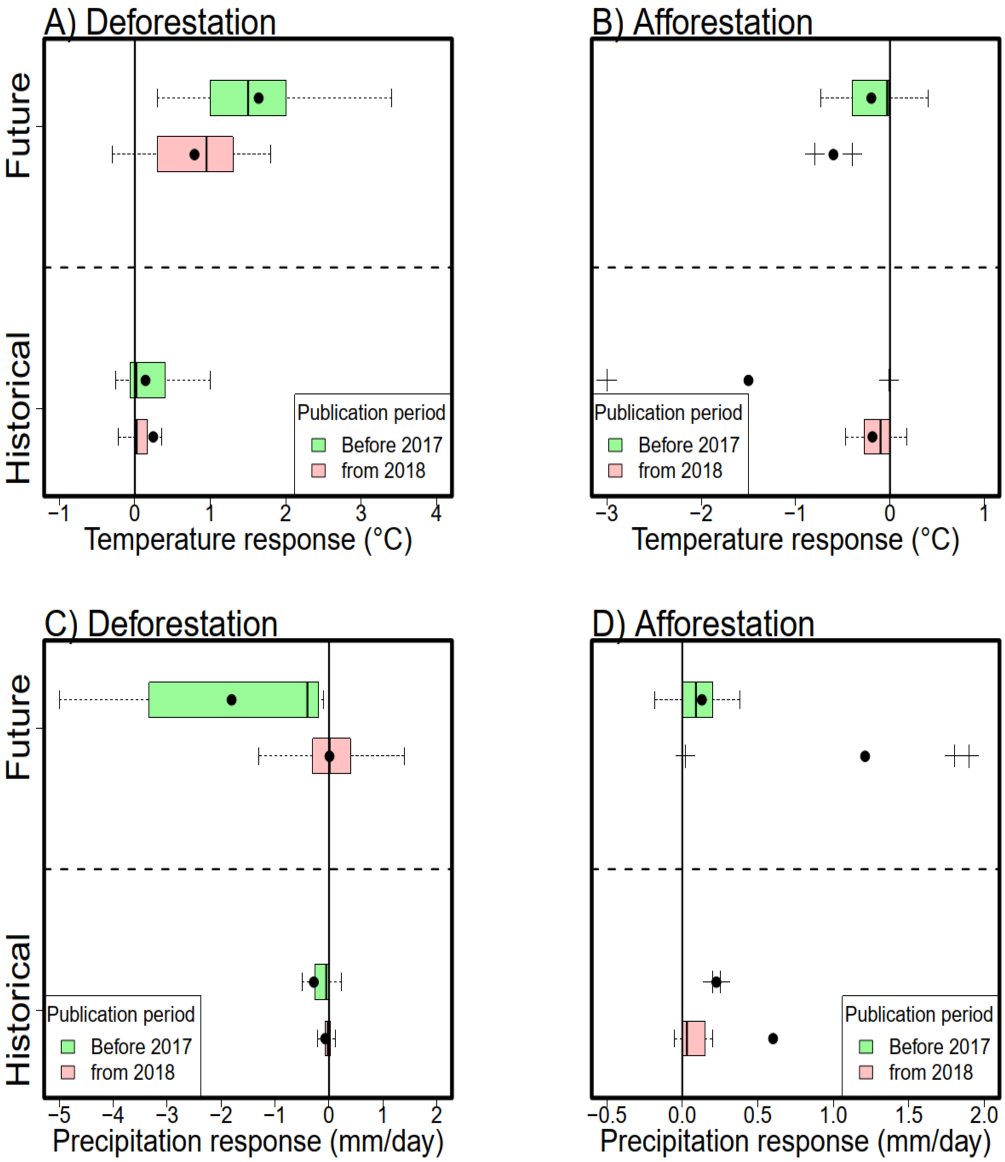


Figure 2.10: Simulated LCC-induced temperature (°C) and precipitation (mm/day) responses based on model outputs from papers published before 2017 (in light green) and those published after 2018 (in light red) for both deforestation (A, C) and afforestation (B, D) scenarios

2.11.3 Uncertainties and limitations in simulated precipitation responses to LULCC

Uncertainties in simulated precipitation responses to LULCC can be attributed to primary mechanisms related to changes in evapotranspiration and moisture availability (Boone et al., 2016; Ingrosso and Pausata, 2024; IPCC-SRCCL, 2019; Perugini et al., 2017; Quesada et al., 2017; Seneviratne et al., 2010). However, different climate models use varying parameterization schemes for key processes affecting precipitation, such as convection, cloud formation, and precipitation dynamics. These variations can cause significant differences in simulated precipitation responses to LULCC (Boone et al., 2016). Glotfelty et al., (2021) attribute differences in precipitation response to LULCC among LSMs to a possible underrepresentation of moisture recycling in atmospheric model configurations. This underrepresentation can result in insufficient moisture convergence or inadequate activation of the cumulus parameterization, leading to excess water vapour forming cloud cover instead of precipitation (G. Wang et al., 2016). (Boone et al., 2016) found that discrepancies in precipitation response can also be linked to how the African Easterly Jet is represented, including shifts equatorward and variations in the strength of these shifts among models.

Second, the interaction between land surface properties and the land atmosphere is complex, and its representation varies widely across different models (Sy et al., 2017). Differences in how land-atmosphere exchanges, such as heat and moisture fluxes, are modelled can lead to discrepancies in simulated precipitation responses (De Noblet-Ducoudré et al., 2012; Pitman et al., 2009). For instance, the net effect on total evaporation due to LULCC is uncertain because different models balance evaporative responses with net radiation changes in various ways (Pitman et al., 2009). This uncertainty may depend on how models represent complex vegetation-atmosphere interactions, the strength of land-atmosphere coupling, and vegetation parameterization in different LSMs (De Noblet-Ducoudré et al., 2012; Koster et al., 2006; Pitman et al., 2009; Rounsevell et al., 2014; Sy et al., 2017). Moreover, feedback processes between LULCC and climate, as well as changes in surface albedo, evapotranspiration, and heat fluxes, can amplify or moderate precipitation changes. Models vary in their representation and sensitivity to these feedback mechanisms, leading to different magnitudes and directions in simulated precipitation responses (Pitman et al., 2009).

Lastly, the model resolutions may also significantly influence their ability to simulate precipitation responses. For instance, global models with coarser resolutions may overlook localized effects of LULCC due to simplified representations of small-scale processes, as discussed by Ingrosso and Pausata, (2024). However, although high-resolution regional models can capture these effects more precisely, they may still face challenges in simulating small-scale precipitation changes resulting from LULCC (Achugbu et al., 2023; Glotfelty et al., 2021).

2.12 Exploring future directions in regional land-based modeling

The future of regional land-based modeling is moving towards incorporating higher details and finer-resolution data to improve predictions of earth and climate interactions (Maréchaux et al., 2021). For example, advancements in land surface modeling and satellite-derived data allow for more detailed characterization of land surface properties and land-use and land-cover classifications, enabling models to capture local variations in ecosystems and LULCC better (Blyth et al., 2021). This approach enhances the capacity to simulate how regional ecosystems respond to climate variability or how regional climate variables respond to LULCC, especially in regions prone to extreme weather events, such as droughts and floods (Chang et al., 2020).

Another key future direction is integrating human and natural systems to simulate how land-use policies and socioeconomic changes will impact ecosystem and climate variables. New models are increasingly considering factors such as urbanization, agricultural expansion, and population growth, alongside natural processes, to offer comprehensive predictions under different policy and land cover scenarios (Blyth et al., 2021; Fisher & Koven, 2020). Including these socioeconomic factors will enable models to assist legislators in determining the long-term viability of land-use policies and weigh the trade-offs between economic growth and preservation efforts (Abbasnezhad et al., 2023).

CHAPTER 3: STUDY AREA AND METHODOLOGY

3.1 Climate overview of the study area

The West African Sahel experiences a semi-arid climate, marked by significant rainfall variability, with the majority of precipitation occurring during a single wet season between June and September(Nicholson, 2013). The region's monsoonal rains are controlled by the Intertropical Convergence Zone (ITCZ), which moves northward during the wet season (Biasutti, 2019). Average yearly rainfall in the Sahel varies between 100 and 600 mm, with amounts decreasing as you move from south to north (Frappart et al., 2009; Satgé et al., 2020). Making it one of the driest regions in the world (IPCC-SRCCL, 2019). Rainfall variability is shaped by local factors like LULCC as well as global climate influences such as the El Niño-Southern Oscillation (ENSO) (Monerie et al., 2020). The region has faced severe droughts, particularly during the late 20th century when a marked decrease in rainfall adversely affected agriculture and livelihoods (Nicholson, 2013b). For example, regions with greater vegetation cover generally experience lower surface temperatures because of the cooling effects of evapotranspiration (Diba et al., 2019). In contrast, bare soil or urban areas can undergo considerable warming due to higher heat absorption and decreased moisture levels (Offerle et al., 2005). Furthermore, the region's vulnerability to CC has intensified the risks of drought and food insecurity, further aggravating pre-existing socio-economic challenges (Ayantunde et al., 2015; Yaro & Hesselberg, 2016).

In the West African Sahel, temperature is affected by a range of land surface physical mechanisms that interact with atmospheric conditions (NourEldeen et al., 2020). The region faces elevated temperatures, frequently surpassing 40 °C during the hottest months, owing to its proximity to the equator and the intensity of solar radiation (Ngoungue Langue et al., 2023). Land surface characteristics, including soil moisture, vegetation cover, and LULCC, are essential for regulating surface temperature and energy exchange (Nicholson, 2000).

Climate projections indicate that the Sahel may face rising temperatures along with shifts in rainfall patterns (Biasutti, 2019). Some research suggests a possible rise in extreme rainfall events, while other studies predict extended droughts and a delayed start to the rainy season, driven by changes in atmospheric circulation patterns (Biasutti, 2019; Monerie et al., 2020). These changes will significantly impact the region's food security, energy and water resources (Sissoko et al., 2011). Adaptation strategies to the changing climate in the Sahel involve adopting sustainable land management practices, promoting agroforestry, and enhancing early warning systems (Goffner et al., 2019; Smiatek & Kunstmann, 2023).

Thus, our focus will be on the Sahelian West African, extending from longitude -15° W to 15° E and latitude 10° N to 17° N, where the extent of LULCC is significantly high, exceeding 45% on average. This is primarily driven by desertification, the effects of CC, population growth, and the expansion of extensive agricultural practices. These factors have contributed to the rapid degradation of land, making the region highly vulnerable to environmental and socio-economic challenges (see Figure 4.1).

3.2 Data and methods used in the systematic review

3.2.1 Search and selection strategy

The eligibility criteria outlined in the PRISMA guidelines were employed to systematically review the peer-reviewed literature on LULCC biophysical impacts over West Africa. PRISMA was primarily designed for systematic reviews of studies evaluating the effects of health interventions (Moher et al., 2009). Nevertheless, it remains widely utilised as a systematic review method in climate impact studies (e.g., Carr et al., 2022; Fiorenza et al., 2023; Harper et al., 2021; Mensah et al., 2022; Petersson-Bloom et al., 2023).

As a preliminary step, the systematic review was conducted to select peer-reviewed scientific articles, books, and book chapters that specifically examine changes in surface air temperature and precipitation resulting from explicit LULCC transition scenarios in West Africa and were published between January 1, 1975, and April 30, 2023. To achieve this, a variety of specific keywords, synonyms, search phrases, and strategies are employed tailored to each database/portal (e.g., Web of Science, Scopus, Google Scholar, and the WASCAL library) to identify relevant studies focusing on biophysical LULCC (deforestation and afforestation) impact on regional climate in West Africa. Due to the sensitivity of search engines and portals to the order of search keywords, a range of keywords for each database source was also utilized.

3.2.2 Selection criteria and data extraction

This study focuses on evidence from studies utilising LULCC model-based outputs at regional or country scales in West Africa. While eddy-covariance flux towers and field experiments can provide local-scale insights into LULCC effects (Bliefernicht et al., 2018), they were excluded from this study due to their limited representativeness at the regional scale. Additionally, the reviewed literature includes only LULCC-modeling-based articles because of data scarcity, limited in-situ measurements, and regional observation-driven assessments in this area. Moreover, this systematic review focused its primary emphasis on surface air temperature and precipitation variables for two significant reasons: (i) they constitute the primary variables of interest for policymakers at both local and regional levels, and (ii) they result as comprehensive indicators of biophysical influences on climate due to their responses to both biophysical radiative and non-radiative effects (Duveiller et al., 2020; Sy et al., 2024). We also focused on modifications of the main biophysical characteristics of the land surface, such as changes in LAI and surface albedo, which ultimately result in changes in energy, moisture, and momentum fluxes (Davin and Noblet-Ducoudre´, 2010; De Noblet-Ducoudré et al., 2012; Sy et al., 2017). An overview of all inclusion and exclusion criteria used for each study is provided in Table 3.1 and Figure 3.1. The selection criteria primarily emphasize studies published in English and cited papers specifically within West Africa. The title and abstract were assessed to determine their relevance to our objectives. Subsequently, we thoroughly reviewed the full papers to extract all quantitative model output results, model types, considered study area, simulation period, published year, and LCC scenarios (see Tables 3.2 and S3 for more details).

Table 3.1: Inclusion and exclusion criteria for the systematic literature review process established to ensure the selection of high-quality and relevant studies. The primary acceptance criteria included studies published in English within high-impact journals and papers specifically focused on West Africa. Rejection criteria were applied to studies that did not meet these standards

Search checkpoints	**Acceptance criteria**	**Rejection criteria**
Initial search	Studies published in English, LULCC, afforestation, deforestation, and climate, scientific articles, book or book chapters, studies focused on the West Africa or West African countries, land surface modelling, climate and LULCC nexus.	Studies published in other languages, no change in climate and land-atmosphere interaction, review, studies that report indicators or parameters other than LULCC change (e.g, deforestation or re/afforestation), studies focused on other regions, sub-region or countries out of West Africa.
Title and abstract screening	Local, country and regional studies in West Africa, focused on land-atmosphere interaction, LULCC modelling studies, biophysical, biogeochemical, climate with quantitative model outputs	No LULCC, studies with qualitative outputs and studies reporting remote sensing experiments, studies reporting non-quantitative model outputs
Full paper review	Original studies published in relevant journals, climate simulation under different LULCC scenarios, climate change under LULCC change vice-versa, Deforestation, Reforestation, Afforestation, Adaptation and mitigation options under different LULCC scenarios, LULCC-climate feedback, model outputs, changes in Temperature or Precipitation due to LULCC induced biophysical factors	Qualitative and quantitative literature review, qualitative description of climate variables changes, non-anthropogenic LULCC impact on climate, adaptation and mitigation options without different LULCC scenarios, lack on details on the methodology and climate input data used to run the model.

