



FACULTY OF AGRONOMY AND FORESTRY ENGINEERING,  
DEPARTMENT OF ECONOMY AND AGRARIAN DEVELOPMENT

**MASTER'S DEGREE IN CLIMATE CHANGE IN AGRICULTURAL SYSTEMS**

**EFFECTS OF CLIMATE VARIABILITY ON RICE PRODUCTION AND  
FARMERS' RESILIENCE IN LIBERIA**

**AUTHOR**

**Bondo T. Simpson**

**SUPERVISED BY:**

**Dr. Celsa Mondlane Macandza, PhD**

**dr. Jone L. Medja Ussalu, MSc.**

**Dr. Arsénio Daniel Ndeve, PhD**

**A Dissertation**

**Submitted to the Department of Economy and Agrarian Development in Partial  
Fulfillment of the Requirements for the Degree of Master (MSc.) in Climate Change in  
Agricultural Systems**

**Maputo, June 2026**

## DECLARATION AND RECOMMENDATION

### Declaration

I, Bondo T. Simpson hereby declare that this dissertation is my original work and has never been presented for conferment of any degree in any University.

---

Signature \_\_\_\_\_ Date \_\_\_\_\_

Name: **Bondo T. Simpson**

Registration Number: **20235564**

### Recommendation

This dissertation has been submitted for examination with our approval as University and Technical supervisors.

---

#### **Dr. Celsa Mondlane Macandza, PhD**

Faculty of Agronomy and Forestry Engineering, Eduardo Mondlane University, Mozambique

Signature \_\_\_\_\_ Date \_\_\_\_\_

#### **dr. Jone. L. Medja Ussalu, MSc.**

Faculty of Agronomy and Forestry Engineering, Eduardo Mondlane University, Mozambique

Signature \_\_\_\_\_ Date \_\_\_\_\_

#### **Dr. Arsénio Daniel Ndeve, PhD**

Faculty of Agronomy and Forestry Engineering, Eduardo Mondlane University, Mozambique

Signature \_\_\_\_\_ Date \_\_\_\_\_

## **DEDICATION**

This dissertation is dedicated to my Heavenly creator, God Almighty for his protection and provision; to my late father, Mr. George M. Simpson, who passed away in February 2026, in loving memory of his guidance and inspiration; to my beloved mother, Mrs. Mary B. Simpson, and my sisters, Gloria M. Simpson and Karleoptria B. Simpson for their unconditional support since the beginning of this achievement. May this work motivate and inspire my siblings and children to aim higher.

## ACKNOWLEDGEMENT

I would like to express my profound gratitude to God Almighty to whom I serve, praise is due for making this dream come true, seeing me through this chapter of life and providing me with supportive people.

The completion of this dissertation would not have been possible without the priceless support of my supervisors: Dr. Celsa Macandza, dr. Jone L. Medja Ussalu, and Dr. Arsénio Daniel Ndeve. I extend my sincere appreciation to them for their prompt review of this work and for their constructive feedback. I am also deeply grateful to my mentor, Dr. Henry T. Nyuma, for his tireless support from the beginning through the completion of the study. Your guidance meant a lot to me. To all the staff of the Faculty of Agronomy and Forestry Engineering who contributed to this work in one form or the other, your support will always be remembered.

To my parents, Mr. and Mrs. Simpson, and siblings, you are so loving for your supportive arms.

I will always be indebted to you, my love, Shanell F. Rogers, for your patience and encouragement throughout this journey.

Finally, I want to thank the Center of Excellence in Agri-Food System and Nutrition (CE-ASFN) who made this programme possible, and I am truly grateful for the opportunity given me to complete my master's programme via this initiative. My heartfelt appreciation also goes to the World Bank for their support, funding this project.

## TABLE OF CONTENTS

DECLARATION AND RECOMMENDATION.....	ii
DEDICATION.....	iii
ACKNOWLEDGEMENT.....	iv
TABLE OF CONTENTS.....	v
LIST OF TABLES.....	viii
LIST OF FIGURES.....	viii
ACRONYMS AND ABBREVIATIONS.....	ix
ABSTRACT.....	x
RESUMO.....	xi
CHAPTER I: INTRODUCTION.....	1
1.1. Background of the Study.....	1
1.2. Objectives.....	4
1.2.1. General.....	4
1.2.2. Specifics.....	4
1.3. Research Questions.....	4
1.4. Problem Statement.....	4
1.5. Justification of the Study.....	6
1.6. Brief Methodological Overview.....	7
1.7. Structure of the Dissertation.....	8
CHAPTER II: LITERATURE REVIEW.....	10
2.1 Definition of Terms and Concept.....	10
2.2. Climate Variability and Change.....	11
2.3. Relationship Between Climate and Rice Production.....	13
2.4. Climate Variability Impact on Rice Production.....	14
2.5. Liberia’s Agriculture Sector and Rice Production.....	16
2.5.1. Trends in Rice Production.....	17
2.6. Farmers’ Perception of Climate Risk and Adaptation Strategies to Climate Change.....	19
2.7. Agroecological Suitability Mapping for Rice Production.....	20
2.7.1. Soil.....	21

2.7.2. Topography Factors .....	22
2.7.3. Climatic Factors .....	23
2.7.4. Land Use and Land Cover .....	23
2.8. Policies and Strategies on Climate Change in Liberia .....	24
2.9. Conceptual Framework .....	24
CHAPTER III: METHODOLOGICAL FRAMEWORK.....	27
3.1. Overall Research Design.....	27
3.2. Study Setting .....	28
3.3. Data Collection Methods.....	29
3.4. Data Analysis Techniques.....	30
3.5. Ethical Considerations.....	31
3.6. Limitations of the Study.....	31
CHAPTER IV: RESEARCH ARTICLE I.....	33
Title: Effect of Climate Variability on Rice Production in Liberia.....	33
Abstract .....	34
1. Introduction.....	35
2. Materials and Methods .....	37
3. Results .....	45
4. Discussion .....	54
5. Conclusions and Policy Recommendations .....	61
6. Patents .....	63
7. References .....	65
CHAPTER V: RESEARCH ARTICLE II.....	76
Title: Geospatial Multi-Criteria Decision-Making for Land Suitability Analysis for Rice Cultivation in Liberia .....	76
Abstract .....	77
1. Introduction.....	78
2. Materials and Methods .....	79
3. Results .....	93
4. Discussion .....	99
5. Conclusions and recommendations.....	104

6. References .....	106
CHAPTER VI: INTEGRATIVE DISCUSSION.....	115
CHAPTER VII: GENERAL CONCLUSION .....	118
REFERENCES .....	120
APPENDICES .....	135
Appendix 1. Ethical Clearance.....	135
Appendix 2. Data Collection Tool .....	135
Appendix 3. Supplementary Materials.....	136
Appendix 3.1. Supplementary Materials (Figure S1. Spatial variability of precipitation and temperature with major and minor rice production areas). .....	136
Appendix 3.2. Supplementary Materials (Figure S2. Liberia climate classes based on Köppen classification).....	136
Appendix 3.3. Supplementary Materials (Figure S3. Climate projection of Precipitation). 137	
Appendix 3.4. Supplementary Materials (Figure S4. Climate projection of temperature). 137	
Appendix 4. Proof of Acceptance/Publication.....	138
Appendix 4.1. Certificate of publication of the article titled: Effect of Climate Variability on Rice Production in Liberia.....	138
Appendix 4.2. Letter of acceptance of the manuscript titled: Geospatial Multi-Criteria Decision-Making for Land Suitability Analysis for Rice Cultivation in Liberia. ....	139