Table 3.2: LULCC model-based articles used for the systematic review

Article	Author (Year)	Title
1	(Glotfelty *et al.*, 2021)	Limitations of WRF land surface models for simulating land use and land cover change in Sub-Saharan Africa and development of an improved model (CLM-AF v. 1.0)
2	(Abiodun *et al.*, 2007)	Simulation of West African monsoon using RegCM3 Part II: impacts of deforestation and desertification
3	(Wang *et al.*, 2015)	Modeling the potential contribution of land cover changes to the late twentieth century Sahel drought using a regional climate model: impact of lateral boundary conditions
4	(Chukwudi *et al.*, 2021)	Modeling the spatiotemporal response of dew point temperature, air temperature and rainfall to land use land cover change over West Africa
5	(Boone *et al.*, 2016)	The regional impact of Land-Use Land-cover Change (LULCC) over West Africa from an ensemble of global climate models under the auspices of the WAMME2 project
6	(Achugbu *et al.*, 2023)	The impacts of land use and land cover change on biophysical processes in West Africa using a regional climate model experimental approach
7	(Sy *et al.*, 2017)	Land-Surface Characteristics and Climate in West Africa: Models' Biases and Impacts of Historical Anthropogenically-Induced Deforestation
8	(Babatunde *et al.*, 2012)	Modeling the impacts of reforestation on future climate in West Africa
9	(Odoulami *et al.*, 2018)	Modelling the potential impacts of afforestation on extreme precipitation over West Africa
10	(Abiodun *et al.*, 2013)	Potential impacts of afforestation on climate change and extreme events in Nigeria
11	(Zheng and Eltahir, 1997)	The response to deforestation and desertification in a model of West African monsoons
12	(Diasso and Abiodun, 2017)	Future impacts of global warming and reforestation on drought patterns over West Africa
13	(Diba *et al.*, 2018)	Potential Impacts of Land Cover Change on the Interannual Variability of Rainfall and Surface Temperature over West Africa
14	(Oguntunde *et al.*, 2012)	Modelling the impacts of reforestation on the projected hydro-climatology of Niger River Basin, West Africa
15	(Diba *et al.*, 2016)	Impacts of the Sahel-Sahara Interface Reforestation on West African Climate: Intra-seasonal Variability and Extreme Precipitation Events
16	(Ji *et al.*, 2018)	Potential climate effect of mineral aerosols over West Africa: Part II—contribution of dust and land cover to future climate change
17	(Bamba *et al.*, 2019)	Effect of the African greenbelt position on West African summer climate: a regional climate modeling study
18	(Charney, 1975)	Dynamics of deserts and drought in the Sahel
19	(Sylla *et al.*, 2015)	Impact of land cover characterization on regional climate modeling over West Africa
20	(Chilukoti and Xue, 2020)	An assessment of potential climate impact during 1948–2010 using historical land use land cover change maps
21	(Mortey *et al.*, 2023)	Interactions between Climate and Land Cover Change Over West Africa
22	(Sy and Quesada, 2020)	Anthropogenic land cover change impact on climate extremes during the 21st century
23	(Smiatek and Kunstmann, 2023)	Potential Impact of the Pan-African Great Green Wall on Sahelian Summer Precipitation: A Global Modeling Approach with MPAS
24	(Crook *et al.*, 2023)	Effects on early monsoon rainfall in West Africa due to recent deforestation in a convection-permitting ensemble
25	(Duku and Hein, 2021)	The impact of deforestation on rainfall in Africa: a data-driven assessment

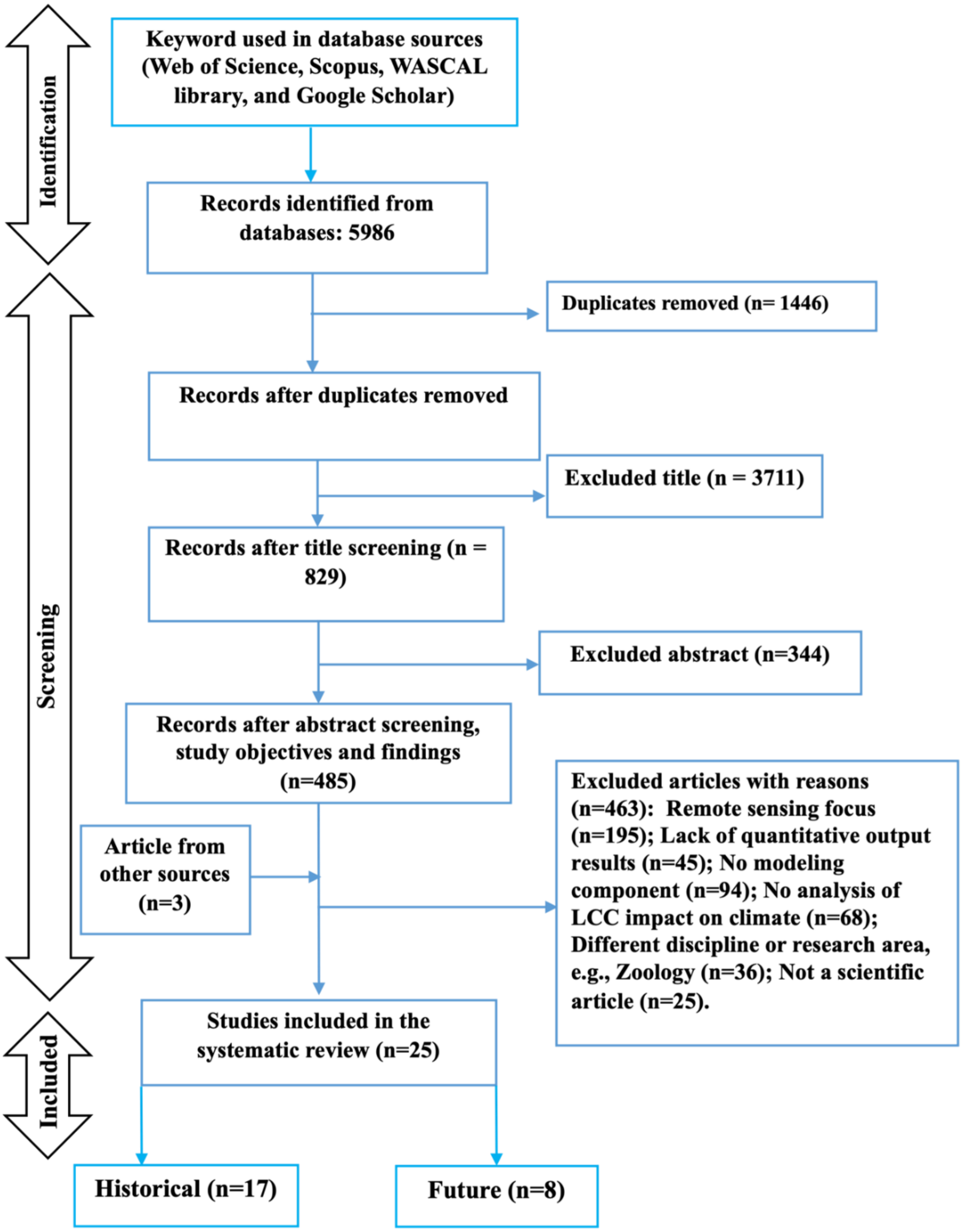


Figure 3.1: Flowchart illustrating the number of articles at each PRISMA manual screening process stage. In the diagram, "n" represents the number of articles. At the final stage, selected articles were classified by model simulation periods rather than publication year, with the number of studies focused on historical (n=17) and future (n=8) climate conditions.

3.2.3 Data screening

The search procedure used several combinations of search keywords pertinent to LULCC model-based investigations. Duplicate articles were removed, and only peer-reviewed and cited English-language articles were included. The systematic review process followed a structured approach for both inclusion and exclusion of articles, as illustrated in Figure 3.1. The initial database search yielded nearly 6000 articles (n=5986). After conducting eligibility screening based on title, research area, and abstract, the number of articles was reduced to 485. Subsequently, some papers were excluded for reasons of unscientific articles or reviews or lack of quantitative data on LULCC impact and/or not a model-based study in West Africa. In the final step, a total of 25 articles remained, from which the data presented in this study were extracted (see Table 3.2). To ensure impartiality, these processes were repeated three times (see Figure 3.1, Table 3.1). Additionally, as shown in Table 3.3, out of the initial 25 articles that passed the data screening and selection criteria, 21 provided model results on changes in surface air temperature, 25 on precipitation, 12 on surface albedo, and 4 on LAI. It is worth noting that among the selected articles, some have investigated the biophysical effects of LULCC using a single model (Achugbu et al., 2022; Wang et al., 2015), while others employed multi-model ensemble simulations (e.g.., 5 GCMs for Boone et al., 2016; 4 RCMs for Glotfelty et al., 2021; and 7 GCMs for Sy et al., 2017), which allows us further to explore the uncertainties and the various mechanisms at play.

Furthermore, modeling studies were categorized under different explicit LULCC scenarios. Specifically, model results were classified into two primary LULCC categories: i) Deforestation scenarios (referred to as "Deforestation"), where total or partial fractions of forest cover are removed or replaced with another land cover type (see Abiodun et al., 2007; Achugbu et al., 2022; Boone et al., 2016; Charney, 1975; Chilukoti and Xue, 2020; Crook et al., 2023; Duku and Hein, 2021; Glotfelty et al., 2021; Idrissou et al., 2022; Ji et al., 2018; Mortey et al., 2023; Obahoundje et al., 2021; Sy et al., 2017; Sy and Quesada, 2020; Wang et al., 2015; Zheng and Eltahir, 1997); ii) Afforestation scenarios (referred to as "Afforestation"), where grassland and/or cropland areas are partially or fully replaced by forest (see Abiodun et al., 2013; Achugbu et al., 2021; Babatunde et al., 2012; Diasso and Abiodun, 2017; Diba et al., 2016; Noulèkoun et al., 2018; Odoulami et al., 2018; Smiatek and Kunstmann, 2023; Sylla et al., 2015), as detailed in Table 3.3.

Table 3.3: Summarized characteristics of the papers investigating changes in surface air temperature (ΔT), precipitation (ΔP), surface albedo (Δ Albedo), and leaf area index (ΔLAI) resulting from different LULCC scenarios in West Africa.

Paper	Variables	Impact scale	Climate models	Land surface models	Simulation periods	LULCC type
(Glotfelty et al., 2021)	ΔT, ΔP, ΔAlb	West Africa	WRF	Noah, Noah-MP, CLM-D, CLM-AF	2010-2015	DEF, AFF
(Abiodun et al., 2007)	ΔT, ΔP, ΔAlb	West Africa	RegCM3	BATS land cover characteristics	2031–2061	DEF
(G. Wang et al., 2015)	ΔT, ΔP, ΔAlb, ΔLAI	West Africa	RegCM4.1, UCLA, CAM5	CLM4	2001–2006	DEF
(A. Chukwudi et al., 2021)	ΔT, ΔP	West Africa	WRF3.9.1.1	Noah-MP	2012	DEF, AFF
(Boone et al., 2016)	ΔT, ΔP, ΔAlb, ΔLAI	West Africa	UCLA-AGCM, UCLA-GFS, UCONN CAM5, GSFC GOES-5, UKMO HadGEM 2-A	SSIB-1, CLM 3.5, CLSM, MOSES	1952–1957	DEF
(Achugbu et al., 2022)	ΔT, ΔP, ΔAlb	West Africa	WRF3.9.1.1	Noah-MP	2011–2012	DEF
(Sy et al., 2017)	ΔT, ΔP, ΔAlb, ΔLAI	West Africa	ARPEGE, CCSM, CCAM, ECEARTH-, ECHAM5, IPSL, SPEEDY	ISBA, CLM, CABLE,TESSEL, JSBACH, ORCHIDEE, LPJmL	1970–1999	DEF
(Oguntunde et al., 2012)	ΔT, ΔP, ΔAlb	West Africa	RegCM3	BATS	2030–2050	AFF
(Odoulami et al., 2018)	ΔP, ΔAlb	West Africa	RegCM 4.3 and WRF	BATS and Noah LSM	2031–2060	AFF
(Babatunde et al., 2012)	ΔT, ΔP, ΔAlb	Nigeria	RegCM3	BATS	2030–2050	AFF
(Zheng & Eltahir, 1997)	ΔT, ΔP	West Africa	zonally-symmetric model	-	1950-1969	DEF
(Abiodun et al., 2013)	ΔT, ΔP	West Africa	RegCM3	BATS	2031–2050	DEF, AFF
(Diasso & Abiodun, 2017)	ΔT, ΔP	West Africa	RegCM4 and WRF3.5.1	BATS1E and MPI-ESM-LR	2031–2060	AFF
(Diba et al., 2018)	ΔT, ΔP	West Africa	RegCM4.5	BATS1E	1990–2009	AFF
(Diba et al., 2016)	ΔT, ΔP	West Africa	RegCM4	BATS1E	2003–2009	AFF
(Ji et al., 2018)	ΔT, ΔP	West Africa	RegCM4.3.4	CLM4.5	2081–2099	DEF
(A. Bamba et al., 2019)	ΔT, ΔP	West Africa	RegCM4.7	BATS	2000–2011	AFF
(Charney, 1975)	ΔP, ΔAlb	West Africa	Hadley circulation	-	1973	DEF
(Sylla, Pal, et al., 2015)	ΔT, ΔP	West Africa	RegCM4.3	CLM3.5	1998–2010	DEF
(Chilukoti & Xue, 2020)	ΔT, ΔP, ΔAlb, ΔLAI	West Africa	GFS	SSiB2	1948–2010	DEF

(Mortey et al., 2023)	ΔT, ΔP	West Africa	GLEAM	ESA CCI LC	1992–2019	DEF
(Sy and Quesada, 2020)	ΔT, ΔP	West Africa	CanESM2, HadGEM2-ES, IPSL- CM5A-LR, MIROC-ESM, MPI-ESM-LR	CTEM, JULES, ORCHIDEE, SEIB-DGVM, JSBACH	2071–2100	DEF
(Smiatek & Kunstmann, 2023)	ΔT, ΔP	West Africa	MPAS7	Noah	1997-2012	AFF
(Crook et al., 2023)	ΔT, ΔP, ΔAlb	West Africa	MetUM	JULES	2014	DEF
(Duku & Hein, 2021)	ΔP	West Africa	-	ConvLSTM	2000-2012	DEF

3.3 Input data sources and brief numerical model description

3.3.1 Input data sources

This study utilised diverse data types and sources to assess the impact of anthropogenic LULCC on mean and extreme weather indices in the Sahel region of West Africa. Thus, various gridded datasets were employed, selected for their distinct temporal and spatial characteristics. The initial conditions and lateral boundaries were constrained using ERA5 data, provided by the European Centre for Medium-Range Weather Forecasts (ECMWF), at a 10 km resolution, incorporating temperature reanalysis data (Hersbach et al., 2020). For precipitation, the Integrated Multi-satellitE Retrievals for GPM (IMERG) product was utilized at a matching 10 km spatial resolution, ensuring consistency in precipitation inputs across the study domain (Zhang, 2018). Furthermore, high-quality Eddy Covariance (EC) data covering the West-Est gradient along the Ghana-Burkinabe border were employed for the model validation, which displays varying intensities of land use/land cover: i) the pristine woody savanna of Nazinga; ii) the agricultural areas of Kayoro and Gorigo, primarily used for cropping and livestock grazing; iv) the recently established rice site in Janga, Ghana, situated south of Bolgatanga; and v) a more recent one situated in Mole National Park.

3.3.2 Brief numerical model description

- **Weather Research and Forecasting (WRF-Only):**

The Weather Research and Forecasting (WRF) model is a modular numerical weather prediction system developed for both operational and research forecasting (Skamarock et al., 2008). The WRF-Only (stand-alone/baseline) model version 4.4 (WRF4.4) was launched in August 2022 (https://www2.mmm.ucar.edu/wrf/users/physics/phys_references.html#CU, (available on 26 November 2022)) (Garcia et al., 2023). Concerning its non-hydrostatic dynamical core, various meteorological phenomena, from large-scale systems to localised convective events, may be accurately simulated (Qi et al., 2018). Because of WRF's highly flexible design, users may tailor the model to various resolutions and physical parameterizations based on their particular research or forecasting requirements (Abedallah, 2018). The model's capacity to replicate intricate atmospheric processes is improved by its support for a variety of physical parameterizations, such as cloud microphysics, boundary layer processes, and surface interactions (Wang & Quiring, 2021). WRF can be used in research mode for long-term climate simulations or in real-time forecasting mode for quick weather predictions (Annor et al., 2018). One of the main advantages of WRF is that it can perform simulations at different spatial resolutions, ranging from tens of kilometres to kilometres, which makes it appropriate for high-resolution research at both the urban and regional levels (B. Yang et al., 2012). Moreover, WRF boasts an extensive and vibrant user base that shares experiences, updates the code, and contributes to the software's ongoing development and improvement (Skamarock et al., 2019). Due to its open-source nature, reliable performance, and flexibility in meeting different research goals, the model has been extensively embraced by academic institutions and meteorological services across the globe (Carvalho et al., 2012). It is particularly valuable for studying the impacts of climate change, LULCC, regional weather patterns, and natural disasters, helping scientists and forecasters make informed decisions (Garcia et al., 2023).

- **Weather Research and Forecasting (WRF-Hydro, hydrological module)**: The WRF-Hydro system is designed to improve the representation of hydrologic processes across scales and improve the prediction of hydrologic conditions, especially in regions where hydrologic modeling is computationally sensitive to errors in forcing data, topographically or hydrologically disconnected landscape elements, or where there are complex hydrologic response dynamics (Cho & Kim, 2022). WRF-Hydro version 5.2 is developed and maintained by a large community of researchers and software developers from various institutions (Gochis et al., 2020). This user guide is intended to both provide a snapshot of WRF-Hydro in early 2020 and to serve as a reference for the system's user community (Wang et al., 2020).

The WRF-Hydro model is a flexible tool developed to support both hydrologic research and operational needs. It can be used for various purposes, such as modeling watersheds, predicting flash floods, studying land-atmosphere interactions, and analysing large-scale hydrologic processes and uncertainties (Sun et al., 2020; W. Wang et al., 2020). The model uses open-source software and is built on a solid framework, which has allowed it to be applied in many different ways, from research to operational modeling projects (Galanaki et al., 2021). Its development and case studies demonstrate the model's typical uses and capabilities. Although WRF-Hydro was originally designed for specific purposes, its features have evolved as the community contributed to its application in diverse forecasting and research efforts (Abbaszadeh et al., 2020).

- **Noah land surface model with Multi-Parameterization (Noah-MP):**

Made possible by the National Centres for Environmental Prediction , the Noah LSM is named after the biblical Noah, regulates the behaviour of vegetation and soil moisture within a 2-meter soil profile divided into four layers and predicts a storm using information about the environment to save all living beings on Earth (C. He et al., 2023; Niu et al., 2011). The model includes detailed physical descriptions of how momentum and energy move between the land and atmosphere, allowing it to simulate the variations in water and energy across the Earth over different spatial, seasonal, and yearly timescales, as shown by various satellite measurements (Döscher et al., 2022).