## LIST OF TABLES

<b>Table 2-1.</b> Calendar of rice production in Liberia.....	17
---	----

## LIST OF FIGURES

<b>Figure 2-1.</b> Conceptual framework .....	26
<b>Figure 3-1.</b> Map of Africa with the Study area. ....	29

## ACRONYMS AND ABBREVIATIONS

AHP	Analytical Hierarchy Process
CARD	Competitiveness Analysis of Local Rice to Imported Rice
CBL	Central Bank of Liberia
CCKP	Climate Change Knowledge Portal
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station
DEM	Digital Elevation Model
EPA	Environmental Protection Agency
FAO	Food Agricultural Organization
FAOSTAT	Food Agricultural Organization Statistics
GDP	Gross Domestic Product
GIS	Geographic Information System
IPCC	Intergovernmental Panel for Climate Change
LAC	Liberia Agriculture Census
LASIP	Liberia Agriculture Sector Investment Program
LIBSIS	Liberia Soil Information System
LISGIS	Liberia Institute of Statistics and Geo-Information Services
LULC	Land Used and Land Cover
MLR	Multiple Linear Regression
MOA	Ministry of Agriculture
NAPA	National Adaptation Programme of Action
NPRSCC	National Policy and Response Strategy on Climate Change
PAPD	Pro-Poor Agenda for Prosperity and Development
SDGs	Sustainable Development Goals
SLF	Sustainable Livelihood Framework
SRTM	Shuttle Radar Topography Mission
UNDP	United Nations Development Programme
UNFCCC	United Nations Framework Convention on Climate Change
USGS	United States Geographical Survey
WB	World Bank

## ABSTRACT

Climate variability poses major challenges to agriculture worldwide amid increasing population growth and rising food demand. In Liberia, rice is a staple crop, however, its production remains low and highly vulnerable to changing climate conditions. This study evaluates the impact of climate variability on rice production while identifying suitable areas for sustainable rice cultivation in Liberia. Rice production and yield data were obtained from the Food and Agriculture Organization Statistics (FAOSTAT) database, while climate variables (temperature and precipitation) were sourced from ERA5 Agrometeorological Indicators and Climate Hazards Group InfraRed Precipitation with Station (CHIRPS), for the period of 1990–2023. Climate trends and relationships with rice production were examined using the Mann–Kendall test, Sen’s slope estimator, and Spearman’s rank correlation, while Multiple Linear Regression was applied to estimate climate impacts on rice productivity. In addition, a GIS-based Multi-Criteria Decision-Making approach using the Analytic Hierarchy Process was employed to map rice suitability. Results indicate that mean, minimum, and maximum temperatures increased by 0.57 °C, 0.55 °C, and 0.55 °C, with a strong variability in precipitation, reaching 180.31 mm. Production observed a total increase of 76,200 tons, while yield remained relative stable at 1.2 tone/hectare. Regression results revealed a significant negative impact of minimum temperature ( $p = 0.015$ ) on rice production and a positive effect of precipitation on yield ( $p = 0.036$ ). Suitability analysis shows that 5.57% of Liberia is highly suitable, 44.57% suitable, 42.41% moderately suitable, and 7.45% unsuitable for rice cultivation, with soil pH, slope, and soil texture identified as key limiting factors. Highly suitable areas are found in the central, northern, and southeastern counties, including Lofa, Bong, Nimba, Gbarpolu, Grand Gedeh, and River Gee. Overall, the findings highlight the sensitivity of rice production to climate variability and demonstrate significant potential for expanding rice cultivation through strategic land-use planning, improved technologies, and institutional support to strengthen farmer resilience and national food security.

---

**Keywords:** rice production; rainfall variability; farmer adaptation strategies; multi-criteria decision-making; land suitability; GIS; Liberia

## RESUMO

A variabilidade climática impõe grandes desafios à prática agrícola ao nível mundial, aliada ao aumento populacional e da demanda alimentar. Na Libéria, o arroz é um alimento básico, no entanto a sua produção continua baixa e altamente vulnerável às alterações climáticas. Este estudo avalia o impacto da variabilidade climática na produção de arroz, identificando áreas adequadas para o seu cultivo sustentável. Os dados de produção e rendimento do arroz foram obtidos a partir da base de dados da FAOSTAT (Organização das Nações Unidas para a Alimentação e a Agricultura), e foram utilizados os dados de alterações climáticas (temperatura e alterações), constituídos por dados de reanálise do ERA5 e do CHIRPS (Climate Hazards Group InfraRed Precipitation with Station), do período de 1990 a 2023. Tendência das variáveis climáticas e suas correlações com a produção de arroz foram examinadas através do teste de Mann-Kendall, tendência de Sen e pela correlação de Spearman, enquanto a Regressão Linear Múltipla foi aplicada para estimar os impactos climáticos na produtividade do arroz. Por outro lado, a aptidão para o cultivo do arroz foi examinada e mapeada a partir do método de Tomada de Decisão Multicritério baseado em SIG, e utilizando o Processo de Hierarquia Analítica. Os resultados indicam que as temperaturas média, mínima e máxima aumentaram 0,57 °C, 0,55 °C e 0,55 °C, respetivamente, com uma grande variabilidade na precipitação. A produção apresentou um aumento total de 76.200 toneladas, enquanto o rendimento se manteve relativamente estável na 1.2 toneladas por hectare. Os resultados da regressão revelaram um impacto negativo significativo da temperatura mínima ( $p = 0,015$ ) na produção de arroz e um efeito positivo da precipitação na produtividade ( $p = 0,036$ ). A análise de aptidão mostrou que 5,57% de Libéria é muito apta, 44,57% apta, 42,41% moderadamente apta, e 7,45% inadequada para o cultivo do arroz. Foram identificados como limitantes para a aptidão os seguintes factores: o pH do solo, o declive do terreno e a textura do solo. As áreas altamente adequadas encontram-se nas zonas centro, norte e sudeste, incluindo Lofa, Bong, Nimba, Gbarpolu, Grand Gedeh e River Gee. De um modo geral, os resultados destacam a sensibilidade da produção de arroz à variabilidade climática e demonstram um potencial significativo para a expansão da cultura do arroz através de um planeamento estratégico do uso da terra, tecnologias melhoradas e apoio institucional para reforçar a resiliência dos agricultores e a segurança alimentar nacional.

---

**Palavras-chave:** produção de arroz; variabilidade das chuvas; estratégias de adaptação dos agricultores; tomada de decisão multicritério; Aptidão da terra; SIG; Libéria

## CHAPTER I: INTRODUCTION

### 1.1. Background of the Study

Climate variability, including changes in rainfall patterns, temperature, and the frequency of extreme weather events, poses significant challenges to climate-sensitive sectors such as agriculture (IPCC, 2023b; Mulungu & Kangogo, 2022; Reyes *et al.*, 2021; Yuan *et al.*, 2024). Agriculture is particularly vulnerable because crop growth and productivity depend strongly on climatic conditions. Among major food crops, rice plays a crucial role in global food security and rural livelihoods. However, rice production is highly sensitive to fluctuations in temperature and precipitation, which influence crop growth, phenology, and yield outcomes (Ayanlade *et al.*, 2018; Adjah *et al.*, 2022). As a result, understanding the relationship between climate variability and rice production has become increasingly important for sustainable agricultural development.

Globally, rice is the primary staple food for more than 60% of the world's population, with Asia accounting for over 90% of global production and consumption worldwide (Robertson & Oinam, 2023). Despite its global importance, rice cultivation is increasingly threatened by climate variability and climate change. Rising temperatures, irregular precipitation patterns, and extreme weather events have been shown to significantly affect rice productivity (Jagadish *et al.*, 2015; Song *et al.*, 2022; Wassmann and Dobermann, 2012). Temperature increases during critical growth stages, particularly panicle initiation, flowering, and fertilization, can substantially reduce grain yield and quality. For instance, Song *et al.* (2022) reported that a 1°C increase above optimal temperature may reduce rice yield by approximately 8%, while Peng *et al.* (2004) found that grain yield declined by about 10% for every 1°C increase in growing-season minimum temperature. Precipitation variability also plays an important role in rice productivity. Maiti *et al.* (2024) observed that rice yield decreased by about 6.4 kg for every 100 mm increase in rainfall beyond optimal levels in India. Similarly, Gumel *et al.* (2017) found that an increase in daily mean rainfall of +1 mm to +2 mm above the threshold, had a decreased yield of -4.0% to -51.5% in Malaysia. These findings highlight the strong sensitivity of rice production systems, particularly rain-fed systems, to climatic fluctuations.

Recent research has also identified threshold effects in the relationship between temperature increases and crop productivity. Using threshold regression and mixed-effects models, Tran *et al.* (2025) demonstrated that rising temperatures negatively affect crop yields, with impacts becoming more severe once certain temperature thresholds are exceeded. For rice, yield losses increase significantly when warming surpasses approximately 3.13°C. Such climatic changes pose serious risks to global food security and diet quality, particularly among vulnerable populations (Micha *et al.*, 2020).

In Sub-Saharan Africa (SSA), rice has become an increasingly important staple food and a major source of calories and income for millions of households (Adjah *et al.*, 2022; Pope *et al.*, 2023). Between 2009 and 2019, annual rice consumption in SSA averaged about 27.4 million metric tons, while production was only around 15.4 million metric tons, resulting in a substantial production deficit (Ibrahim *et al.*, 2022). Rapid population growth, urbanization, and changing dietary preferences have further increased rice demand in the region (Daszkiewicz, 2022; Saito *et al.*, 2023). Despite this rising demand, rice production remains constrained by factors such as limited access to improved technologies, declining soil fertility, and increasing climate variability, forcing many countries to rely heavily on imports.

Liberia represents a clear example of this growing dependence on rice. Rice is the dominant staple food in the country and contributes approximately 50% of the daily caloric intake of adults, with an estimated annual per capita consumption of about 133 kg (Pope *et al.*, 2023). Approximately 69% of farmers cultivate rice, making it one of the most important crops for food security and rural livelihoods (MOA, 2018). Despite its importance, domestic rice production remains insufficient to meet national demand. Rice consumption reached approximately 560,000 metric tons in 2021, while local production has struggled to keep pace, declining from about 257,995 metric tons in 2018 to approximately 170,000 metric tons in 2021 (Pluato *et al.*, 2024). Consequently, Liberia spends over USD 100 million annually on rice imports, placing significant pressure on the national economy.

Rice productivity in Liberia is also relatively low, with average yields ranging between 1.1 and 1.2 tons per hectare—far below the regional average of 4–6 tons per hectare (Pope *et al.*, 2023; Saysay *et al.*, 2018; Sumo *et al.*, 2023). Several factors contribute to this low productivity, among

which climate variability has become increasingly important. Over the past three decades, Liberia has experienced noticeable shifts in climate patterns, including rising temperatures, irregular rainfall distribution, and more frequent extreme events such as floods and droughts (CCKP, 2021; Funk *et al.*, 2015). Because Liberia's agricultural system relies predominantly on rain-fed farming, these climatic changes have direct implications for crop productivity. This challenge is further intensified by the fact that nearly 70% of the population depends on agriculture and forestry for their livelihoods (CBL, 2023; Jr & Diallo, 2025).

Although several studies have examined climate change and agriculture in Liberia, most have focused on localized areas or farmers' perceptions rather than nationwide empirical analyses. For instance, Dorbor-soko (2024) examined the impacts of climate variability and change on rice production in Bong County, while Dorbor Wuokolo (2023) investigated farmers' perceptions of climate change and barriers to adaptation among smallholder farmers in Todee District. Similarly, Sarnoh (2024) assessed climate risks in central and northern Liberia. Although these studies provide valuable insights, they are limited in geographic scope and do not capture national-scale dynamics. In contrast, Jr & Diallo (2025) conducted a systematic review focusing on climate change impacts on Liberia's agricultural sector and associated adaptation strategies, rather than empirical analysis of rice production trends. Consequently, there remains a lack of comprehensive, country-wide studies examining the relationship between climate variability and rice production.

Given this gap, the present study evaluates the effects of climate variability on rice production in Liberia using national datasets covering the period 1990–2023. Specifically, it analyzes trends in rice production and yield, examines temporal patterns in key climate variables, particularly temperature and precipitation; and assesses their statistical relationships with rice productivity. In addition, the study incorporates future climate projections under the RCP8.5 scenario to determine whether current climatic trends are likely to persist. The findings provide important insights for developing climate-resilient agricultural policies and strengthening food security in Liberia and across Sub-Saharan Africa.

## **1.2. Objectives**

### **1.2.1. General**

The overall aim of this study is to evaluate the effects of climate variability on rice productivity and to examine the resilience and adaptive strategies of farmers in Liberia.

### **1.2.2. Specifics**

1. To determine trends in rice production and yield in Liberia from 1990 to 2023.
2. To examine patterns and changes in key climate variables (precipitation and temperature) and trends from 1990 to 2023 in Liberia.
3. To assess statistical relationship between climate variables and rice production and yield.
4. To investigate the resilience and adaptation strategies employed by rice farmers in Liberia.
5. To map the agroecological areas suitable for rice production based on climate variables (temperature and precipitation), soil type and topography data in Liberia.

## **1.3. Research Questions**

The following research questions are to be addressed.

- a. What are the trends in rice production and yield in Liberia from 1990 to 2023?
- b. How have precipitation and temperature patterns changed in Liberia from 1990 to 2023?
- c. How do temperature and precipitation affect rice yield in Liberia?
- d. What resilience and adaptation strategies do rice farmers employ in response to climate variability?
- e. Which agroecological areas are suitable for rice production in Liberia based on climate, soil, and topography factors?

## **1.4. Problem Statement**

In Liberia, rice serves as a key staple food crop and is a primary source of income for smallholder farmers, who largely rely on rainfed agriculture (Pope *et al.*, 2023). Despite its central role in food security, rice productivity remains low, averaging 1.2 MT ha<sup>-1</sup>, insufficient to meet national

demand (Sumo *et al.*, 2023). Consequently, Liberia imports over 60% of its annual rice consumption (Pluato *et al.*, 2024), making the country highly vulnerable to external market fluctuation and global price shocks. Strengthening domestic rice production is therefore essential to safeguard national food security.

This challenge is compounded by increasing climate variability. Over the past three decades, Liberia has experienced rising temperatures, irregular rainfall, and a growing frequency of extreme weather events, including floods and droughts (CCKP, 2021; Funk *et al.*, 2015). Because rice cultivation is largely rainfed, these changes disrupt planting and harvesting calendars, adversely affecting yields and highlighting food security (Nelson *et al.*, 2013; Tarway-twalla, 2013; Page *et al.*, 2023; EPA, 2024). Smallholder farmers, who constitute over 70% of the population, are particularly vulnerable, often lacking access to irrigation, improved seeds, and modern technologies that could buffer against climate-related shocks (Sarnoh, 2024; World Bank, 2024).