An essential component of the Earth's system, the land surface significantly influences the water and energy exchange between land and atmosphere . It also serves as a fundamental sub-model in ESMs. LSMs as well as Noah-MP model have gained prominence due to their importance in studying how the land responds to physical and human-induced changes, which carry significant implications for society (Rockström et al., 2023). The performance of these models affects the accuracy of weather and climate forecasts, water resource management and land restoration options, local and regional land-atmosphere interactions, and understanding of the impact of anthropogenic activities on the Earth system (Tebaldi et al., 2021). Accurate representations of land surface processes are critical for creating reliable models. In terrestrial systems, the land component of an ESM, often referred to as the land surface model, simulates interactions between land and atmosphere, such as energy fluxes and the movement of water and carbon (Fisher & Koven, 2020). For some models such as Noah-MP, the most important applications focus on dynamic features of the Earth's surface, such as snow cover, soil moisture, and temperature, and how these interact. Examples of human-related studies that rely on these complex physical-human feedbacks include investigations into animal migration, hydroelectric power, and LULCC (Fan et al., 2021). By incorporating a land surface component, scientists and stakeholders can better explore synergies, assess risks, provide adequate solutions and address observational needs across various timescales (Wulder et al., 2022).

3.4 Research Method

3.4.1 Specific Objective 1: Evaluate the regional effects of LULCC on mean and extreme climate in Sahelian West Africa using a fully coupled WRF-Only-Noah-MP with dynamic vegetation.

3.4.2 Specific Objective 2: Evaluate the sensitivity of both WRF-Only-Noah-MP vs. WRF-Hydro-Noah-MP models to LULCC in Sahelian West Africa

3.4.2.1 Experimental setup

The simulations spanned from January 1st, 2011, to January 1st, 2022, with the first year dedicated to spin-up, allowing the model to stabilise and reach equilibrium before the actual analysis period. These fully coupled simulations were designed to capture the complexities of a specific land use/land cover scenario within the Sahel region of West Africa, a region known for its dynamic climate and ecological variability. The topography, measured in meters above sea level, was integrated into the model to accurately represent the region’s elevation and influence on hydrological processes. This was particularly important for modeling the surface water and energy balances, which plays a crucial role in understanding precipitation and temperature behaviour and land-atmosphere interactions in semi-arid environments. The WRF-Hydro system was used to simulate surface and subsurface hydrological processes, allowing for a comprehensive evaluation of the land surface water balance. Figures 3.2 and 3.3 illustrate respectively the land cover scenario and topographic setup used in the model, ensuring that the physical environment was appropriately represented for hydrological and climate simulations.

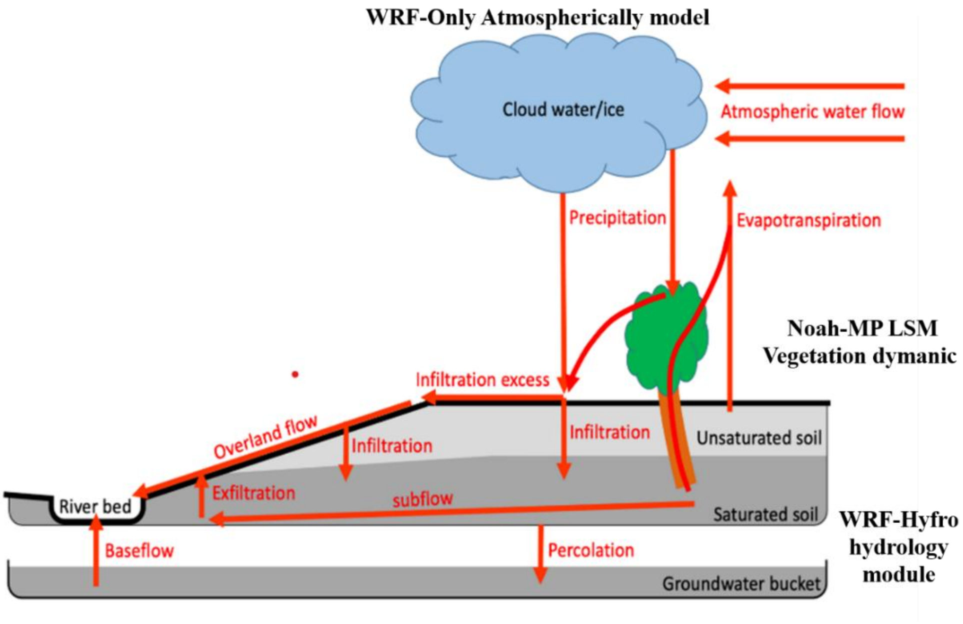


Figure 3.2: Fully coupled system WRF-Only and WRF-Hydro with Noah-MP (climate-vegetation-hydrology) (source, Joel Arnault, UA/KIT., 2024).

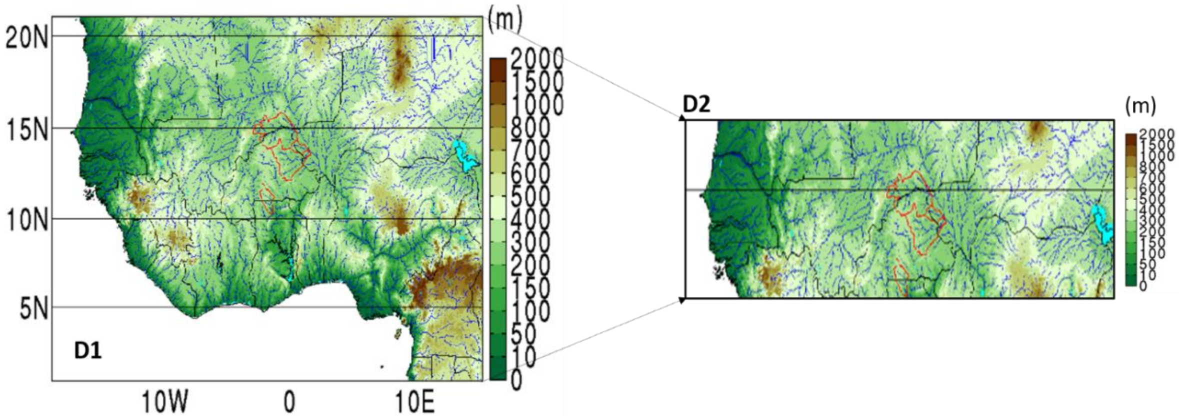
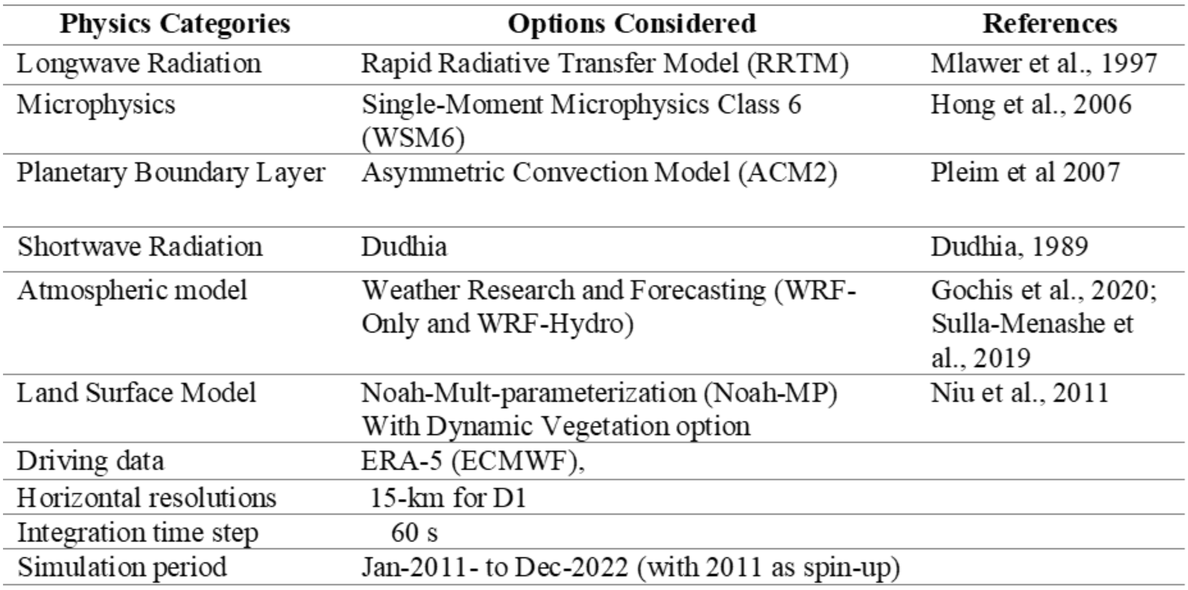


Figure 3.3: Topography (in m above sea level) and groundwater (main river) routing computation (blue curved lines) at 15 km resolution.

First, a control (CTL) experiment made use of the default land cover map produced from the MODIS product MCD12Q1 (version 6.0; Sulla-Menashe et al., 2019), as part of the Weather Research and Forecasting (WRF-Only) model. This reference simulation reflects current conditions using a 2015 land cover map. Based on MODIS land cover classification, the dominant land types in the region were cropland, grassland, and savanna, driven by food demands and land degradation (Figure 3.1).

Secondly, to evaluate the regional effects of LULCC on means climate (temperature and precipitation) and extreme weather indices, a no land use (**NoLCC)** experiment was performed using a pre-industrial land cover map. In this scenario, urban and agricultural areas were replaced with natural vegetation, specifically Tropical Broadleaf Forest, representing the potential natural vegetation that would exist in each grid cell without anthropogenic activities on the landscape (Findell et al., 2017). Therefore, the difference between CTL and NoLCC (CTL minus NoLCC) indicates the biophysical impacts of LULCC. The simulated LULCC fraction between the CTL and NoLCC experiments, averaging around 20% (see Figure 3.1), matches the observed expansion of agricultural land (around 19%; see Potapov et al., 2022) despite challenges, limitations and uncertainties in accurately identifying actual LULCC, in the Sahelian-Sudanian Savanna region of West Africa. In West Africa, where agricultural regions are frequently misclassified, discrepancies in LULCC maps may stem from issues in satellite data collection, processing techniques, extraction methods, and insufficient training datasets. Satellite-based vegetation maps face challenges in accurately depicting land-use changes (Boone et al., 2016; Sy et al., 2017). Additionally, Table 3.1 summarizes all the physical categories and the options considered in our simulation and experimental setup.

Table 3.4: Regional Earth system model development: Experimental setup



Physics Categories	Options Considered	References
Longwave Radiation	Rapid Radiative Transfer Model (RRTM)	Mlawer et al., 1997
Microphysics	Single-Moment Microphysics Class 6 (WSM6)	Hong et al., 2006
Planetary Boundary Layer	Asymmetric Convection Model (ACM2)	Pleim et al 2007
Shortwave Radiation	Dudhia	Dudhia, 1989
Atmospheric model	Weather Research and Forecasting (WRF-Only and WRF-Hydro)	Gochis et al., 2020; Sulla-Menashe et al., 2019
Land Surface Model	Noah-Mult-parameterization (Noah-MP) With Dynamic Vegetation option	Niu et al., 2011
Driving data	ERA-5 (ECMWF),	
Horizontal resolutions	15-km for D1	
Integration time step	60 s	
Simulation period	Jan-2011- to Dec-2022 (with 2011 as spin-up)	

3.4.3 Statistical analysis and extreme indices

3.4.3.1 Statistical analysis

The impact of LULCC on mean and extreme temperature and precipitation indices (refer to Table 3.2) was assessed for the Sahelian region of West Africa. To determine the statistical significance of each simulated change, the Mann-Whitney-Wilcoxon (MWW) test (Wu et al., 2014) was employed, comparing two sets of 11-year simulations (2011–2022): the control scenario (CTL) against the no land cover change scenario (NoLCC). A robust result was defined by a p-value < 0.05 (95% confidence interval) in the MWW test. Both modeling systems, WRF-only and WRF-Hydro, were used to validate the findings. The MWW test was chosen due to its effectiveness with non-normally distributed data, in contrast to the Student's t-test (Kishore & Jaswal, 2022; Sy et al., 2021).

3.4.3.2 Extreme indices

This study focused on the mean temperature and precipitation (Tmean and Pmean), alongside a selection of 10 extreme temperature and precipitation indices, out of a total of 27 defined by the World Meteorological Organization Expert Team on Climate Change Detection and Indices (ETCCDI; https://www.wcrp-climate.org/etccdi). These indices were chosen to offer a comprehensive representation of climate extremes in the Sahelian zone of West Africa. They were derived from daily rainfall, minimum, and maximum temperatures, and were applied to both the CTL and NoLCC simulations. The selection of these 10 extreme weather indices was based on their importance in enhancing understanding of climate extremes, supporting risk assessments, and informing social decision-making processes.

Table 3.5: Description of the 10 temperature and precipitation indices (Tmean, Pmean and 10 ETCCDI extreme indices) with acronyms, names and units.

Index	**Name**	**Description**	**Unit**
TXn	Annual minima of daily maximum temperature	Annual minima value of daily maximum temperature	°C
TNx	Annual maxima of daily minimum temperature	Annual maxima value of daily minimum temperature	°C
TNn	Annual minima of daily minimum temperature	Annual minima value of daily minimum temperature	°C
DTR	Daily temperature range	Monthly mean difference between daily maximum and minimum temperature	°C
TR	Number of tropical nights	Annual count of days when daily minimum temperature > 20 °C	Days
R1mm	Wet days	Annual count when precipitation ≥1 mm	Days
R10mm	Heavy precipitation days	Annual count when precipitation ≥10 mm	Days
R20mm	Very heavy precipitation days	Annual count when precipitation ≥20 mm	Days
CDD	Consecutive dry days	Maximum number of consecutive days when precipitation <1mm	Days
SDII	Simple Daily Intensity Index	Average precipitation amounts on days on wet days ≥ 1mm	mm/day
Tmean	Mean temperature	Mean temperature value	°C
Pmean	Mean precipitation	Mean precipitation value	mm/day

3.4.3.3 Validation of the model and data used

In this study, the extent of regional LULCC fractions in Sahelian West Africa was validated by comparing our simulation results, which show an average change of up to 45% over the past two decades, with the findings of Potapov et al. (2022), which report a comparable change of up to 49% (see Figure 3.4 and Figure 4.1). Moreover, a comprehensive bias assessment was conducted to evaluate the daily mean biases in precipitation and temperature using the Integrated Multi-satellite Retrievals for GPM (IMERG) product for precipitation data and the ERA5-land dataset for temperature data. The assessment involved comparing the simulated values obtained from the WRF (WRF-Only) model against the reference datasets over the specified study period. For precipitation, the analysis revealed an average bias of less than 10% across the entire study region, indicating a relatively close alignment with observed precipitation values. Similarly, the temperature assessment showed that the mean bias was below 0.2 (°C), demonstrating a good correspondence with actual temperature measurements. These findings were visually represented in Figures 3.4 and 3.5, respectively, which illustrate the distribution and magnitude of biases across the study area.

Despite the identified biases in both precipitation and temperature, the overall simulation results indicate that the model remains a robust tool for further research. The existing biases not only highlight the potential limitations of the datasets but also serve as a foundation for model refinement and calibration. By acknowledging these discrepancies, future studies can enhance the predictive capabilities of the model, ultimately leading to improved accuracy and reliability in climate simulations. Consequently, this bias assessment methodology underscores the importance of critical evaluation in regional climate modeling efforts. The findings affirm that, despite the identified biases, the simulation framework can provide valuable insights into climate dynamics and land-atmosphere interactions. Therefore, this research method is deemed suitable for informing ongoing investigations into climate variability, resource management, and regional policy-making.

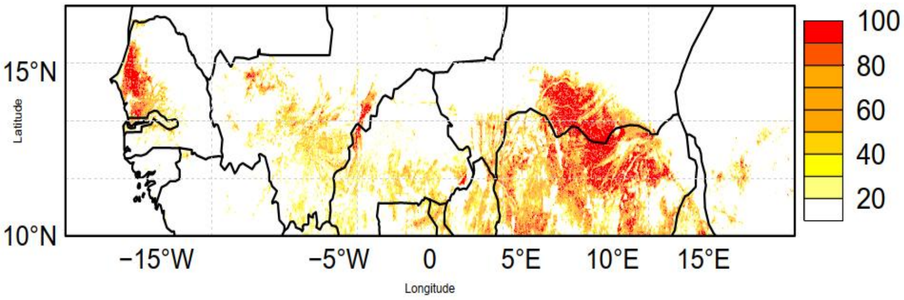


Figure 3.4: Validation of LULCC extent in Sahelian West Africa (Potapov et al., 2022).

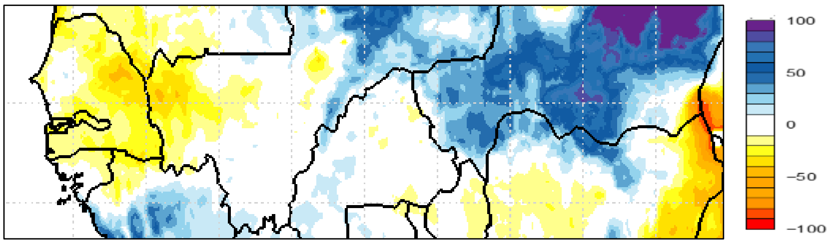


Figure 3.5: Percentage of precipitation daily mean bias (%)

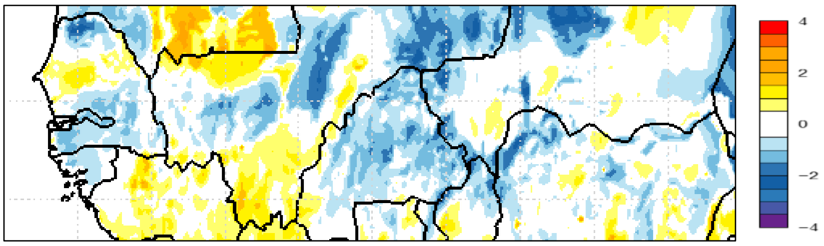


Figure 3.6: Daily temperature mean bias (°C)

3.4.4 Specific Objective 3: Investigate the physical mechanisms driving the surface temperature in response to land use and land cover change

3.4.4.1 Decomposition of Surface Energy Balance

For this specific Objective 3, we focused on the same fully coupled system described in the previous model experimental setup and statistical analysis (WRF-Only-Noah-MP and WRF-Hydro-Noah-MP) to explore the physical mechanisms that influence surface temperature in the West African Sahelian region. This investigation aims to deepen our understanding of the interactions between various environmental factors and their effects on temperature dynamics in this region.

To explore the local biophysical impacts of LULCC on surface temperature, we adopt an energy balance decomposition approach, as used in previous studies (e.g., Ge et al., 2021; Luyssaert et al., 2014; Winckler et al., 2017). This approach allows us to dissect the surface temperature response into distinct contributions from each element of the surface energy balance, such as downward shortwave radiation (ΔDSR), downward longwave radiation (ΔDLR), surface albedo (Δα), sensible heat flux (ΔSH), plant transpiration (ΔEt), canopy evaporation (ΔEc), soil evaporation (ΔEs), and ground heat flux (ΔG). By understanding these individual contributions, we can better pinpoint the mechanisms driving temperature changes due to LULCC and offer insights for climate adaptation and land management strategies. In addition, this method breaks down the surface temperature response to LULCC into contributions from each component of the surface energy balance, as follows:

$$S_{\downarrow}\,(1-\alpha)+L_{\downarrow}-L_{\uparrow}=SH_f\,+\,LH_f\,+\,GH_f \qquad (3.1)$$

$S_{\downarrow}$ represents downward shortwave radiation, $L_{\downarrow}$ and $L_{\uparrow}$ are downward and upward longwave radiations, SH_f and LH_f denote sensible and latent heat fluxes, and GH_fThe ground heat flux (mainly soil heat storage) is all in W.m². Surface albedo (α) represents the ratio of upward to downward shortwave radiation. This is a key factor in determining how much solar energy is reflected by the surface. Utilizing the Stefan-Boltzmann law, the outgoing longwave radiation ($L_{\uparrow}$) can be reformulated as follows:

$$L_{\uparrow} = \varepsilon\sigma Ts^{4} \quad (3.2)$$

In this context, σ denotes the Stefan–Boltzmann constant (5.67×10^{-8} $Wm^{-2}K^{-4}$), ε represents surface emissivity, and Ts is the surface temperature in Kelvin (K). By taking the first-order derivative and rearranging the equations, we can express the surface temperature response to LULCC as follows:

$$\Delta \mathrm{Ts} = \frac{1}{4\varepsilon\sigma \mathrm{Ts}^{3}} (\Delta S_{\downarrow} - \alpha\Delta S_{\downarrow} - S_{\downarrow}\Delta\alpha + \Delta L_{\downarrow} - \Delta SH_{f} - \Delta LH_{f} - \Delta GH_{f}) \quad (3.3)$$

In this context, Δ represents the changes induced by LULCC. To examine the effects of LULCC on plant transpiration, soil evaporation, and canopy evaporation, we break down the latent heat flux (LH_f), which correlates with total evapotranspiration, into its distinct components, as illustrated in Equation 3.4. This decomposition allows us to analyze the specific pathways through which LULCC alters the water cycle, providing insights into its broader impacts on local ecosystems and climate dynamics.

$$\Delta LH_{f} = L\mathrm{Hvap}\,(\Delta \mathrm{Ep} + \Delta \mathrm{Es} + \Delta \mathrm{Ec}) \quad (3.4)$$

In this context, LHvap refers to the latent heat of vaporization (2.260 kJ/kg), while Ep, Es, and Ec represent plant transpiration, soil evaporation, and canopy evaporation, respectively, measured in millimetres (mm). By substituting Equation (3.4) into Equation (3.3), we can express the surface temperature's response to LULCC in the following way:

$$\Delta \mathrm{Ts} = \frac{1}{4\varepsilon\sigma \mathrm{Ts}^{3}} ((1-\alpha)\Delta S_{\downarrow} - S_{\downarrow}\Delta\alpha + \Delta L_{\downarrow} - \Delta SH_{f} - \Delta \mathrm{Ep} - \Delta \mathrm{Es} - \Delta \mathrm{Ec} - \Delta GH_{f}) \quad (3.5)$$

While the energy balance decomposition method does not directly attribute changes to every surface property, including aerodynamic roughness (e,g., Davin & Noblet-Ducoudre, 2010; Li et al., 2016), it provides valuable insights into the relative contributions of each component within the surface energy balance, as outlined in Equation 3.5. This approach allows us to discern how various factors interplay and influence the overall energy dynamics at the surface, contributing to a more comprehensive understanding of the impacts of LULCC.

3.5 Summary of Methods

This research first utilises the PRISMA guideline to systematically review peer-reviewed literature on the biophysical impacts of deforestation and afforestation (LULCC) on West Africa's climate. The review focused on studies utilising LULCC model-based outputs at regional or country scales in West Africa, excluding eddy-covariance (EC) flux towers and field experiments due to their limited representativeness at the regional scale. The review primarily emphasized surface air temperature and precipitation variables as they constitute the primary variables of interest for policymakers and serve as comprehensive indicators of biophysical influences on climate. The study included 25 articles, with 21 providing model results on changes in surface air temperature, 25 on precipitation, 12 on surface albedo, and 4 on LAI. The model's output results were classified into two primary LULCC scenarios: deforestation scenarios, where forest cover is removed or replaced with another land cover type, and afforestation scenarios, where grassland and cropland areas are partially or fully replaced by forest.

Secondly, we employ both a fully coupled WRF-Only-Noah-MP and WRF-Hydro-Noah-MP model (at 15km horizontal resolution) to evaluate the regional impacts of LULCC on mean and extreme climates in West Africa, specifically focusing on the Sahel region. The simulation period spans from January 1st, 2011, to January 1st, 2022, with the initial year (2011) allocated for spin-up to ensure model stability. We focused on 10 extreme temperature and precipitation indices, out of a total of 27 defined by the World Meteorological Organization Expert Team on Climate Change Detection and Indices (ETCCDI). The research integrates topographic data to accurately capture hydrological processes, emphasizing the significance of surface water and energy balances in understanding precipitation and temperature dynamics. A control (**CTL**) experiment using the MODIS land cover map from 2015 reflects current conditions, while a no land cover change (**NoLCC**) scenario replaces urban and agricultural areas with pre-industrial natural vegetation, allowing for a comparative analysis of the biophysical impacts of LULCC. The results indicate a simulated LULCC fraction of around 20% on average, corroborating observed agricultural expansion and population growth despite challenges in accurately identifying LULCC due to misclassification and satellite data limitations. Statistical analysis utilizing the Mann-Whitney-Wilcoxon (MWW, at 95%) test assesses the significance of changes in mean and extreme temperature and precipitation indices. The study also investigates the physical mechanisms behind surface temperature changes in response to LULCC using an energy balance decomposition approach (Stefan–Boltzmann law). This methodology allows for the examination of contributions from various components such as downward shortwave and longwave radiation, surface albedo, and heat fluxes, ultimately enhancing the understanding of LULCC effects on local ecosystems and climate dynamics in the Sahel. By dissecting these interactions, the research provides valuable insights for climate adaptation and informed land management strategies in the context of ongoing environmental changes in West Africa. Furthermore, a bias assessment of daily mean precipitation and temperature using the IMERG product and ERA5-land dataset were conducted. Comparisons of simulated values from WRF-Only model revealed an average precipitation bias of less than 10% and a temperature bias below 0.2°C. Despite these biases, the simulation results indicate that the model is robust for further research. The findings underscore the importance of evaluating biases in climate modeling, providing a foundation for future refinements, and affirming the model's utility in exploring climate dynamics and informing resource management and policy-making in the region.

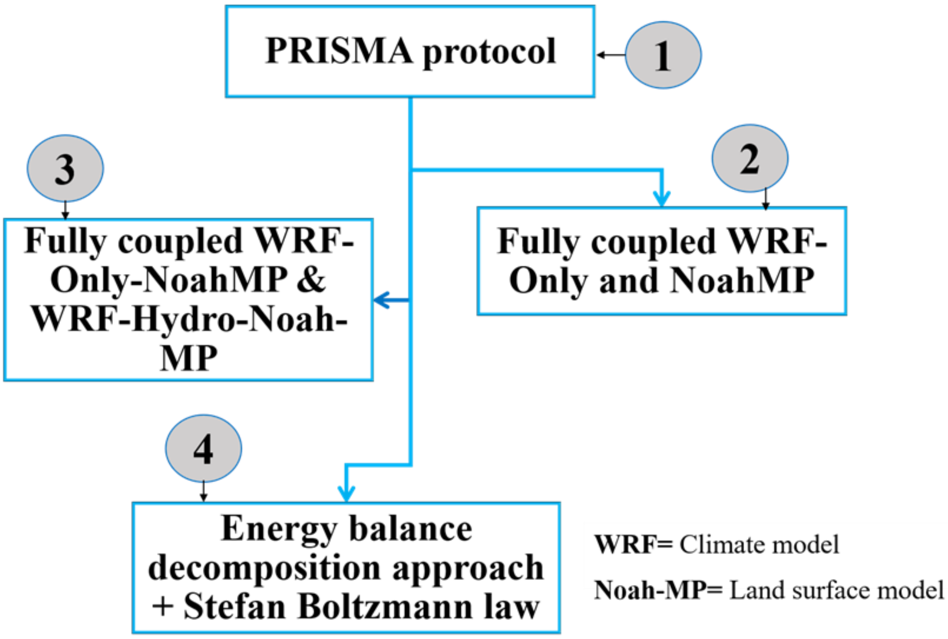


Figure 3.7: Flowchart summarising the methods used for the 4 specific objectives.

RESULTS AND DISCUSSIONS

Chapters 4 to 6 present the results and discussions corresponding to the 3 specific objectives introduced in Chapter 1. A concise introduction along with the sub-objectives is provided. The analytical techniques applied to reach these goals are clarified; next, the outcomes are presented and discussed

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CHAPTER 4: The regional effects of land use and land cover change on mean and extreme climate in West Africa using a fully coupled WRF-Noah-MP with dynamic vegetation.

The focus of Research Objective 1 is to evaluate how LULCC impacts both the average (mean) and extreme climate (temperature and precipitation) conditions in the West African Sahelian region. This evaluation is conducted using the fully coupled WRF-Only-Noah-MP model, which includes dynamic vegetation to capture interactions between land surface changes and climate processes. The aim is to understand the regional climate effects of LULCC in terms of both gradual and extreme weather events.

4.1 Preamble to the regional effects of LULCC on mean and extreme climate in West Africa

LULCC has become a critical factor influencing regional climate dynamics in West Africa (Oguntunde et al., 2012). Understanding the link between LULCC and atmospheric processes is crucial for informing climate change adaptation and mitigation strategies. While previous studies have primarily concentrated on assessing the climatic impacts of deforestation in tropical rainforests and temperature changes in temperate regions, the full range of benefits from conserving or restoring forests can only be appreciated in the context of their specific regional climate (Seddon et al., 2020). Additionally, population growth in West Africa is increasing the strain on traditional land use and management practices. Ecosystem goods and services from altered landscapes, such as croplands, grazing areas, and urban spaces often affect a larger number of people compared to those provided by forests (Spinoni et al., 2021). The sharp rise in greenhouse gas emissions has led to regional warming, with temperature changes being more pronounced at higher latitudes. Extreme climate events have become rather more frequent and intense over the West African Sahel (Marelle et al., 2020). LULCC also significantly impacts rainfall distribution, with some areas experiencing more frequent droughts, while others see intensified rainfall events (Yira et al., 2016). Specifically, the influence of recurrent LULCC such as desertification/deforestation followed by reforestation/afforestation within the semi-arid West African Sahel on climate extremes at the sub-regional level awaits investigation (Erdsystemforschung, 2023). Furthermore, over the past century, West Africa has experienced some of the most extensive and intense human exploitation and degradation of land globally (Flintan et al., 2021).

The present work seeks to help fill both the quantification and description gaps of anthropogenic West African Sahelian region LULCC on the region's climate (temperature and precipitation). The main differences between the present work and some past works are the combination of very high-resolution land use/land cover (Noah-MP) data and the high-resolution regional climate model (WRF-Only) used. Specifically, (i) the regional extent of LULCC fraction between CTL and NoLCC experiment is evaluated, (ii) the spatial response (that shows the most significant) of mean and extreme climate indices to LULCC are identified and analysed. (iii) the regional contribution of LULCC to mean and extreme climate indices is assessed over the West African Sahelian region using a fully coupled RCM (WRF-only, coupled exclusively to Noah-MP) with dynamic vegetation.

4.2 A brief analytical procedure

To simulate how climate means and extreme indices respond to LULCC, we chose to use the coupled WRF system, commonly referred to as "WRF-only". This includes the Weather Research and Forecasting model (WRF, version 4.4; Skamarock et al., 2019)), a well-regarded RCM. Our setup integrates surface and subsurface lateral flow alongside dynamic vegetation descriptions, which allows us to capture the subgrid-scale biophysical effects of LULCC effectively. We ran simulations for a decade (10 years), from January 1st, 2011, to January 1st, 2022, on a single domain (see Figure 3.1). The model operates at a horizontal resolution of 15 km and includes 50 vertical levels, reaching up to 10 hPa. The initial conditions and lateral boundaries for our simulations were informed by ERA5 reanalysis data provided by ECMWF (Hersbach et al., 2020). The WRF-only model was coupled with the Noah-MP LSM, which incorporates dynamic vegetation and offers multiple physics options, what we refer to as "multi-parameterization." This flexibility allows for varied representations of land surface processes (Liu et al., 2022; Salamanca et al., 2018). Two main experiments were conducted. First, we established a control (CTL) experiment using the default land cover map from the MODIS product MCD12Q1 (version 6.0; Sulla-Menashe et al., 2019) as a reference for current conditions. Second, we ran a no-land use (NoLCC) experiment using a pre-industrial land cover map. In this setup, urban and agricultural areas were replaced with potential natural vegetation, reflecting what would exist in each grid cell without human influence (Findell et al., 2017). The comparison between CTL and NoLCC simulations (CTL minus NoLCC) reveals the biophysical impacts of LULCC. We also assessed the statistical significance of the simulated changes using the MWW test, with a p-value threshold of < 0.05 (95% confidence interval) (Wu et al., 2014). The MWW test was selected due to its robustness and appropriateness for handling non-normally distributed data, in contrast to the student t-test (Sy et al., 2021). Our analysis focuses on mean temperature and precipitation (Tmean and Pmean) as well as a selection of 10 extreme temperature and precipitation indices from the 27 indices established by the World Meteorological Organization's ETCCDI; https://www.wcrp climate.org/etccdi.

4.3 Results

4.3.1 The regional extent of LULCC fraction

The simulated LULCC fraction between the CTL and NoLCC experiments reveals notable spatial variability across the West African Sahelian region, with an overall average change of around 19% (Figure 4.1). These experiments capture the impact of land-cover modifications on the region's surface characteristics. The most substantial changes were observed in the Eastern part of the study area, where the LULCC fraction reached up to 45%. This suggests a significant alteration/degradation in land cover, likely due to agricultural expansion, deforestation and desertification. In contrast, most of the entire parts of the region showed much lower LULCC fractions, averaging around 10%. This relatively smaller change might indicate more stable land-use patterns or less intensive land management activities in those areas.