Despite mounting evidence of climate-related risks, national-level evidence on its long-term effects on rice production remains limited. Most studies focus on localized areas or specific aspects of climate impact. For instance, Dorbor-Soko (2024) examined the impacts of climate variability and change on rice production in Bong County, Dorbor Wuokolo (2023) assessed farmers' perceptions and adaptation barriers in Todee District, and Sarnoh (2024) evaluated climate risks in central and northern Liberia. While informative, these studies do not provide a comprehensive understanding of climate-rice dynamics across the country. Additionally, systematic reviews (Jr & Diallo, 2025) did not empirically explore statistical relationships between climate variables and rice yields.

Another critical gap concerns land suitability. GIS-based Multi-Criteria Decision-Making (MCDM) integrated with the Analytical Hierarchy Process (AHP) has proven effective for assessing crop suitability by evaluating climatic, topographic, and soil factors (Ayehu and Besufekad, 2015; December *et al.*, 2022; Hossen *et al.*, 2021). Applications in Nigeria (Victor and Samson, 2019), Ghana (December *et al.*, 2022), Kenya (Joseph Kihoro, 2013), and Bangladesh (Islam *et al.*, 2018) have enhanced evidence-based agricultural planning. While agroecological zoning is a proven tool for guiding crop suitability, there is a lack of comprehensive national-level GIS-based assessment to identify areas suitable for rice cultivation under current and future climatic conditions in Liberia, limiting strategic planning and sustainable production.

Furthermore, resilience-building efforts in the rice sector remain fragmented inadequate. Many farmers lack access to timely climate information, extension services, credit facilities, and climate-smart technologies that could enhance their capacity to cope with climate shocks (Asfaw *et al.*, 2019; Fosu-Mensah *et al.*, 2012; World Bank, 2024).

Given the central role of rice in Liberia's food system and the increasing risks posed by climate variability, there is an urgent need for a national-level assessment of climate impacts on rice production. This study, therefore, seeks to address the existing gaps by analyzing trends in rice production and yield from 1990 to 2023, determining changes in temperature and precipitation, assessing statistical relationships of these climatic variables with rice productivity, and mapping agroecologically suitable areas for rice cultivation using GIS-based MCDM and AHP. The findings are expected to inform climate-resilient rice production strategies, strengthen farmers' adaptive capacity, and support sustainable agricultural development and policy planning in Liberia.

### **1.5. Justification of the Study**

The study holds significance for several interconnected reasons. First, it directly addresses a critical national priority: enhancing food security and reducing Liberia's reliance on imported rice by strengthening domestic production. As the country's staple crop, rice is not only a vital source of nutrition but also carries considerable political and economic importance (Pope *et al.*, 2023). Improving rice productivity requires a comprehensive understanding of multiple constraints affecting production, particularly the growing impacts of climate variability (NAP, 2020).

Although the global effects of climate change are widely acknowledged, their specific manifestations are often localized and context-specific (Joseph *et al.*, 2023). In Liberia, empirical evidence on how climate variables, especially rainfall and temperature affect rice production remains limited. This study aims to fill this gap by analyzing long-term climatic trends in Liberia and linking them to observed changes in rice yields. Such evidence is crucial for informing national climate adaptation planning and for guiding more targeted investments aimed to strengthening in agricultural resilience (Niang *et al.*, 2014; Bouteska *et al.*, 2024).

This research underscores the importance of farmers' perceptions and their adaptation behaviors. Existing literature demonstrates that perception is key driver of adaptation; farmers who recognize climate risk and understand their implications are more likely to adopt effective coping strategies, such as changing planting dates, selecting climate-resilient crop varieties, or modifying their farming systems (Fosu-Mensah *et al.*, 2012). In Liberia, however, many smallholder farmers continue to rely heavily on traditional knowledge and often limited access to reliable climate information, thereby constraining the effectiveness of their adaptive responses (World Bank, 2024). Furthermore, the study seeks to identify areas most suitable for rice cultivation, emphasizing the critical role of land use and land cover in agricultural planning and development.

The study findings are expected to inform evidence-based policy implementation, particularly in alignment with Liberia's National Adaptation Plans (NAP) (NAP, 2020), the National Climate Change Policy and Response Strategy (NPRSCC, 2018), the Climate-Smart Agriculture Investment Plan (CSAIP), and the Liberia Agricultural Sector Investment Plan (LASIP-II) (EPA, 2018; NAP, 2022). The research also contributes to the broader Sustainable Development Goals (SDGs), specially SDG 1 (No Poverty), SDG 2 (Zero Hunger), and SDG 13 (Climate Action) (Grigorieva *et al.*, 2023). By assessing the impact of climate variability on rice production and integrating remote sensing, GIS-based climate data, and literature-based assessment of farmer adaptation, this study provides novel, Liberia-specific evidence that enhances understanding of how climate variability influences agricultural productivity, contributing to the broader literature on climate impacts in Liberia and across sub-Saharan Africa. Additionally, this study presents a practical and replicable research model that can be applied and scaled in other data-scarce regions.

## **1.6. Brief Methodological Overview**

This study adopts a mixed methodological framework integrating statistical time-series analysis and spatial multi-criteria evaluation to assess rice production dynamics and land suitability in Liberia. Secondary data were obtained from multiple reliable sources, including Food and Agriculture Organization Statistics (FAOSTAT) data base, for rice production and yield, while temperature and precipitation were obtained from the Copernicus Climate Change Service for temperature, and the Climate Hazards Group for precipitation (CHIRPS), covering the period

1990–2023. Future climate projections data were derived from Coordinated Regional Climate Downscaling Experiment under the RCP8.5 scenario.

Data preprocessing included quality control procedures such as missing value checks, outlier detection, and consistency verification. Climate raster datasets were processed in ArcGIS (version 10.8) to extract seasonal (April–September) national-level averages relevant to rice cultivation. For trend detection, the non-parametric Mann–Kendall test and Sen’s slope estimator were applied. Relationships between climate variables and rice production were assessed using Spearman’s rank correlation, followed by multiple linear regression to quantify the combined effects of these independent variables (temperature and precipitation) on rice productivity. Spatial suitability analysis was conducted using Geographic Information Systems (GIS) integrated with a Multi-Criteria Decision-Making (MCDM) approach, considering ten key factors: precipitation, temperature, elevation, slope, soil texture, soil pH, soil organic carbon, nitrogen, phosphorus and potassium. Factor weights were determined using the Analytic Hierarchy Process, ensuring consistency ( $CR < 0.1$ ). The weighted linear combination was then applied to generate final land suitability maps.

Together, these approaches provide a robust and integrated assessment of historical trends, climate impacts, and areas suitability for rice production in Liberia.

## **1.7. Structure of the Dissertation**

This dissertation is structured into seven chapters that are connected to the study objectives. Following this introductory chapter, is chapter two (literature review), which discusses the relationship between climate and production, reviews the relevant literature on climate change and variability and the impacts of these on agricultural crop production and livelihoods with reference to Liberia and Sub-Sahara Africa (SSA). Additionally, chapter two explores literature on various frameworks that have been used to assess climate impacts to agricultural crop production and livelihoods of rural households, and land suitability assessment. In addition, this chapter also place emphasis on developments and policies instituted by government in the combat of climate change in Liberia. Correspondingly, the study framework is also discussed in this chapter. Chapter three illustrates the study area (Liberia) emphasizing the farming system and practices employed by smallholder farmers and the climate condition in Liberia. The overall research design and

methodology are also discussed in this Chapter, depicting the range of quantitative approaches used to collect and analyze data. The relevance of these approaches for this study is discussed in this chapter. Besides, Issues relating to ethical considerations are explored in Chapter three. Finally, Chapter three also investigates the strengths and limitations of the research. Chapter four and Chapter five focussed on the provision of details of articles submitted for publication. Chapter four provides detailed information on the first articles which is integrated in the dissertation. The chapter provides brief information about articles, including the title of the article, name of the journal submitted to, and the publication status of the article. The full length of the article is also provided in this chapter.

In chapter five, detailed information about the second article. This encompasses of brief introduction about article II, including the name of the journal submitted to, and the current publication status of the article. It also provides the full article. Chapter six provides an integrative discussion of the full dissertation. This chapter highlights the improvement in rice production in Liberia over time, the contributing factors, and its actual or general implication to current productivity gains. It highlights factors contributing to low yields despite high land suitability areas, recommending the integrated strategies to improve productivity and resilience, thus providing recommendations for future research. Lastly, chapter seven summarises the main conclusions and provides a synthesis of the key findings, exploring the implications for agricultural production and food security in Liberia. This chapter also provides the list of reference, appendices and extra figures that support the finding of the thesis, as well as other key information, including data collection tools and proof of publication for manuscripts.

## CHAPTER II: LITERATURE REVIEW

### 2.1 Definition of Terms and Concept

Key terminologies such as vulnerability, adaptation, and resilience are yet, have universally accepted definitions, and their interpretations remain debated. Considering this, the current study adopts specific working definitions that will be consistently used throughout the research. The rationale for selecting these definitions is presented to guide and support the analysis and discussion.

**Adaptation:** is defined as the actions, practices, and strategies undertaken by farmers to adjust to actual or expected climate variability and change in order to reduce vulnerability, minimize adverse impacts, and sustain agricultural productivity. Such measures may include changing planting dates, adopting drought-tolerant crop varieties, diversifying crops, improving drainage and irrigation systems, and implementing soil and water conservation practices.

**Climate change** is a long-term shift in the condition of the climate that is demonstrated by variations in the average and variability of its possessions. It refers to any environmental change caused by human or natural causes (UNFCCC, 2021). Climate change also refer to long-term changes in the average climate conditions, usually over decades to centuries (Hansen *et al.*, 2012; Matulla *et al.*, 2018).

**Climate variability:** refers to the natural fluctuations in climate patterns over shorter periods, such as months, years, or decades, due to natural processes like solar radiation changes, volcanic eruptions, or oceanic cycles like El Niño and La Niña (Katz & Rothenberg, 2005; Roy, 2020).

**Resilience:** can be defined as the capacity of farmers or farming systems to absorb, recover from and continue functioning after climate shocks such as droughts, floods or heatwaves while maintaining their essential functions, productivity, and livelihoods. According to the Intergovernmental Panel on Climate Change resilience is defined as "the capacity of social, economic and environmental systems to cope with a hazardous event or trend, responding or reorganizing in ways that maintain their essential function, identity and structure."

**Rice production:** is defined as the total quantity of rice harvested within a given area and period, influenced by cultivated area, agronomic practices, and environmental conditions (Japhet *et al.*,

2025). It is a complex process involving interactions among soil, climate, inputs, and management (Japhet *et al.*, 2025).

**Rice yield:** refers to the amount of rice produced per unit area (e.g., tonnes per hectare) and is a key indicator of productivity (Wang *et al.*, 2024). It is determined by physiological and agronomic factors such as grain number, grain weight, and tiller number.

**Vulnerability:** is defined as the propensity or predisposition to be adversely affected and encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt (IPCC, 2021).

**Livelihoods:** “a livelihood comprises the abilities, assets (stores, resources, claims and access) and activities that are required for a means of living” (Sarnoh, 2024). An assessment of livelihoods offers the opportunity to point out the various adaptations that might be available to determine how rural communities can cope with declining crop yields due to drought.

## 2.2. Climate Variability and Change

Climate change has evolved significantly over time across global, regional, and local scales, reflecting both natural processes and increasing anthropogenic influences. Globally, long-term observations indicate a clear warming trend since the mid-20th century, accompanied by increased frequency and intensity of extreme events such as heatwaves, heavy precipitation, and prolonged droughts (IPCC, 2021). For instance, Asfaw *et al.* (2018) reported inter-annual variability in rainfall, with mean and minimum temperatures showing significant increasing trends over time, whereas the maximum temperature trend was not significant. These changes have also been reported in other regions across the globe. Mamun *et al.* (2023) revealed that maximum and minimum temperatures were steadily increasing, with the southwest experiencing a more rapid rise compared to other regions in Bangladesh. These changes are closely linked to rising greenhouse gas concentrations, which have altered atmospheric and oceanic circulation patterns, thereby influencing temperature and precipitation regimes (Bedair *et al.*, 2023).

Across Africa, climate variability has intensified over recent decades, with rising temperatures occurring faster than the global average and rainfall patterns becoming more unpredictable, particularly in semi-arid and tropical regions (African Development Bank Group (AFDB), 2020). Historically, Africa has experienced cycles of drought and wet periods, but recent trends show

increased climate instability, exacerbating water stress and agricultural vulnerability. In West Africa, climate variability has undergone notable shifts since the 1970s, marked by severe droughts during the Sahelian drought period (1970s–1980s), followed by partial rainfall recovery but with increased interannual variability and more frequent extreme events (WMO, 2021, 2024). Changes in the West African Monsoon system have contributed to delayed rainfall onset, early cessation, and uneven spatial distribution, all of which affect agricultural calendars and productivity.

In Liberia's climate is predominantly tropical and humid, characterized by minimal diurnal and seasonal temperature variations and influenced by monsoon, tropical savanna, and equatorial systems (EPA, 2018; CCKP, 2021). In recent decades, the country has experienced rising temperatures, shifting rainfall patterns, and increasingly erratic seasonal cycles, leading to greater uncertainty in planting seasons and heightened risks of floods, droughts, coastal erosion, and sea-level rise (EPA, 2018; TNA, 2020; CCKP, 2021). These changes particularly affect smallholder farmers who are more dependent on rain-fed agriculture, with significant implications for crop productivity, especially rice. Historical records indicate that between 1991 and 2020, Liberia's mean annual temperature was approximately 25.7°C, ranging from 23.9°C in August to 26.8°C in March (CCKP, 2021).

Overall, the temporal evolution of climate variability from global to local scales reflects a shift toward more unstable and extreme conditions, underscoring the growing need for adaptation and resilience strategies. Future projections indicate substantial warming, with temperatures expected to rise by about 3.2°C by the 2080s and potentially exceeding 4.8°C by the end of the century under high-emission scenarios, with more pronounced increases in northern inland regions than along the coast (CCKP, 2021). This warming is expected to intensify the frequency and duration of extreme heat, with hot days projected to account for 24–65% of all days by mid-century and 29–90% by century's end, alongside a marked increase in warm nights (37–89% and 49–95%, respectively), suggesting a prolonged and intensified hot season (CCKP, 2021; EPA, 2021c; World Bank, 2024). Even near-term projections (2010–2050) indicate temperature increases of 0.4°C to 1.3°C, which are likely to disrupt water balance and reduce agricultural productivity (EPA, 2021c; NAP, 2020).

Concurrently, precipitation patterns exhibit high variability, with mean annual rainfall around 2,500 mm, though coastal regions receive over 4,000 mm compared to significantly lower amounts inland (EPA, 2021b). While rainfall has generally declined since 1960, uncertainty persists regarding long-term trends due to variability. Peak rainfall occurs in June and July, reaching up to 1,000 mm monthly, and projections suggest that coastal areas such as Monrovia could receive up to 5,000 mm annually by 2050 (EPA, 2013). These patterns are further compounded by high relative humidity along the coast (>80%) and strong seasonal contrasts inland, where humidity can drop to 20% during the dry season but rise to 90–100% during the rainy season (EPA, 2018; CCKP, 2021). Collectively, these climatic changes underscore increasing environmental stress and pose serious challenges to Liberia's water resources, agricultural systems, and overall climate resilience. Hence, the temporal development of climate variability from global to local scales highlights a transition toward more unstable and extreme climate conditions, underscoring the growing need for climate adaptation and resilience strategies.