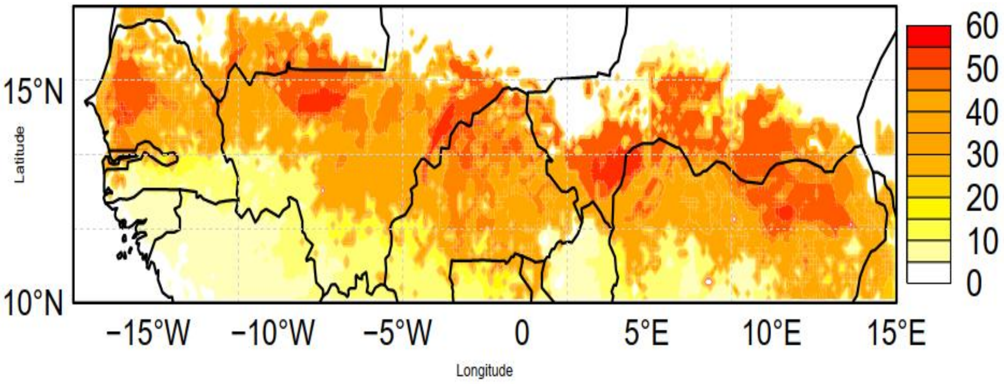


Figure 4.1: Simulated regional extent (%) of LULCC fraction between CTL and NoLCC experiment.

4.3.2 Spatial response of mean and extreme climate indices to LULCC

The spatial patterns of changes in extreme climate indices and mean, driven by LULCC, are presented in Figure 4.2. These results focus on a selection of the most significantly impacted temperature and precipitation extreme indices (5 from each category) in response to LULCC (see Table 3.5 for a detailed description of these indices). Figure 4.2 a) illustrates the changes in mean and extreme temperature indices, while Figure 4.2 b) shows the corresponding changes in precipitation indices.

For temperature indices, a biophysical warming response to LULCC is observed across the entire study region, with the warming signal reaching up to 2 °C in some areas. This warming response is evident in both mean surface temperature (Tmean) and extreme temperature indices, including TXn (0.2 °C), TNx (1.5 °C), TNn (1.8 °C), and TR (30 days in maximum); however, DTr shows a cooling effect (up to -2 °C). The spatial distribution of these extreme temperature indices closely mirrors the patterns seen in Tmean, indicating a consistent regional warming effect associated with LULCC, except for DTr.

In terms of precipitation, LULCC impacts are also notable. A decrease in mean precipitation (Pmean) is simulated, with reductions of up to -0.5 mm/day. Extreme precipitation indices, such as R1mm and R10mm, also show declines, with reductions of up to -10 days and -3 days, respectively. However, certain extreme indices respond differently, with increases in the number of consecutive dry days (CDD, up to 10 days), heavy precipitation days (R20mm, up to 2 days), and the simple daily intensity index (SDII, up to 2 mm/day). The spatial patterns of these extreme precipitation indices (CDD, R20mm, and SDII) differ from those of mean precipitation (Pmean), but they show similarities to R1mm and R10mm, highlighting a complex and regionally variable response to LULCC in terms of precipitation extremes.

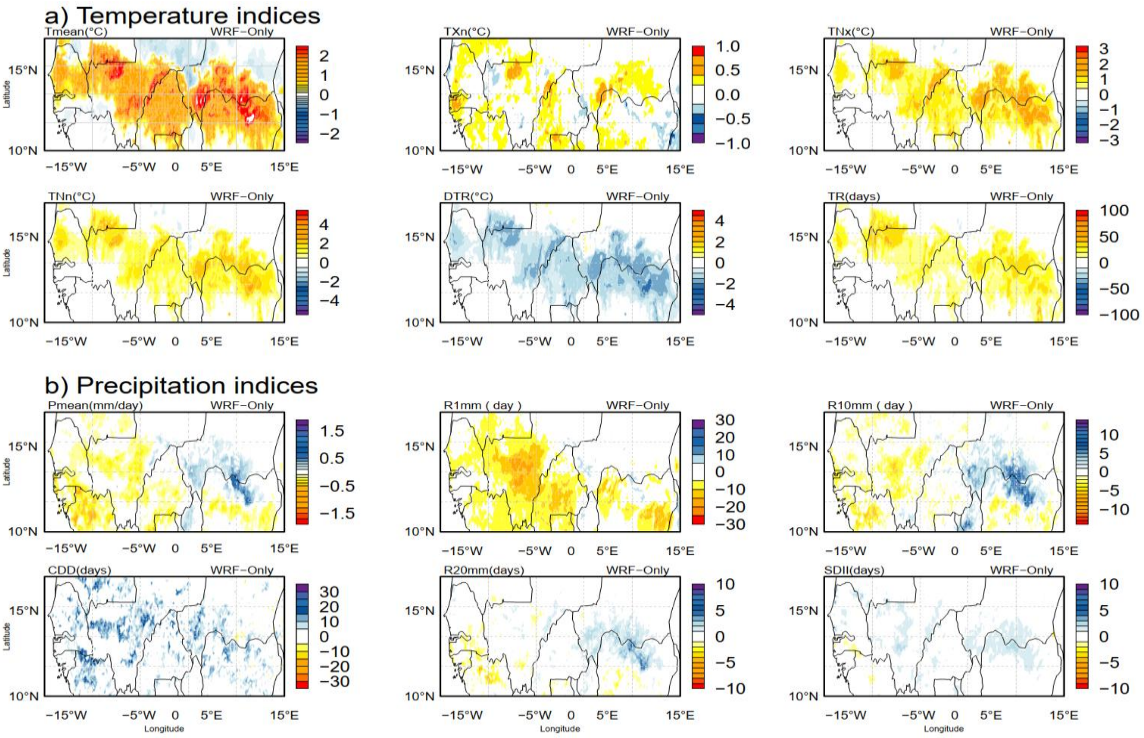


Figure 4.2: Spatial patterns of changes (in mean) temperature (a) and precipitation (b), and extreme indices in response to the LULCC experiment (CTL - NoLCC).

4.3.3 Regional contribution of LULCC to mean and extreme climate indices

Figure 4.3 illustrates the relative contribution of LULCC (%) to changes in mean and extreme climate indices. Our analysis reveals that LULCC has a more pronounced effect on temperature extremes compared to mean conditions. Specifically, changes in extremes temperature are significantly larger than the changes in mean temperature (Tmean), except for DTR, where the changes remain statistically insignificant. The response to LULCC increases by 4%, 3.8%, 1.9%, 0.4%, and 0.3% for TR, TNn, TNx, TXn, and Tmean, respectively. This indicates that temperature extremes are more sensitive to LULCC than the mean temperature.

In contrast, precipitation extremes are also impacted by LULCC, though to a lesser extent than temperature. Significant changes are observed for SDII (4.1%), R20mm (2.2%), and CDD (2.8%), with the Mann–Whitney–Wilcoxon test showing statistical significance at the 95% confidence level (see Figure 4.3). However, the Pmean, R1mm, and R10mm changes remain statistically insignificant. Overall, our results suggest that LULCC has a stronger impact on regional temperature extremes (TR, TNn, TNx, TXn) and rainfall extremes (SDII, R20mm, CDD) than on mean conditions (Tmean, Pmean). Additionally, the statistical significance of LULCC's impact is more pronounced for temperature indices than for precipitation indices.

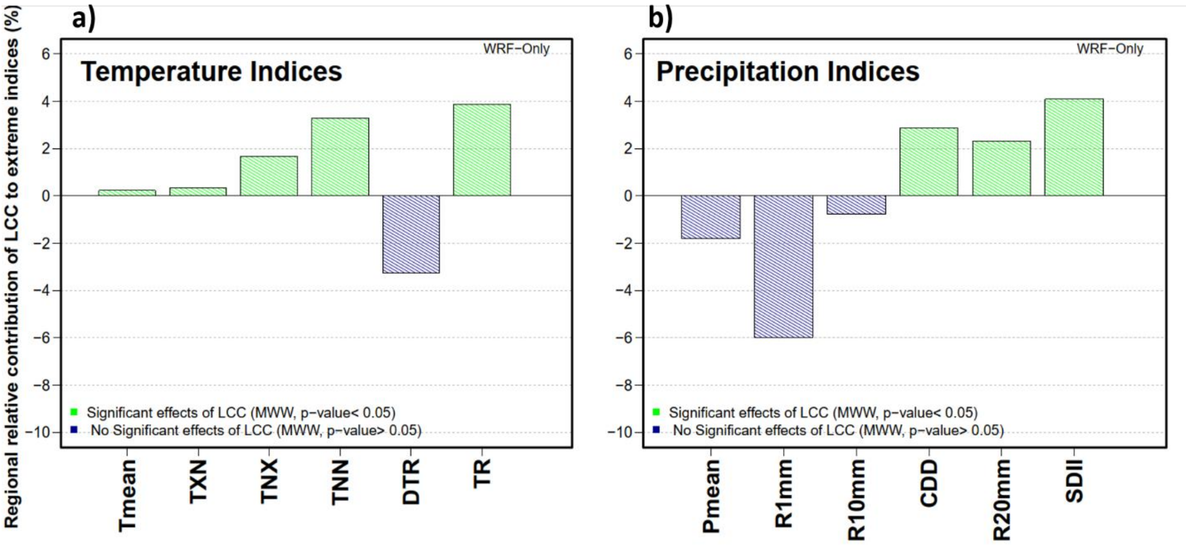


Figure 4.3: Annual relative contribution of LULCC to mean and extreme climate indices ((a) for temperature and (b) for precipitation).

4.4 Discussions

This study provides valuable insights into the extent of regional LULCC, revealing an average impact of 20% and a maximum of up to 50% within the West African Sahelian region. The significant drivers of this change are identified as rapid population growth and increasing anthropogenic activities, including agricultural expansion, deforestation, and urbanization, as noted in previous research (e.g., Boone et al., 2016). Our investigation employs through two primary approaches, a control simulation (CTL, reference simulation) with a no land use simulation reflective of the pre-industrial period (CTL minus No Land Use), utilizing a fully coupled atmosphere-land surface model (WRF-Only coupled with Noah-MP) at a 15 km horizontal resolution. It is essential to emphasize that the spatial heterogeneity of LULCC fractions underscores the complex and uneven nature of land-cover dynamics across the Sahel (Dezfuli and Nicholson, 2013). Understanding these variations is vital for accurately assessing the broader impacts of LULCC on regional climate and ecosystem services.

The findings illustrate a pronounced impact of LULCC on temperature extremes, with changes in extremes ranging from 0.2% to as much as 4%. Notably, all analysed climate indices indicate a detrimental influence of anthropogenic LULCC, except the Daily Temperature Range (DTR), which remained statistically insignificant. The analysis further reveals that extreme temperature indices, such as the number of tropical nights (TR), the annual count of days when daily minimum temperature > 20 °C, have increased significantly averaging an additional 15 days, peaking at 30 days during our simulation period. This rise in tropical nights has profound implications, potentially intensifying heat stress on both agricultural systems and natural ecosystems, thereby disrupting the life cycles of flora and fauna and heightening the existing vulnerabilities in the region (e.g., Diba et al., 2019). Correspondingly, findings from Yavaşlı and Erlat, (2024) corroborate this trend, indicating a notable increase in the frequency of tropical nights (TR) in the Mediterranean region (17.3 days per decade), driven by the compounded effects of anthropogenic climate change and urban expansion. Furthermore, winter temperature indices, including the minimum values of daily maximum temperature (TXn), maximum values of daily minimum temperature (TNx), and minimum values of daily minimum temperature (TNn), have experienced warming effects of 0.2 °C (0.3%), 1.5 °C (0.4%), and 1.8 °C

(1.9%), respectively. These changes can be attributed to LULCC-induced alterations in surface albedo (see Figure 4.2 and Figure 4.3).

Conversely, while the regional influence of LULCC on extreme precipitation indices is notable, the mean precipitation measures (Pmean), the number of wet days (R1mm), and heavy precipitation days (R10mm) show statistically insignificant changes. In contrast, consecutive dry days (CDD) have increased by 10 days (2.8%) across the region, a trend likely driven by shifts in evapotranspiration and moisture availability (Seneviratne et al., 2010). This suggests that the reduction of wooded shrub savannahs and dense forests due to LULCC exacerbates desertification, leading to diminished plant transpiration and soil evaporation. These patterns align with findings from numerous studies(Mahmood et al., 2014; Perugini et al., 2017; Sy & Quesada, 2020). Moreover, our results indicate an increase in very heavy precipitation days (R20mm) by 2 days (2.2%) and a rise in the Simple Daily Intensity Index (SDII) by 2 mm/day (4.1%). These changes are predominantly attributed to shifts in atmospheric circulation, elevated sea surface temperatures, ongoing climate change, and variations in intraseasonal weather patterns. However, these findings underscore the critical need for further research and adaptive strategies to mitigate the adverse impacts of LULCC on climate dynamics and ecological stability in the West African Sahelian region.

4.5 Summary

This chapter examines the profound influence of LULCC on both average and extreme climate conditions (temperature and precipitation) in the West African Sahel using a fully coupled WRF-Only-Noah-MP model that incorporates dynamic vegetation. The findings indicate that LULCC significantly impacts temperature extremes more than average conditions, leading to more frequent and intense hot nights (e.g., TR), which could increase heat stress and disrupt ecosystems. These temperature changes also suggest alterations in surface properties like albedo. Although average rainfall patterns remain statistically insignificant, the research shows a lengthening of dry periods (e.g., CDD), potentially worsening desertification and affecting local and regional agriculture. The study emphasizes the need for targeted research and strategies to address the impacts of LULCC on regional climate and ecosystems, as well as to develop effective adaptation and mitigation measures.

CHAPTER 5: The sensitivity of both WRF-Only-Noah-MP vs. WRF-Hydro-Noah-MP models to LULCC in West Africa

In this chapter, the sensitivity of LULCC has been Evaluated by comparing two fully coupled systems: WRF-Only-Noah-MP and WRF-Hydro-Noah-MP models. The analysis focuses on the West African Sahelian region, an area significantly impacted by LULCC. Mean and extreme climate indices, particularly temperature and precipitation, were evaluated to determine the influence of LULCC on the regional climate.

5.1 Preamble to the sensitivity analysis of WRF-Only-Noah-MP vs. WRF-Hydro-Noah-MP.

Anthropogenic LULCC particularly in West Africa, have profound implications for regional climate dynamics (Diasso & Abiodun, 2017; Diba et al., 2018; Mehboob et al., 2020; Naabil et al., 2022). Over the past 50 years, global land use patterns have shifted dramatically, leading to both direct and indirect impacts on global climate change (Deng et al., 2013). This is becoming increasingly common in the Sahelian region of West Africa mainly due to desertification, population growth and climate change effects (Gangneron et al., 2022; Ouedraogo et al., 2010; Sylla et al., 2015). Thus, changes in LULC can cause local or regional cooling/warming and change in precipitation by altering the earth's surface reflectance (albedo), with an increase in albedo leading to a cooling effect on land surface temperature and change in precipitation amount (Bounoua et al., 2002; Mortey et al., 2023b). LULCC impacts climate and land-atmosphere interactions by altering physical properties as well as energy balances, soil moisture, and surface roughness. This complexity arises from the numerous interlinked processes at the surface-atmosphere interface and their competing effects (Boone et al., 2016; Sambieni et al., 2024; Sy et al., 2017). The West African Sahelian region is known for having some of the strongest soil moisture feedbacks with the atmosphere over the globe, yet most climate and land surface models neglect this hydrological process (Descroix et al., 2018; Dirmeyer, 2011; Sy et al., 2017). It has been identified as having the world's highest impact of biophysical processes on climate and extreme weather indices (Xue et al., 2004, 2010). Only a limited number of land-based modeling studies focus on long-term and finer spatial resolution in West Africa (Asenso Barnieh et al., 2023; García-Álvarez, 2018). Inappropriate assumptions and biogeophysical processes can introduce significant uncertainties in model structure and sensitivity parameters, potentially leading to incorrect decisions regarding the output of LULCC (Ferchichi et al., 2018). Over the past four decades, West Africa's extreme climate indices, including temperature and precipitation, have shown significant variability, influenced by deforestation-induced land degradation. Changes in intensity, duration, spatial distribution, and annual/daily amounts highlight the profound impact on the region's climate patterns (Abiodun et al., 2007; Mouhamed et al., 2013). It is important to highlight that extreme temperature and precipitation indices assessment for West Africa’s region, is limited (Adeyeri et al., 2019; Barry et al., 2018). Similarly, by the end of the 21st century, future LULCC significantly influence extreme climate indices globally and regionally under RCP2.6 and RCP8.5 scenarios (Adeyeri et al., 2019; Sy & Quesada, 2020). Anthropogenic activities are anticipated to exacerbate future changes in climate extremes indices, leading to more intense, frequent, and prolonged (S. Bamba et al., 2016; Khan et al., 2020; Sy & Quesada, 2020). Despite extensive efforts, investigations into extreme climate indices have faced challenges such as coarse resolutions, parameterisation, and calibration, resulting in outputs that fail to reliably reproduce accurate local weather extremes (Avila-Diaz et al., 2020). However, Regional Climate Models (RCMs) significantly enhance climate services, particularly in providing extreme indices, and inform effective climate change adaptation measures (Giorgi, 2019; Lee & Cha, 2020). Due to their higher spatial resolution compared to Global Climate Models (GCMs), RCMs can capture greater topographic diversity and more localized atmospheric/climate dynamics (Lee & Cha, 2020; López-Moreno & Beniston, 2009). Nevertheless, understanding changes in extreme climate indices is crucial for implementing effective adaptation/mitigation strategies to counter the negative impacts of climate change (Agyekum et al., 2023; Klassou & Komi, 2021). Then, It is crucial for decision-makers, scientists, and academics to develop effective adaptation and mitigation strategies to address extreme climate indices and combat CC (Adeyeri et al., 2019).

This study aims to: (i) assess how regional LULCC influence the spatial patterns of extreme climate indices, specifically temperature and precipitation, (ii) quantify the regional relative impact of LULCC on these indices in Sahelian West Africa and (iii) evaluate the regional relative contribution of hydrological processes in the WRF-Hydro model compared to the WRF-Only model. To achieve this, the study employs a comparative analysis between a high-resolution (15 km) WRF-only model, which integrates atmosphere and vegetation dynamics, and a WRF-Hydro model, which includes the interactions among atmosphere, hydrology, and vegetation dynamics.

5.2 A brief analytical procedure

In addition to the analytical procedure described in Chapter 4, we utilised an extended version of the WRF model (referred to as WRF-Only) known as WRF-Hydro (version 5.2). This model integrates advanced hydrological and land surface components (Gochis et al., 2020; W. Wang et al., 2020). Developed by the National Center for

Atmospheric Research (NCAR), WRF-Hydro is designed to enhance the WRF model's ability to simulate observed climate variables more accurately compared to the WRF setup (Naabil et al., 2022). This enhanced configuration includes both surface and subsurface lateral flows, alongside dynamic vegetation modeling, allowing for a finer representation of subgrid-scale biophysical impacts of LULCC, as well as incorporating terrestrial hydrological processes (Arnault et al., 2023). The simulations were conducted over a regional sub-domain with a 60-second timestep to ensure numerical stability. Initial conditions and lateral boundaries were defined using ERA5 reanalysis data from the ECMWF (Hersbach et al., 2020). The setup employed WRF-Hydro's hydrological module to simulate lateral terrestrial flow, while the community Noah land surface model with Multi-Parameterization (Noah-MP) handled vegetation dynamics and soil moisture across a 2-meter soil column divided into four layers (Niu et al., 2011). Two simulations were executed to examine the impact of LULCC on extreme climate indices in the West African Sahel. The control experiment (CTL) used the default land cover map from MODIS product MCD12Q1 as the baseline, representing present-day conditions based on 2015 data (e.g., Sulla-Menashe et al., 2019). Additionally, a simulation without land cover change (NoLCC) was conducted using a pre-industrial land cover map. The contrast between CTL and NoLCC (CTL minus NoLCC) highlighted the biophysical effects of deforestation, termed here as "LULCC effects." To evaluate the statistical significance of the simulated changes, the MWW test was applied, with results considered significant if the p-value < 0.05, indicating a 95% confidence level (Wu et al., 2014).

5.3 Results

5.3.2 Spatial response of extreme climate indices to LULCC: A comparison between WRF-Only and WRF-Hydro simulations.

Figure 5.1 illustrates the spatial patterns of changes in extreme climate indices, focusing on 10 significantly impacted temperature and precipitation extremes in response to LULCC. Panel (a) highlights variations in mean and extreme temperature indices, while panel (b) displays changes in precipitation indices.

For extreme temperatures, LULCC generally induces a biophysical warming response across all indices except for the daily temperature range (DTR), which shows a cooling effect of -1.5 °C in the WRF-Only simulation and -2 °C in the WRF-Hydro simulation. This cooling effect is more pronounced in the WRF-Hydro results compared to WRF-

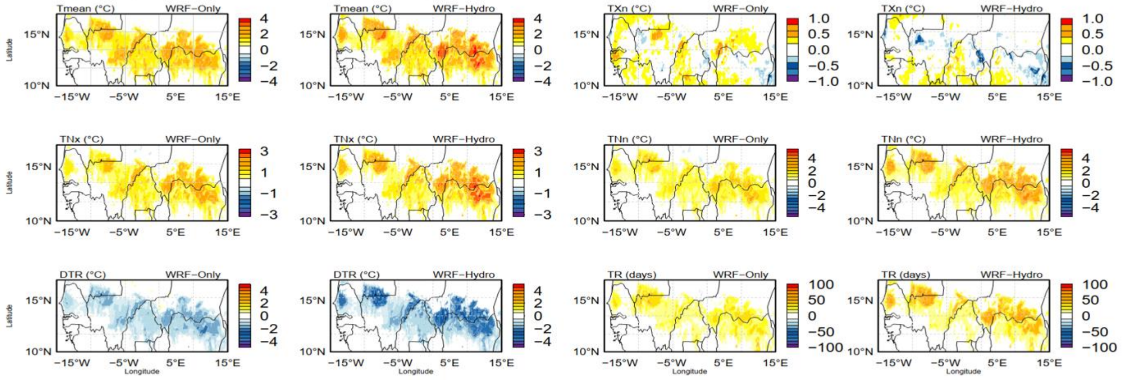
Only. Conversely, the annual minima of daily maximum temperature (TXn) increase by +0.3 °C in WRF-Only and +0.1 °C in WRF-Hydro. Overall, panel (a) demonstrates a clear warming trend due to LULCC, with WRF-Only simulating increases of +1.5 °C for the mean temperature (Tmean), +1 °C for the annual maxima of daily minimum temperature (TNx), +1.5 °C for the annual minima of daily minimum temperature (TNn), and +15 days for the number of tropical nights (TR). In comparison, the WRF-Hydro simulation produces even greater increases, with +2 °C for Tmean, +1.5 °C for TNx, +2 °C for TNn, and +20 days for TR.

Similarly, panel (b) reveals distinct spatial patterns in mean and extreme precipitation indices. While all extreme precipitation indices exhibit significant responses to LULCC, these effects are more pronounced in the WRF-Hydro simulation compared to WRF-Only, except for mean precipitation (Pmean). The Pmean shows a reduction of -0.8 mm/day in WRF-Only and -0.5 mm/day in WRF-Hydro. Additionally, the wet day (R1mm) and heavy precipitation days (R10mm) of precipitation decreases in WRF-Only by -10 and -5 days, respectively, while in WRF-Hydro, the reductions are -15 and -7 days over Sahelian West Africa.

In contrast, indices such as very heavy precipitation days (R20mm), consecutive dry days (CDD), and the simple daily intensity index (SDII) increase for both models, with more pronounced effects in WRF-Hydro. On average, WRF-Only simulates increases of +10 days, +2 days, and +2.5 mm/day for CDD, R20mm and SDII, respectively. In comparison, WRF-Hydro exhibits an increase of +15 days for CDD, +4 days for R20mm and +3.5 mm/day for SDII.

Overall, while both models exhibit relatively consistent spatial patterns for extreme temperature and precipitation indices, the impacts are more substantial in the WRF-Hydro simulations compared to WRF-Only. This underscores the importance of hydrological processes in modulating LULCC-induced climate extremes.

a) Temperature indices:WRF compared to WRF−Hydro



b) Precipitation indices:WRF compared to WRF−Hydro

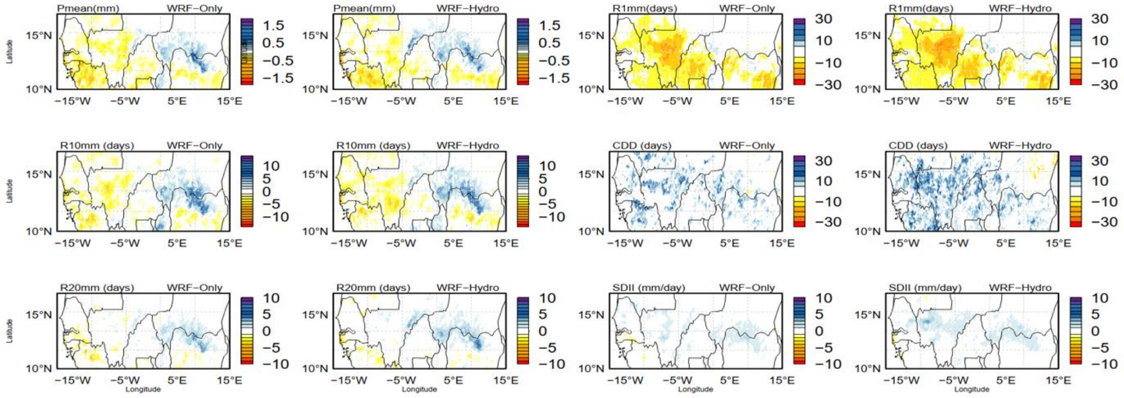


Figure 5.1: Spatial patterns of changes (in mean) temperature (a) and precipitation (b), and extreme indices in response to the LULCC experiment (CTL - NoLCC): A comparison between WRF-Only and WRF-Hydro simulations.

5.3.3 Regional contribution of LULCC to mean and extreme climate indices: A comparison between WRF-Only and WRF-Hydro simulations.

Figure 5.2 illustrates the regional relative contribution of LULCC (%) to changes in mean and extreme climate indices (temperature and precipitation) across the West African Sahelian region, using two different modeling systems (WRF-Only and WRF-Hydro). The green box indicates where the MWW test is significant, while the blue box indicates where the test is not significant. When considering the effects of LULCC at a regional level, the study finds a significant impact on extreme temperature indices with small average impacts (Tmean) in both the WRF-Only and WRF-Hydro modeling systems, except only for TXn. Specifically, the signals are significantly higher for all extreme temperature indices and mean temperature with WRF-Hydro (up to a maximum of +5.4%) compared to WRF-only coupled systems (up to a maximum of 3.9%). In more detail, the effect of LULCC with WRF-Hydro modeling systems demonstrates pronounced impacts (warming) on mean temperature (Tmean), TXn, TNx, TNn, and TR, showing increases of +0.4%, +0.1%, +2.1%, +5%, and +5.4%, respectively in maximum. In comparison, using WRF-only results are less pronounced increases (warming): +0.2% for Tmean, +0.3% for TXn, +1.8% for TNx, +3.2% for TNn, and +3.9% for TR in maximum. Similarly, the findings show increases in extreme precipitation indices with both WRF-Only and WRF-Hydro where changes remain statistically significant (CDD, R20mm and SDII). However, the increases are much more pronounced with WRF-Hydro except for CDD. Thus, with WRF-Hydro, CDD, R20mm, and SDII increased by +2.8%, +5.9%, and +5.9% respectively. In contrast, with WRF-Only, the increases are less pronounced such as +2.4% for R20mm and +4.1% for SDII except for CDD +3 %. More importantly, the regional effects of LULCC have a greater impact on extreme temperature and precipitation indices than the mean values in the West Africa Sahelian zone.

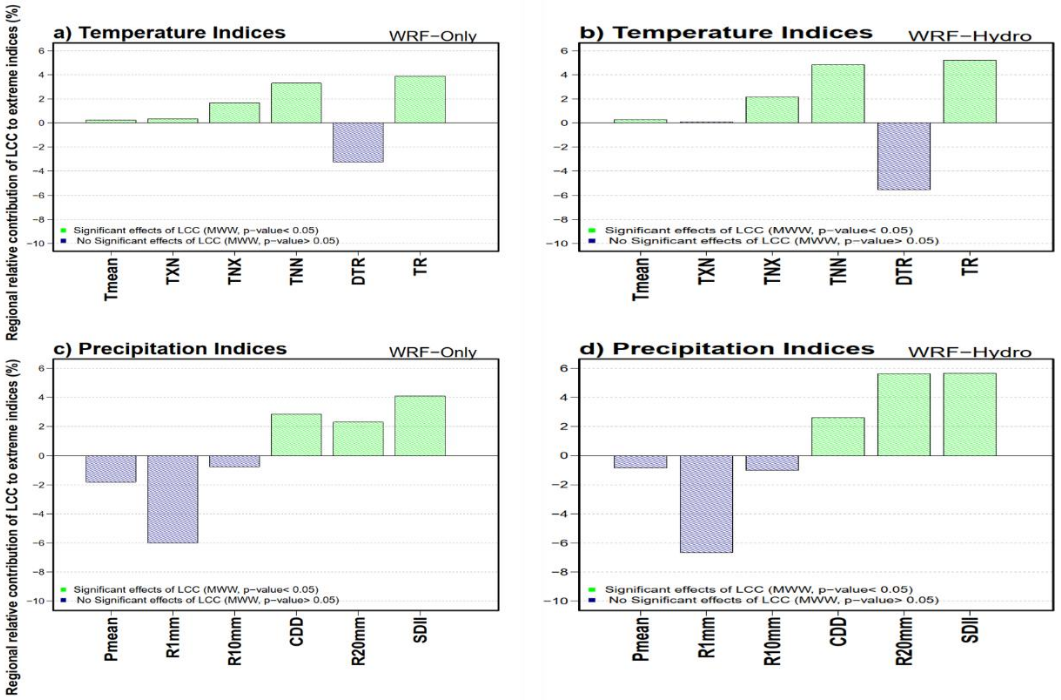


Figure 5.2: Annual relative contribution of LULCC effects to mean and extreme climate indices (averaged over 2012–2022). Bars (y-axis) correspond to the percentage contribution of LULCC relative to the CTL simulation ((CTL-NoLCC)/CTL) for each of the five temperature indices (upper panel, x-axis) and five precipitation indices (lower panel, x-axis) corresponding to the most impacted indices. Green bars indicate simulated changes that were statistically significant according to the MWW test,

showing a notable difference between the CTL and NoLCC groups at the 0.05 significance level (p-value < 0.05). In contrast, blue bars represent indices that were not significantly impacted with a p-value > 0.05.

5.3.4 Regional relative contributions of hydrological processes in the WRF-Hydro model compared to the WRF-Only model

In Figure 5.3, the contribution of WRF-Hydro simulation relative to WRF-Only is illustrated, demonstrating how the two atmospheric models despite having identical experimental setups differ in their response to LULCC. WRF-Hydro offers a more refined evaluation of extreme indices due to its incorporation of detailed hydrological processes, resulting in increased sensitivity compared to WRF-Only. The results indicate that the hydrological processes simulated by WRF-Hydro amplify certain temperature indices, with a rise in mean temperature (Tmean) by +0.1%, TNx by +0.5%, TNn by +1.7%, and TR by 1.5%. Conversely, the minimum TXn decreases by -0.3%.

Regarding precipitation indices, WRF-Hydro exhibits a more pronounced impact than temperature indices, with a wet effect observed in very heavy precipitation days (R20mm) increasing by +3.2% and the Simple Daily Intensity Index (SDII) rising by +1.7%. A minor dry effect is observed in consecutive dry days (CDD), which decreases by -0.3%. However, no statistically significant difference is noted for other variables such as DTR, mean precipitation (Pmean), and other rainfall events including R1mm and R10mm.

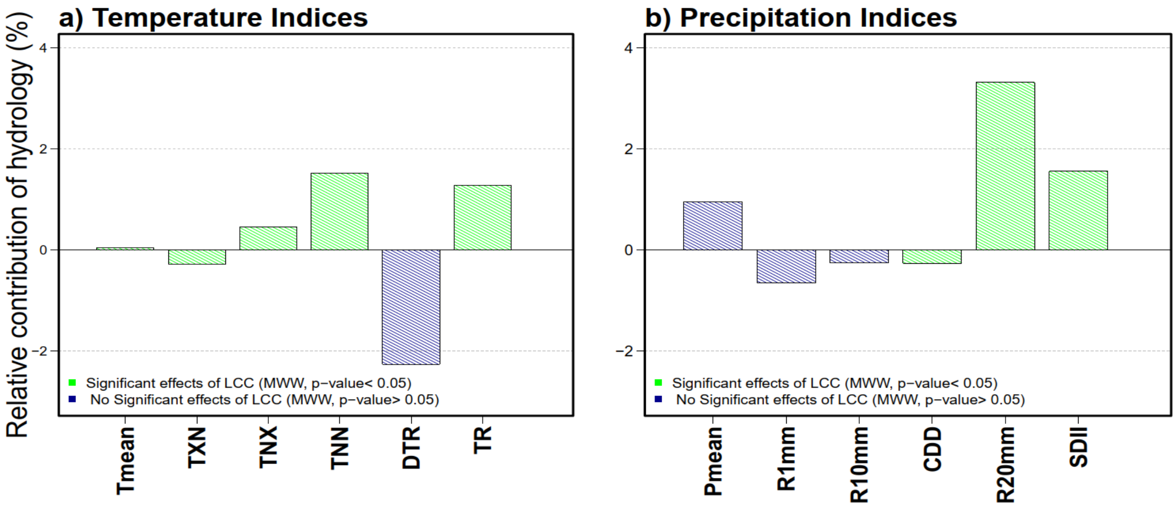


Figure 5.3: Regional relative contribution of hydrological processes (WRF-Hydro minus WRF-Only).