### **2.3. Relationship Between Climate and Rice Production**

The nexus between climate and rice production is complex and bidirectional. On one hand, rice production is highly sensitive to climate variability. Changes in temperature, rainfall patterns, and the frequency of extreme events such as droughts and floods directly affect rice growth, yield stability, and overall productivity (Reyes *et al.*, 2021; Song *et al.*, 2022). Rising temperatures can shorten growing periods and increase evapotranspiration, while erratic rainfall disrupts water availability, making rice systems particularly vulnerable and threatening global food security (Gwambene *et al.*, 2023; Yu *et al.*, 2024).

On the other hand, rice cultivation significantly contributes to climate change. Traditional flooded paddy systems create anaerobic conditions that promote methane emissions, a potent greenhouse gas. Rice cultivation is estimated to account for a notable share of global anthropogenic methane emissions, largely due to continuous flooding and organic matter decomposition (Jena, 2023).

Therefore, rice production is both a victim and a driver of climate change. Addressing this nexus requires climate-smart agricultural practices, such as improved water management and low-emission technologies, to enhance resilience while reducing environmental impacts.

## 2.4. Climate Variability Impact on Rice Production

Climate change and increasing climate variability pose significant threats to agricultural production and food security worldwide, particularly in regions reliant on rainfed systems (Reyes *et al.*, 2021; IPCC, 2023a). Climate variability encompasses natural fluctuations in temperature, precipitation, and the frequency or intensity of extreme weather events over short to medium timescales (months to decades), driven by processes such as changes in solar radiation, volcanic activity, and ocean-atmosphere cycles including El Niño and La Niña (Katz & Rothenberg, 2005; Roy, 2020). In sub-Saharan Africa, where rainfed agriculture predominates, such variability critically affects crop production systems, rural livelihoods, and food security (Niang *et al.*, 2014). For instance, Liberia's agricultural sector, heavily dependent on rainfed rice cultivation and characterized by limited adaptive capacity, is highly vulnerable to these climatic fluctuations (Adjah *et al.*, 2022; Ayanlade *et al.*, 2023).

Temperature and precipitation are the primary climatic factors influencing rice growth, development, and productivity (Adjah *et al.*, 2022; Shrestha *et al.*, 2022). Deviations from optimal conditions frequently result in substantial yield reductions (Jie *et al.*, 2020; Yila *et al.*, 2023). Rising temperatures negatively affect physiological processes including germination, tillering, flowering, and grain filling (Su *et al.*, 2023; Yu *et al.*, 2024).

Empirical studies indicate that a 1°C increase above the optimal threshold can reduce yields by 8% (Song *et al.*, 2022), while grain yield may decline by 10% for each 1°C increase in minimum growing-season temperatures during the dry season, with maximum temperatures showing less effect (Peng *et al.*, 2004). Temperature increases during reproductive stages such as panicle initiation, flowering, and fertilization severely reduce both yield and grain quality (Wassmann and Dobermann, 2012). Similarly, another work (Nguyen *et al.*, 2024) investigates the impact of seasonal climate change on rice productivity in Vietnam's Central Coast. The results revealed that a 1% increase in maximum temperature leads to a 1.66% increase in winter–spring rice yields but results in a 1.01% decline in summer–autumn yields. Conversely, a 1% rise in minimum temperature reduces winter–spring yields by 0.30% while increasing summer–autumn yields by 3.32%. The same authors found that higher levels of both maximum and minimum relative humidity are associated with improvements in rice yields. In contrast, a 1% increase in maximum precipitation slightly decreases summer–autumn yields.

Precipitation variability further increases these risks. Excess rainfall beyond optimal thresholds reduces rice yields, as demonstrated by a 6.4 kg decline per 100 mm increase in India (Maiti *et al.*, 2024) and reductions ranging from  $-4.0\%$  to  $-51.5\%$  in Malaysia for daily rainfall increases of +1 to +2 mm above thresholds (Gumel *et al.*, 2017). Timing and distribution of rainfall are especially critical in tropical regions such as Liberia, where rainfed rice cultivation predominates. Delayed or early rainfall onset can disrupt planting calendars, while insufficient or excessive rainfall may cause water stress or flooding during sensitive growth stages such as transplanting, flowering, and grain development (Jagadish *et al.*, 2015; Song *et al.*, 2022). Another study, Sultan *et al.* (2013) reported that even a one-week delay in rainfall onset could reduce rice yield by 10%–20%.

In Liberia, climate records indicate rising temperatures and increasingly erratic rainfall patterns. Between 1971 and 2020, the mean temperature increased at an estimated rate of  $0.13^{\circ}\text{C}$  per decade, accompanied by delayed rainfall onset, shortened rainy seasons, and high-intensity precipitation events that cause flooding and soil erosion (Niang *et al.*, 2014; CCKP, 2021; EPA, 2021b). These anomalies, compounded by prolonged dry spells, unseasonal rainfall, and heatwaves, are adversely impacting rice productivity and farmers' ability to plan and invest (Dorbor-soko, 2024; EPA, 2021b). Projections by the sixth assessment report of the Intergovernmental Panel on Climate Change (Calvin *et al.*, 2023; IPCC, 2023a) forecast an increase in the frequency and severity of extreme weather events in Africa. For Liberia, this suggests a heightened risk of multiple climatic events such as simultaneous droughts and heatwaves, which could result in severe crop failures in the absence of adequate resilience measures. Climate-induced risks in Liberia are compounded by structural constraints, including limited irrigation infrastructure, declining soil fertility, inadequate access to agricultural technology, credit, climate information, and weak extension services, exacerbate vulnerability and reinforce reliance on traditional knowledge and experiential learning (Chala *et al.*, 2020; NAP, 2020).

To address these challenges, there is a pressing need to integrate climatic and agronomic data to better assess rice yield responses under varying climatic conditions and support climate-resilient agricultural practices, such as the adoption of drought-tolerant rice varieties, conservation agriculture, and supplemental irrigation. Such an approach can inform both short-term cropping decisions and long-term adaptation strategies, ultimately safeguarding rice productivity.

## 2.5. Liberia's Agriculture Sector and Rice Production

Liberia continues to face challenges in its transition from a prolonged 14-year civil crisis towards peace, alliance, and economic recovery (Longzhu *et al.*, 2025). In 2006, the new government established critical measures to address urgent challenges, prioritizing sustainable peace and development. Central to these efforts was the agriculture sector, aimed at improving access to food, employment, and income (CBL, 2023). Despite these initiatives, agriculture remains a major contributor to Liberia's economic development (CBL, 2023; Longzhu *et al.*, 2025).

According to the Liberia Agriculture Census (LAC) 2022/2023 household report, there are over 1 million of Liberia's population engaged in agriculture, amounting to approximately 499,732 agricultural holders, averaging two per household with about 338,630 agricultural households, which are predominantly led by males (64.5%) (LISGIS, 2024). These households are predominantly located in the rice-producing counties, such as Nimba, Bong, and Lofa accounting 21.4%, 16.7%, and 12.7%, respectively, which account for approximately 56.3% of the total farmers' households producing the nation's primary crop particularly rice (LISGIS, 2024).