5.4 Discussions

Coupled atmospheric-hydrologic systems enhance our comprehension of the interactions between atmospheric and land-surface processes. They also improve the spatial and temporal precision of hydrologic forecasts and extreme climate indices (Wang et al., 2022). Therefore, the comparison between the coupling of the stand-alone WRF model (referred to as WRF-Only) and the hydrological model (WRF-Hydro) aims to reduce uncertainties associated with the spatial and temporal distribution of LULCC effects on extreme climate indices in the Sahelian West African. In this study, we considered the 10 most impacted extreme climate indices alongside the mean climate conditions (temperature and precipitation). Our findings indicate that the extreme climate indices exhibit greater sensitivity to LULCC compared to the mean conditions for both WRF-Only and WRF-Hydro (see Figure 5.1 and Figure 5.2). Numerous studies (e.g., Avila et al., 2012; Camara et al., 2022; L. Chen & Dirmeyer, 2019; Hong et al., 2022; Hu et al., 2019; Sy & Quesada, 2020; Zhang et al., 2024) highlight the profound impacts of anthropogenic LULCC on extreme climate events, posing critical challenges to the regional climate systems, ecosystem integrity, and human health.

Figure 5.1 highlights the spatial patterns of changes in extreme climate indices, detailing the effects of LULCC on both temperature (panel a) and precipitation (panel b). For temperature, LULCC consistently induces a warming response across most indices, reflecting a significant biophysical impact, except for DTR, which shows a cooling effect of -1.5 °C in WRF-Only and -2 °C in WRF-Hydro, the latter indicating stronger hydrological influences. The TXn increased modestly, with changes in WRF-Hydro (+0.1 °C) compared to WRF-Only (+0.3 °C). In contrast, mean temperature (Tmean) and TNx exhibit pronounced warming, with WRF-Hydro amplifying the changes (+2 °C and +1.5 °C, respectively) relative to WRF-Only (+1.5 °C and +1 °C). Additionally, the TR increases significantly, by +15 days in WRF-Only and +20 days in WRF-Hydro, highlighting more persistent nighttime warming in hydrology-coupled simulations. These patterns underscore the dominant role of LULCC in driving extreme temperature increases, with hydrological feedbacks further intensifying the impacts.

Precipitation indices in panel (b) display more heterogeneous spatial patterns, with contrasting responses between mean and extreme precipitation. Mean precipitation (Pmean) decreases under both simulations, with reductions of -0.8 mm/day in WRF-Only and -0.5 mm/day in WRF-Hydro, indicating a slight mitigation in hydrology-coupled models. Extreme precipitation indices, however, show complex changes: the R1mm and R10mm declines, more prominently in WRF-Hydro (-15 and -7 days, respectively) compared to WRF-Only (-10 and -5 days). Conversely, R20mm, CDD and SDII increase, with sharper effects in WRF-Hydro (+4 days for R20mm, +15 days for CDD and +3.5 mm/day for SDII) relative to WRF-Only (+2 days, +10 days, and +2.5 mm/day). These results highlight a pattern of intensified dry spells interspersed with heavier but less frequent rainfall events, reflecting the dual influence of LULCC on reducing overall precipitation while amplifying extremes. The stronger responses in WRF-Hydro simulations underline the importance of hydrological feedback in modulating both mean and extreme climate conditions, emphasizing their inclusion in assessments of LULCC impacts to improve the accuracy of climate projections and inform land-use management strategies. These findings align with previous studies, underscoring the superior performance, robustness, and enhanced capabilities of the WRF-Hydro modeling system over WRF-Only (Galanaki et al., 2021; Kerandi et al., 2018; Senatore et al., 2015; Somos-Valenzuela & Palmer, 2018; Sun et al., 2020).

Regarding the regional relative contribution to LULCC (e.g., see Figure 5.2), we observed significant increases in extreme temperature and precipitation indices where the statistical test (MWW) is significant, with changes being more pronounced in the WRF-Hydro simulation than in WRF-Only. Specifically, the WRF-Hydro simulation showed extreme temperature increases of up to +5.4 % and more substantial increases in extreme precipitation, reaching up to +5.9%, except for CDD due to LULCC. The limited response in CDD can be attributed to the lower hydrological process representation in the model, which may affect its overall performance. In contrast, the WRF-Only simulation exhibited a smaller response, with maximum changes of up to +3.9% for extreme temperature and +4.1% for extreme precipitation.

On the other hand, the findings in Figure 5.3 highlight the distinct contributions of WRF-Hydro compared to WRF-Only in simulating LULCC impacts, emphasizing the value of incorporating hydrological processes. WRF-Hydro demonstrates increased sensitivity to extreme indices, amplifying temperature metrics such as TNx (+0.5%), TNn (+1.7%), and TR (+1.5%), while slightly reducing TXn (-0.3%), reflecting its ability to capture nuanced thermal feedbacks. Precipitation indices exhibit a more pronounced response, with significant increases in very heavy precipitation days (R20mm, +3.2%) and simple daily intensity index (SDII, +1.7%), alongside a minor reduction in consecutive dry days (CDD, -0.3%) in Sahelian West Africa. Unlike Mortey et al. (2024), who used the WRF-Hydro model to demonstrate that deforestation increases drought risk in tropical West Africa, this study adopts a distinct experimental setup.

These results underscore the importance of hydrological coupling in refining the simulation of extreme weather events, particularly for rainfall or precipitation extremes, while indicating that moderate events and mean conditions remain comparable to WRF-Only. This enhanced representation of land-atmosphere interactions provides valuable insights for assessing the impacts of LULCC under changing climatic and hydrological conditions.

5.5 Summary

Coupled atmospheric-hydrologic systems improve our understanding of land-atmosphere interactions, enhancing the precision of hydrological forecasts and extreme climate indices. This study compared stand-alone WRF (WRF-Only) and WRF-Hydro models to assess the effects of LULCC on extreme climate indices and mean conditions in Sahelian West Africa. Results showed that extreme climate indices are more sensitive to LULCC than mean conditions, with WRF-Hydro capturing amplified impacts due to hydrological feedback. For temperature, LULCC induced consistent warming across indices, with stronger effects in WRF-Hydro. Precipitation indices displayed heterogeneous patterns, highlighting reduced mean precipitation but intensified extremes, such as TR and R20mm. The WRF-Hydro model demonstrated superior performance in simulating these dynamics, emphasizing the need for hydrological coupling to improve climate projections and inform sustainable land management strategies. These findings highlight the critical role of hydrological feedback in refining assessments of LULCC impacts on regional climate systems.

CHAPTER 6: The physical mechanisms driving the surface temperature in response to LULCC

This chapter examines the physical mechanisms affecting surface temperature changes due to LULCC by utilizing both the WRF-Only and WRF-Hydro modeling systems. The study employs an energy balance decomposition approach, which allows for detailed attribution of the surface temperature response to LULCC, dividing contributions from the distinct terms of the surface energy balance. This analysis is further complemented by applying the Stefan-Boltzmann law, enabling a clearer understanding of how radiative and non-radiative components influence temperature dynamics and feedback mechanisms in response to LULCC (see Figure 6.a for detail).

6.1 Preamble to investigate the physical mechanisms driving the surface temperature in response to land use and land cover change

Temperature is a critical component of the climate system and directly influences ecosystems, agriculture, water resource management, and various aspects of human society. Understanding patterns of temperature change and their driving mechanisms is crucial for developing effective response strategies and predicting future climate change adaptation and mitigation options (Yang et al., 2024). Land surface temperature is a key component of the climate system and is critical for evaluating interactions between the land and atmosphere, as well as the impacts of climate change. Recognized as a priority parameter often driven by physical mechanisms, it is also considered a significant climate variable by the Global Climate Observing System (GCOS) of the World Meteorological Organization (GCOS, 2016).

Recent studies emphasize that LULCC can significantly alter surface temperature via biogeophysical feedback. These changes affect energy and water balance as well as momentum exchanges between land and atmosphere (Chen & Dirmeyer, 2016; Devaraju et al., 2015; Oleson et al., 2004). For example, shifts in vegetation cover can modify albedo, evapotranspiration rates, heat flux and soil moisture content, leading to variations in surface temperature, precipitation patterns, and even local wind systems. These impacts highlight the critical role of LULCC in climate dynamics and underscore the need for integrative land-atmosphere modeling approaches (Arneth et al., 2017; Perugini et al., 2017). Increasing land surface temperature can modify precipitation patterns, significantly impacting soil moisture levels. A warmer atmosphere, with its higher capacity to hold water vapour, often extends the duration of dry periods (L. Jiang et al., 2022). Atmospheric water vapour functions as a potent natural GHG, substantially raising the Earth's equilibrium temperature (Fahey et al., 2017). In the Sahelian and Guinea regions of West Africa, changes in land surface temperature are mainly influenced by the components of the surface energy balance (Sy et al., 2017). In contrast, greening helps cool both local and regional climates more effectively by boosting evapotranspiration, especially in arid and semi-arid regions, thereby significantly enhancing climate mitigation. For example, prioritizing vegetation restoration and conservation in such areas can increase the climate mitigation potential of vegetation through biophysical processes (Cao et al., 2023; Chen et al., 2022). Thus, to promote sustainable development, a deeper comprehension of the driving physical mechanisms behind variations in surface temperature dynamics is crucial (Yang et al., 2020). In this study, the physical mechanisms influencing surface temperature (K) resulting from anthropogenic LULCC are evaluated, including changes in downward shortwave radiation (ΔDSR), downward longwave radiation (ΔDLR), surface albedo (Δα), sensible heat flux (ΔSH), plant transpiration (ΔEt), canopy evaporation (ΔEc), soil evaporation (ΔEs) and ground heat flux (ΔG).

6.2 A brief analytical procedure

To undertake this study, we employ an energy balance decomposition approach using our two modeling simulations experiment (WRF-Only and WRF-Hydro). This approach decomposes the surface temperature response to LULCC, attributing contributions to each component of the surface energy balance, as outlined below:

$$S_{\downarrow}(1-\alpha) + L_{\downarrow} - L_{\uparrow} = SH_f + LH_f + GH_f \quad (1)$$

By applying the Stefan–Boltzmann law, $L_{\uparrow}$ (the surface upward long-wave radiation) can be rewritten as follows. He concluded that there is an empirical relationship between the power emitted by an ideal blackbody and its temperature change (ΔT)(Fermi & Suzuki, 2018):

$$L_{\uparrow} = \varepsilon\sigma Ts^4 \quad (2)$$

where σ is the Stefan–Boltzmann constant (5.67 x 10^{-8} $\mathrm{Wm^{-2}K^{-4}}$), ε is surface emissivity, and Ts is the surface temperature (K).

By applying a derivation and rearranging the equation (1), the surface temperature determined by $L_{\uparrow}$ response to LULCC can be represented as follows:

$$\Delta \mathrm{Ts} = \frac{1}{4\varepsilon\sigma \mathrm{Ts}^3}\left(\Delta S_{\downarrow} - \alpha\Delta S_{\downarrow} - S_{\downarrow}\Delta\alpha + \Delta L_{\downarrow} - \Delta SH_f - \Delta LH_f - \Delta GH_f\right) \quad (3)$$

$$\Delta LH_f = L\mathrm{Hvap}\,(\Delta\mathrm{Ep} + \Delta\mathrm{Es} + \Delta\mathrm{Ec}) \quad (4)$$

Here, LHvap is the latent heat of vaporisation (2.260 kJ/kg), and Ep, Es, and Ec stand for plant transpiration, soil evaporation, and canopy evaporation (all in mm). By applying Equation (4) to Equation (3), the surface temperature's reaction to LULCC can be expressed in the following manner:

$$\Delta \mathrm{Ts} = \frac{1}{4\varepsilon\sigma \mathrm{Ts}^3}((1-\alpha)\Delta S_{\downarrow} - S_{\downarrow}\Delta\alpha + \Delta L_{\downarrow} - \Delta SH_f - \Delta \mathrm{Ep} - \Delta \mathrm{Es} - \Delta \mathrm{Ec} - \Delta GH_f) \quad (5)$$

Equation (5) represents the final approach employed to assess the relative contributions of individual components within the surface energy balance in response to LULCC. This evaluation helps clarify the specific impacts and interactions of altered land surfaces with atmospheric processes.

6.3 Results

6.3.1 Mechanisms driving the contrasting temperature responses to LULCC in WRF-Only simulations

To further determine the potential physical mechanisms driving land surface temperature responses to LULCC, (Figure 6.a) displays how surface temperature increase (black line) relates to distinct surface energy balance components. A key finding is the significant biophysical warming effect for almost the entire year, with a particularly notable temperature increase (up to +0.5 K) during the wet-to-dry seasonal transition (August to January). This warming is largely attributed to a reduction in plant transpiration (ΔEt), as depicted in the blue bar plot. The observed dynamics suggest critical links between vegetation changes and shifts in energy partitioning at the land surface. Moreover, hot temperatures are shaped by various regional LULCC-induced compensatory physical processes. Key factors include reduced evapotranspiration, decreased surface water interception, and diminished soil moisture and atmospheric water content. During pre- or post-monsoonal periods, hot temperatures are primarily intensified by albedo-driven warming effects, alongside increased downward longwave radiation (ΔDLR). This, in turn, enhances the absorption of downward shortwave radiation (ΔDSR) by the surface. During the monsoon period, the albedo-driven (Δα) temperature response becomes even more pronounced due to reduced soil evapotranspiration with WRF-only simulation.

with the WRF-Hydro simulation, which was slightly more pronounced (up to +0.6 K maximum) compared to the WRF-Only simulation. In addition, from March to June, the temperature increased (up to +0.15 K) in the WRF-Hydro simulation, while in the WRF-Only simulation, the increase was less than +0.1 K. This rise in surface temperature in the WRF-Hydro simulation is primarily attributed to the inclusion of hydrological processes, which improves the model's ability to produce more accurate and reliable results.

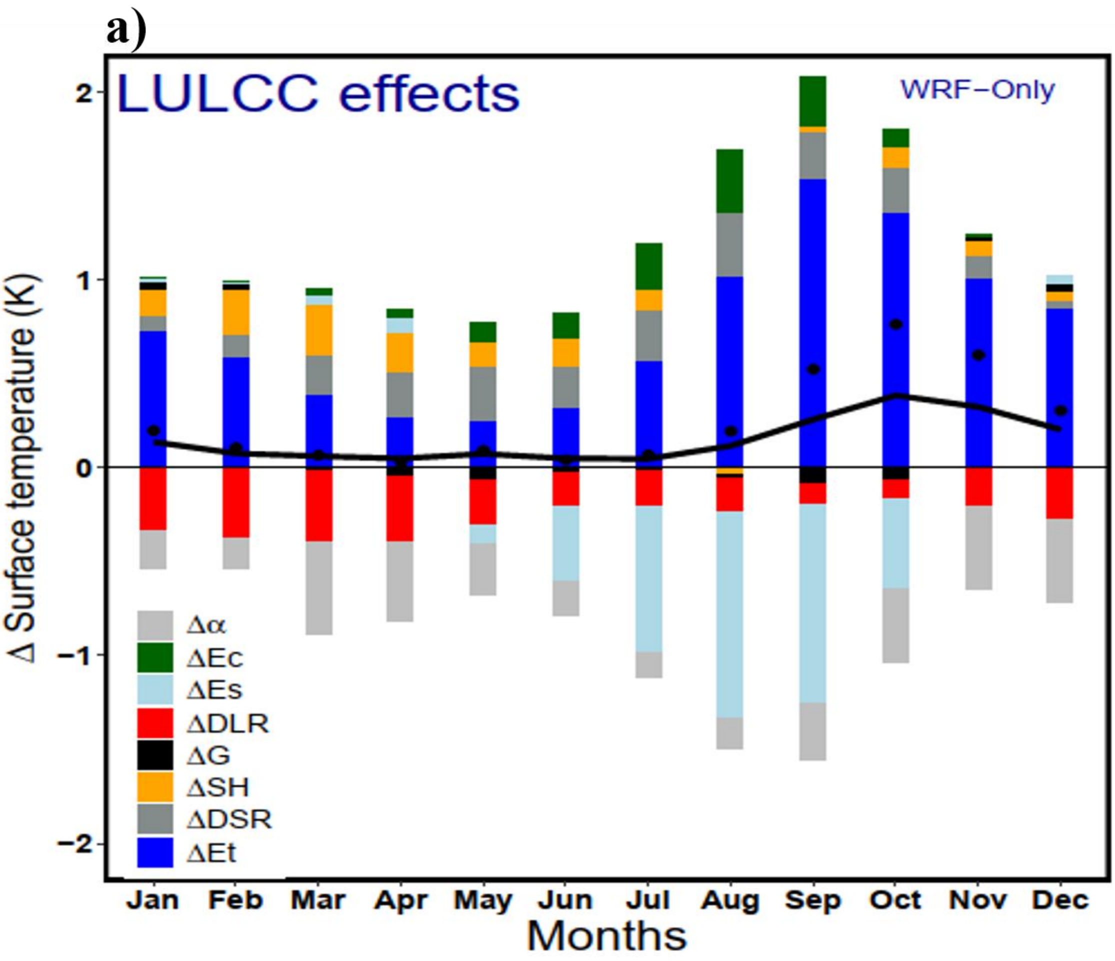


Figure 6.1: The decomposition of the surface energy balance for monthly mean surface temperature changes (K) in response to LULCC is shown for the WRF-Only simulation. The black line represents the net change in land surface air temperature (Tmean) caused by LULCC, while the dots indicate the calculated total change in surface temperature, which is approximately the sum of the stacked bars for each month. The stacked bars illustrate the surface temperature changes resulting from various factors: changes in downward shortwave radiation (ΔDSR in dark grey), downward longwave radiation (ΔDLR in red), surface albedo (Δα in light grey), sensible heat flux (ΔSH in yellow), plant transpiration (ΔEt in blue), canopy evaporation (ΔEc in dark green), soil evaporation (ΔEs in light blue), and ground heat flux (ΔG in black).

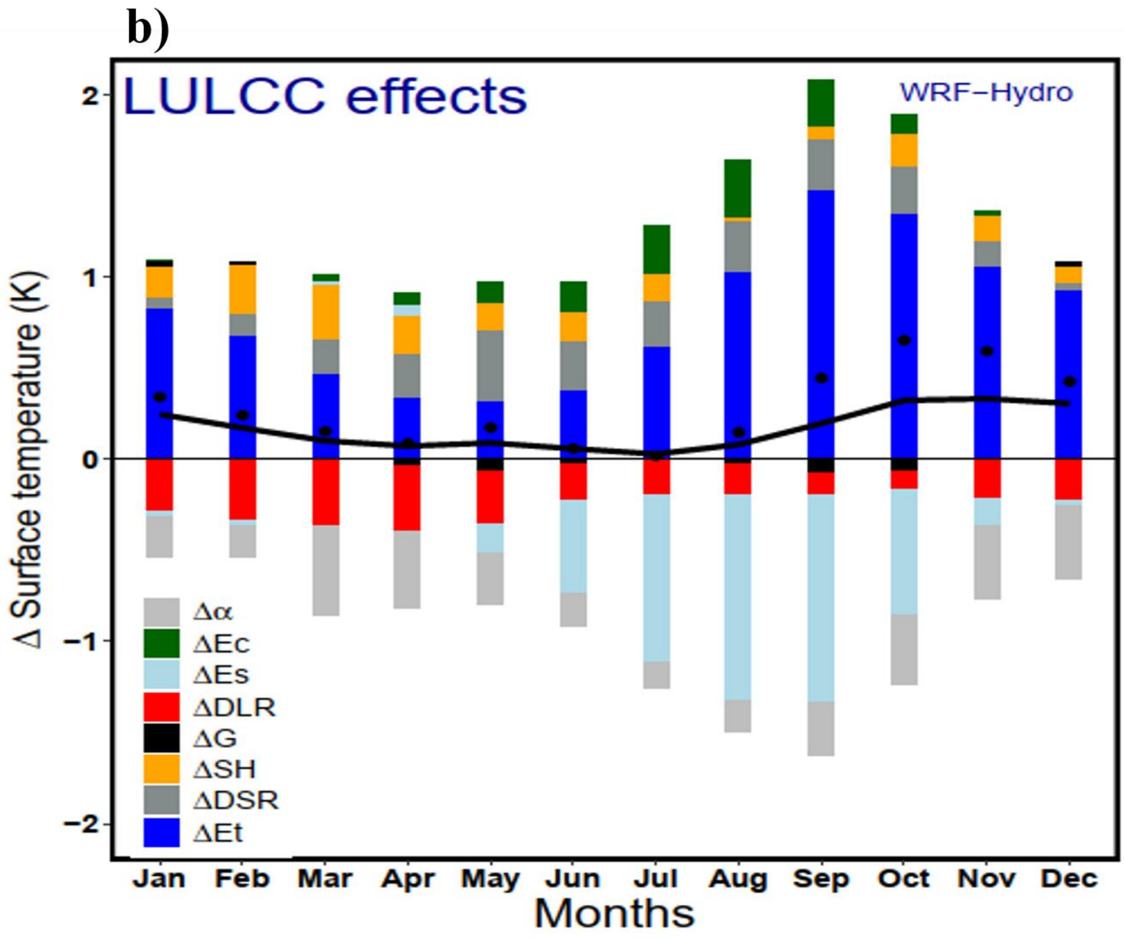


Figure 6.2: Similar to Figure 6.a, but based on the WRF-Hydro simulation.

6.4 Discussions

Our findings highlight the critical role of physical mechanisms underlying land surface temperature changes and their broader implications for land-atmosphere interactions in the context of LULCC. Our results demonstrate that LULCC such as deforestation and land degradation, leads to contrasting biophysical responses, with a notable warming effect observed throughout the year. Peak land surface temperature increases from August to January, reaching up to +0.5 K with WRF-only and +0.6 K with WRF-Hydro simulations. Plant transpiration dynamics primarily influence these temperature changes (see Figures 6.a and 6.b). In the same vein, Cao et al. (2023) and Chen et al. (2022) have highlighted that LULCC indirectly affects land surface temperatures and extreme weather through atmospheric feedback driven by physical mechanisms.

Thus, the observed warming can be attributed to multiple mechanisms. Firstly, reduced plant transpiration due to decreased canopy foliage, commonly triggered by deforestation and land degradation, produces a diminished cooling effect from evapotranspiration. This phenomenon underscores the importance of vegetation cover in regulating local and regional temperatures (e.g., Doelman et al., 2020; Duncan et al., 2019). Secondly, the albedo-induced warming effect further amplifies land surface temperature. Degraded land surfaces typically exhibit higher albedo, reflecting less solar energy and enhancing net longwave radiation fluxes, trapping more heat near the surface. This effect is particularly evident during extreme heat events and is exacerbated by increases in downward longwave radiation (Santos et al., 2023; Zhang et al., 2001). In addition, the observed warming is reduced soil evaporation, particularly during the peak monsoon period when the canopy foliage plays a significant role in surface energy balance. Reduced soil evaporation limits latent heat flux, increasing the proportion of absorbed solar radiation allocated to sensible heat, further intensifying the warming effect.

The cumulative impact of these processes indicates that LULCC, particularly through deforestation, can significantly alter regional climate dynamics by modifying key land-atmosphere feedback mechanisms (albedo, heat flux, evapotranspiration etc…). By amplifying land surface temperature through disrupted transpiration, reduced evapotranspiration, and altered radiation balance, LULCC not only influences local thermal regimes but also potentially exacerbates regional heat extremes (Abera et al., 2024; Lejeune et al., 2015; Muluneh et al., 2017; Sy et al., 2017). Precisely simulating this feedback is essential for capturing accurate responses of temperature and rainfall to LULCC (Chen et al., 2022; Sy & Quesada, 2020). These findings underscore the necessity of implementing sustainable land management practices as well as land-based mitigation options that prioritize vegetation cover to mitigate warming impacts and maintain balanced land-atmosphere interactions.

6.5 Summary

This chapter emphasizes the significant influence of physical processes driving land surface temperature changes and their implications for land-atmosphere interactions caused by anthropogenic LULCC. Findings indicate that LULCC, such as deforestation and land degradation, generates contrasting biophysical effects, primarily a warming trend throughout the year. Temperature increases peak between August and January, with rises of up to +0.5 K in WRF-only simulations and +0.6 K in WRF-Hydro. The key driver of these changes is reduced plant transpiration due to diminished canopy foliage, weakening the cooling impact of evapotranspiration. Additionally, increased surface albedo and reduced soil evaporation, especially during monsoon peaks, amplify this warming. These mechanisms collectively alter regional climate dynamics by modifying land-atmosphere feedbacks, such as albedo effects and heat fluxes, potentially exacerbating regional heat extremes. Thus, the study stresses the importance of sustainable land management and vegetation preservation to mitigate warming and maintain balanced land-atmosphere interactions.

CHAPTER 7: Conclusions and Recommendations

7.1 Conclusions

Land-based climate change solutions derived from LULCC models are essential for analysing and understanding the complex interactions between land surface processes and the climate system. This study synthesised global research on the biophysical impacts of LULCC in West Africa, focusing on temperature and precipitation changes. Findings reveal that deforestation leads to significant regional warming (+0.26°C historically and +0.88°C under future scenarios) and reduced rainfall (-47.45 mm/year historically and -55 mm/year in the future). Conversely, afforestation cools the region (-0.24°C historically and -0.22°C in the future) and increases precipitation (up to +200 mm/year historically and +635 mm/year in the future).

A unique, fully coupled simulation procedure was employed, utilising WRF-Only and WRF-Hydro model setups, to address the specific objectives of this study. Despite uncertainties in model simulations stemming from methodological assumptions, the models provided critical insights into regional spatiotemporal variations in land degradation and the role of LULCC in shaping extreme climate patterns. For instance, LULCC, driven by rapid population growth, desertification, and intensified human activities, was shown to alter climate patterns significantly, with average impacts in Sahelian West Africa including temperature increases of +1.16°C and precipitation reductions of -0.5 mm/day.

The fully coupled atmosphere-land surface model (WRF-Only with Noah-MP) provided robust evidence of amplified temperature extremes, with most indices (Tmean, TXn, TNx, TNn) showing consistent warming trends. In contrast, precipitation indices displayed increased variability, with extremes such as R20mm, CDD, and SDII becoming more pronounced. The lack of statistically significant changes in mean precipitation highlights the complexity of moisture dynamics and desertification trends. Spatial analyses underscored the influence of LULCC on temperature and precipitation extremes, with WRF-Hydro exhibiting stronger sensitivity compared to WRF-Only.

For temperature indices, WRF-Hydro demonstrated higher sensitivity, amplifying warming effects on metrics such as Tmean, TNn, and TR, while showing nuanced feedback such as a pronounced cooling response in the DTR. For precipitation indices, WRF-Hydro captured stronger increases in extremes (R20mm and SDII) while reflecting reductions in mean precipitation (Pmean). The enhanced performance of WRF-Hydro highlights the critical role of hydrological coupling in capturing the complexity of LULCC impacts on regional climate extremes, with significant increases of up to +5.4% for TR and +5.9% for R20mm and SDII.

Surface energy balance components emerged as pivotal drivers of land surface temperature responses to LULCC, with pronounced seasonal variations. A biophysical warming effect of up to +0.5 K was observed during the wet-to-dry seasonal transition (August to January), driven by reduced plant transpiration and shifts in energy partitioning. Albedo-driven warming effects and increased downward longwave radiation amplified temperatures during pre- and post-monsoon periods. WRF-Hydro simulations highlighted more substantial warming effects, reaching +0.6 K during transitional periods and +0.15 K during the dry season, emphasizing the importance of hydrological processes in modulating temperature responses.

The integration of detailed hydrological processes in WRF-Hydro demonstrates its superior ability to assess the impacts of LULCC on regional climate dynamics. These findings provide valuable insights for developing targeted land management and climate adaptation strategies in Sahelian West Africa, emphasizing the importance of coupling atmospheric and hydrological processes to mitigate the impacts of LULCC on regional climate extremes.

In summary, this study provides (i) valuable insights into the effects of LULCC on mean and extreme climate conditions in Sahelian West Africa using the fully coupled WRF-Noah-MP model with dynamic vegetation; (ii) an assessment of the sensitivity differences between the WRF-Noah-MP and WRF-Noah-MP-Hydro models to LULCC in the region and (iii) an in-depth understanding of the physical mechanisms driving surface temperature responses to LULCC.

7.2 Contribution to Knowledge

Though climate models are capable of reproducing the effects of LULCC, there are still major uncertainties, especially in the calculation of precipitation and temperature reactions, which usually produce different outcomes among models. The present study offers the first multidisciplinary systematic review of LULCC impacts in West Africa using the PRISMA approach, therefore providing both a thorough legal viewpoint and a broad summary of how LULCC affects the climate of the region.

At the regional level, the impact of LULCC on extreme weather events in West Africa is yet mainly unclear. The absence of sophisticated models capable of producing accurate results, limited acceptance of advanced modeling approaches such as fully coupled land surface and climate models, and the lack of high-resolution simulations with robust parameterising efforts undertaken in this study for the Sahelian region of West Africa have been identified for this discrepancy.

Moreover, most West African scientific studies have concentrated on the negative impact of LULCC on temperature. Still, the neglect to look at the physical processes causing these changes sometimes restricts these research opportunities. This work closes this gap by demonstrating that the regional temperature effects of LULCC are mostly driven by variations in plant transpiration.

7.3 Recommendations

7.3.1 Policy action

This study offers new insights into the regional impact of LULCC on our climate systems. For the entire West African region, it is recommended that governments implement a comprehensive land restoration policy focused on promoting sustainable agriculture. The policy should encourage practices such as soil conservation, agroforestry, and sustainable organic farming. It should also provide funding for land restoration, support capacity building for farmers, and establish a monitoring and evaluation system to track the success of restoration efforts. Foster collaboration among government agencies, local communities, and private sector partners to ensure the long-term sustainability and resilience of agricultural landscapes. This approach will create a unified strategy for sustainable agriculture, addressing both environmental and socioeconomic challenges.

The government and its agencies should intensify tree-planting efforts in the region as a key component of the Green for Africa initiative. This policy should focus on large-scale reforestation, afforestation or regreening projects, such as the GGW, prioritizing native tree species that enhance biodiversity and contribute to carbon sequestration. It should include financial incentives for local communities, farmers, and businesses to participate in tree-planting activities, along with the establishment of nurseries to provide seedlings. The government should also integrate tree planting into climate adaptation strategies, promote public awareness campaigns about the benefits of trees, and ensure the monitoring and maintenance of planted areas to guarantee long-term success. This approach would align with regional climate goals, support environmental sustainability, and foster community engagement.

Decision-makers should prioritize the application of scientific findings and climate data to enhance the prediction and mitigation of climate-related risks. This should include the development of a robust climate information system and tools, such as WRF-Hydro, that integrate local, regional, and global data to optimize land management practices and mitigation strategies. Policymakers should implement strategies focused on climate resilience, including the promotion of sustainable agricultural practices, water management techniques, and infrastructure planning. Additionally, emphasis should be placed on improving adaptation strategies by building capacity at all levels of government, supporting research, and ensuring that climate adaptation measures are inclusive and evidence-based.

Finally, the government should intensify the implementation of carbon pricing mechanisms in collaboration with the private sector to incentivize emissions reductions and promote sustainable development. This policy should include the establishment of a clear carbon pricing framework, such as carbon taxes or cap-and-trade systems, that aligns with international climate goals. The government should work with businesses to design flexible, market-based solutions that encourage innovation in low-carbon technologies and sustainable practices. Revenues generated from carbon pricing should be reinvested into climate adaptation and mitigation projects, with a focus on supporting vulnerable communities and industries during the transition to a green economy. This approach would drive both environmental and economic benefits, aligning regional efforts with global climate objectives.

7.3.2 Further research

Scientists should explore the application of fully coupled regional modeling to project the potential future impacts of various land management strategies and scenarios. This modeling approach, by integrating both land surface and climate processes, will offer more accurate predictions of how different land use and management practices affect regional climate dynamics, water resources, and biodiversity. Additionally, it would provide critical insights into the effectiveness of mitigation and adaptation strategies under varying environmental and socio-economic conditions. The findings could guide policy development for sustainable land management, climate resilience, and long-term ecosystem preservation. Studies should also investigate the interactions between land use, carbon sequestration, and climate feedback mechanisms, ensuring that both mitigation and adaptation efforts are considered holistically.

Climate modeling experts should review and define the default boundaries for the model, considering the most relevant spatial context for the research. For instance, one study might use political boundaries, such as national or regional borders, to focus on governance and policy impacts. In contrast, another study could opt for ecological zones, which are based on natural environmental features like climate, land cover (vegetation) and ecosystems, to capture more precise ecological processes. It is essential to select the appropriate boundary type that aligns with the research objectives, ensuring the model effectively addresses the key factors influencing LULCC, climate interactions, and policy outcomes within the defined space.

Performance of the WRF-Hydro model validated by means of observational data comparison with outputs, such as precipitation, temperature, streamflow, and soil moisture, from weather or Eddy Covariance (EC) stations and river gauges. Statistical metrics, including Root Mean Square Error (RMSE), Nash-Sutcliffe Efficiency (NSE), MWW and correlation coefficients, should be used to assess the model's accuracy and predictive power. Additionally, spatial and temporal validation across different scales and periods is crucial to ensure consistency. Sensitivity analysis should be conducted to identify the most critical input parameters, while cross-validation with separate training and testing datasets can help evaluate the model's robustness. Comparing WRF-Hydro's performance with other hydrological models and conducting model intercomparisons will further highlight its strengths and areas for improvement, ensuring the model’s reliability in simulating hydrological processes for informed land and water management decisions.

Enhancing understanding within our university and conducting a comprehensive sensitivity analysis of feedback mechanisms are essential steps toward elucidating how land surface-atmosphere interactions influence hydrological dynamics in the WRF-Hydro model. By systematically varying key parameters, such as soil moisture, vegetation characteristics, and precipitation inputs, and analysing their impact on feedback loops, researchers can assess the model's ability to capture these complex interactions. Such studies enhance confidence in the model's capacity to simulate real-world scenarios, especially under changing climatic and land-use conditions, and provide valuable insights for improving model parameterization and reducing uncertainties.

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