Rice (*Oryza sativa*), an Asian crop, belongs to the family Gramineae (Poaceae), is the most widely cultivated and traded crop globally for food, feed, and industrial purposes (Benjamin *et al.*, 2024). In Liberia, rice holds key importance for socio-economic and food-security and is primarily cultivated countrywide using three methods, including drilling, dibbling, and broadcasting, with the last used by 98.2% of farmers (Pope *et al.*, 2023). Rice is cultivated across both upland and lowland ecosystems in Liberia. Nevertheless, the majority of the local rice in Liberia is grown under upland environments, which make up about 62% of the country's total rice-growing area (CARD, 2021). Despite of the diverse rice farming systems in the study area, production is predominantly slash-and-burn methods (MOA, 2012, 2017), resulting to a lengthy time (nearly a year) from land preparation to harvest, indicating one season per year, as shown in Table 2-1. These practices are employed by approximately 69% of the farming population in Liberia (MOA, 2018), which contributes to low productivity levels.

However, approximately 71% of the rice produced comes from smallholder farmers with an average rice yield of 1.2 MT/ha (Sumo *et al.*, 2023). Despite over 60% of Liberians farmers engaged in rice cultivation, yields remain low compared to other West African countries such as

Côte d’Ivoire (3.0 t/ha), Ghana (2.7 t/ha), Mali (3.4 t/ha), and 4 t/ha in Benin (Saysay *et al.*, 2018; Sumo *et al.*, 2023). For instance, the country produces 309,144 MT of rice annually, while an additional 364,000 MT must be imported to meet national demand. Consequently, the rice import bill increased from USD 76.8 million in 2010 to USD 217.5 million in 2017 (Ministry of Commerce and Industry (MOCI, 2017).

**Table 2-1.** Calendar of rice production in Liberia

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Upland rice	Land Preparation	Land Preparation	Land Preparation	Land Preparation	Planting	Planting	Planting	Farm management	Farm management	Farm management	Harvesting	Harvesting
Lowland rice	Land Preparation	Land Preparation	Land Preparation	Land Preparation	Land Preparation	Planting	Planting	Planting	Farm management	Farm management	Farm management	Harvesting



Source: CARD (2021)

Therefore, Liberia’s rice production continues to face challenges related to poor infrastructure, climate variability, droughts, flooding, poor soil fertility, pest infestation, inadequate agricultural inputs, limited access to machineries, and weak research support (Tarway-twalla, 2013; EPA, 2024). Notably, production declined significantly by 20.55% from 257,995 MT in 2018 to 170,000 MT in 2021 (Pluato *et al.*, 2024). In response to the country’s reliance on rice imports, the government is promoting climate-smart techniques to boost self-sufficiency in rice production (NPRSCC, 2018; NAP, 2022). These persistent constraints highlight the urgent need for a comprehensive assessment of climate variability and its impact on rice production, together with evaluating farmers’ resilience and adaptation strategies to inform sustainable and climate-smart interventions in Liberia.

**2.5.1. Trends in Rice Production**

Rice production has experienced a noticeable increase over recent decades at the global scale, driven by rising demand, population growth, and policy efforts aimed at food security

(Daszkiewicz, 2022; Saito *et al.*, 2023). However, this growth has been uneven across regions, particularly in Africa, where structural and climatic constraints continue to limit productivity. In sub-Saharan Africa (SSA), rice production has expanded nearly tenfold since 1961; nevertheless, consumption continues to outpace production, with a regional self-sufficiency rate of only 48% as of 2020 (Saito *et al.*, 2023). This increase has been driven primarily by the expansion of harvested area rather than improvements in yield. For instance, between 2000 and 2020, the harvested rice area in SSA increased from 6.9 million ha to 16.6 million ha, while average yields rose only marginally from 1.7 to 2.1 t ha<sup>-1</sup> (Saito *et al.*, 2023). Consequently, the region's average yield remains low, at approximately 2 t ha<sup>-1</sup>, highlighting a persistent gap between production growth and productivity gains.

In West Africa, similar trends have been observed, where increases in rice output have largely resulted from the expansion of cultivated land areas and government-led initiatives aimed at achieving rice self-sufficiency (FAO, 2018; Soullier *et al.*, 2020). Studies by Ibrahim *et al.* (2022) and Saito *et al.* (2023) further confirm that production gains across SSA are predominantly area-driven rather than yield-driven, demonstrating limited technological advancement and persistent production inefficiencies.

Within this regional context, Liberia presents a particularly compelling case. Analyzing the historical trends in Liberia's rice production from 1990 to 2023 provides critical insight into how both climatic and non-climatic factors have influenced rice productivity. The period of civil conflict (1990–2003) was marked by a sharp decline in rice production due to widespread displacement, destruction of agricultural infrastructure, and reduced farming activities (World Bank, 2024; Longzhu *et al.*, 2025). Although some recovery was observed in the post-conflict period, particularly after 2005, rice production has remained highly vulnerable to climatic shocks, including floods, droughts, and pest outbreaks.

Accordingly, Liberia's average national rice yield remains low, at approximately 1.2 t ha<sup>-1</sup>, significantly below yields reported in neighboring West African countries, such as 3.0 t ha<sup>-1</sup> in Côte d'Ivoire, 2.7 t ha<sup>-1</sup> in Ghana, 3.4 t ha<sup>-1</sup> in Mali, and 4.0 t ha<sup>-1</sup> in Benin (Saysay *et al.*, 2018; Sumo *et al.*, 2023). This disparity underscores the combined effects of limited technological adoption, weak institutional support, and high climate sensitivity. Previous studies across West Africa have reliably demonstrated strong relationships between rice yield variability and climatic

factors, particularly temperature extremes and rainfall irregularities (Birkmann *et al.*, 2023; Yeleliere *et al.*, 2023; Maiti *et al.*, 2024). Using approaches such as the Mann–Kendall test and Sen’s slope estimator, Berhane (2018) and Yila *et al.* (2023) identified significant correlations between yield trends and climate variability. Similarly, Fosu-Mensah *et al.* (2012) established that erratic rainfall patterns and delayed onset of the rainy season significantly reduced rice productivity in Ghana, especially under rainfed conditions.

Despite facing similar agroecological and climatic conditions, Liberia lacks countrywide comprehensive long-term studies that explicitly quantify the relationship between rice yields and key climate variables, such as temperature and precipitation. This gap in empirical evidence limits the ability of policymakers and researchers to design effective climate adaptation and agricultural development strategies. Therefore, this study seeks to address this critical gap by investigating rice yield data alongside meteorological variables from 1990 to 2023. By identifying trends and relationships of production data and climate variables, the study aims to improve understanding of how climate variability has influenced rice productivity in Liberia and to provide a scientific basis for forecasting future yields under changing climatic conditions.

## **2.6. Farmers’ Perception of Climate Risk and Adaptation Strategies to Climate Change**

The understanding and interpretation of climatic changes by smallholder farmers play a significant role in shaping their adaptive behavior and decision-making processes. Across sub-Saharan Africa, including Liberia, a growing body of research reveals that farmers are increasingly aware of shifts in climate conditions (Ceci *et al.*, 2021; Jalloh *et al.*, 2023; Kissi *et al.*, 2023; Sarnoh, 2024). These observations often stem from personal experience and prolonged exposure to climate variability, such as changes in rainfall distribution, delayed rainfall onset, extended dry periods, and rising temperatures, all of which adversely affect agricultural productivity (Fosu-Mensah *et al.*, 2012). Due to limited access to meteorological information, farmers predominantly rely on traditional knowledge to interpret climate trends (Tambo & Abdoulaye, 2013).

For the case of Liberia, both empirical studies and official reports have highlighted that rice farmers frequently experience erratic rainfall patterns and increased heat stress as primary threats to production outputs (EPA, 2021b; Dorbor-soko, 2024; World Bank, 2024). However, differences in climate risk awareness are evident and often linked to demographic and economic variables

such as educational level, age, duration of farming experience, and the availability of agricultural extension services (Wuokolo, 2023). To address these challenges, farmers adopt a range of adaptive practices. These include adjusting farming dates, using drought-tolerant or early maturing crop varieties, crop diversification, soil conservation, and increased reliance on local knowledge (Wuokolo, 2023). Nevertheless, many farmers face challenges that prevent effective adaptation, such as lack of credit, inadequate access to improved seeds and irrigation, poor extension services and weak institutional frameworks (Asfaw *et al.*, 2019).

Findings from other West African countries, including Ghana, emphasize these changes, indicating that adaptation capacity is closely tied to socioeconomic status, institutional access, and the dissemination of relevant information (Fosu-Mensah *et al.*, 2012). These insights are consistent across the region, underscoring major role of social and institutional contexts in bridging the gap between climate perception and adaptive action (Chala *et al.*, 2020). Therefore, understanding how climate variability interacts with farmers' socioeconomic characteristics and institutional support systems is essential for assessing adaptive capacity and strengthening resilience in Liberia's rice production systems.

## **2.7. Agroecological Suitability Mapping for Rice Production**

Achieving food security and sustainable resource management has become the main goal for many developing countries. Agroecological suitability mapping involves the spatial assessment of land based on its capacity to support specific crops under current and projected environmental conditions (Yohannes & Soromessa, 2018). Identifying areas suitable for rice cultivation in Liberia is crucial for enhancing agricultural productivity, ensuring food security, and promoting sustainable farming practices. By identifying land with optimal conditions for rice farming, Liberia can reduce its dependence on rice imports and improve local food systems.

Recent studies have strongly utilized Geographic Information System (GIS)-based Multi-Criteria Decision-Making (MCDM) approach, as effective tool for assessing land suitability for crop production, supporting sustainable agriculture, and food security (Ayehu and Besufekad, 2015; December *et al.*, 2022; Hossen *et al.*, 2021; Joseph Kihoro, 2013; Victor and Samson, 2019). Studies in neighboring West African countries such as Côte d'Ivoire Bamba *et al.* (2015), and Mali

Sissoko *et al.* (2015), provide valuable insights into land suitability mapping, particularly through the application of geographical information system (GIS), remote sensing, and multi-criteria decision-making (MCDM) methods. Similarly, Victor and Samson (2019) used GIS-based MCDM for land evaluation and suitability mapping for rice cultivation in Oye-Ekiti, Nigeria. Also, December *et al.* (2022) conducted a study in Northern Ghana, aimed to evaluate land suitability for crop production with the adoption of GIS-based MCDM and the Analytical Hierarchy Process (AHP).

Despite these advances, a comprehensive land suitability analysis for rice cultivation in Liberia is still a gap. This study aims to identify agricultural land suitable for rice cultivation in Liberia, using a GIS-based MCDM and AHP, considering ten key factors: precipitation, temperature, elevation, slope, soil texture, soil pH, soil organic carbon, nitrogen, phosphorus and potassium. As the country aims to increase domestic rice production, such mapping initiatives, alongside targeted investments in infrastructure and water resource management, can support the development of a more self-reliant and resilient agricultural industry.

### **2.7.1. Soil**

Soil quality, encompassing both physical and chemical properties, is a critical factor in enhancing rice production and maximizing agricultural productivity. These soil types significantly influence crop growth and yield, with their varying properties affecting overall agricultural potential (Lal, 2015; Shah & Wu, 2019). According to the Food and Agriculture Organization (FAO) classification, Liberia soil is more Ferralsols, and Ultisols under the United States Department of Agriculture (USDA) Soil Taxonomy. About 75% of the country are Ferralsols (clay-rich) that are highly weathered soils with low richness, low ability to maintain nutrients, and low cation exchange capacity (CEC) (USAID-BEST, 2014). Furthermore, approximately 4% of Liberia's land is covered by Gleysols (Histosols), which are typically found in swamps and valley bottoms that become waterlogged during the rainy season (USAID, 2013). These soils are rich in humus and, with proper water management, are particularly suitable for rice cultivation (Bationo *et al.*, 2006; Brandolini and Tigani, 2006).

However, the consideration of soil physical (texture) and chemical properties such as pH, nitrogen, phosphorus (P), potassium (K) and soil organic carbon (SOC), are highly recommendable for

suitability analysis due to the valuable roles they play during plant growth. The availability of these nutrients can fluctuate significantly post-deforestation and farming activities (Samanta *et al.*, 2011). Various soil properties will be categorized based on their suitability rating for rice cultivation. For instance, soil pH between 6 and 7 is more ideal for paddy fields but adaptable from 4 to 8, influencing cultivation success (Samanta *et al.*, 2011; Rath *et al.*, 2018).

## **2.7.2. Topography Factors**

### **2.7.2.1. Slope**

Slope is one of the fundamental topographic factors for mapping the suitability of the land for crop production. When integrated with other factors, slope can aid in site and suitability analysis (Ayehu and Besufekad, 2015). The slope values indicate terrain steepness while lower values suggest flatter terrain, which is ideal for rice production, ensuring consistent and informed water circulation.

### **2.7.2.2. Elevation**

Liberia's landscape is categorized into four major regions, such as coastal plains, rolling hills, plateaus, and northern highlands with differentiated elevation (EPA, 2020). The coastal plains reach 32-40 km inland and consist of low plains and moderately rolling hills with altitudes not exceeding 15 m (EPA, 2020). Rolling hills extend 90 m and are mostly used for agricultural purposes, and the plateau covers over 120 km, with heights up to 300 m, while mountains rise to 600 m (CCKP, 2021; EPA, 2020). On the other hand, the northern highlands contain significant ranges, with Mount Wutivi reaching 1,440 meters, and are vital to biodiversity (EPA, 2013, 2020).

This demonstrates that Liberia's land complexity exacerbates its vulnerability to climate events, such as temperature variation and rainfall variability. For instance, for every 4 kilometers of the troposphere, the temperature drops vertically by 0.5°C for every 100 meters; however, at 4 km, it falls by 0.6°C and by 0.7°C-0.8°C close to the tropopause (Akinici *et al.*, 2013). Unusually, each 100-meter rise in mountain height corresponds to 100 m of distance from south to north or from lower latitudes to higher latitudes. However, for every 100-meter increase in mountain altitude, the time frame for vegetation and flowering in plants is delayed by 4-6 days (Bozdağ *et al.*, 2016;

Kılıc *et al.*, 2022). This circumstance adversely impacts the selection of plant types for farming purposes. For instance, rice crops mostly flourish under elevations at sea level up to approximately 500 meters, particularly lowland. These regions usually possess suitable temperature and water supply, important factors for rice growth (Hussain *et al.*, 2012). Rice cultivation is still viable at heights up to 1,000 meters for both lowland and upland types, though production may reduce somewhat because of cooler climates and shorter growing periods unless the variety is adapted to cooler (Mubarak *et al.*, 2025). Upland rice can thrive at elevations reaching 1,500 meters but encounter difficulties related to temperature and water management.

### **2.7.3. Climatic Factors**

#### **2.7.3.1. Temperature and Precipitation**

Temperature and precipitation are two weather conditions that can either positively or negatively influence the growth, development, and production of rice (Dubey *et al.*, 2018; Nguyen *et al.*, 2024). Rice is normally cultivated in tropical and sub-tropical regions based on its tropical characteristics, grows well in a climate with temperatures from 20° to 35°C and annual rainfall levels ranging from 1,250 mm to 2,000 mm (Ayehu and Besufekad, 2015). Nighttime temperatures should not drop below 20°C to ensure proper development. Temperature below or higher than optimal negatively affects the growth of roots and shoots and poses a challenge to pollination as well as poor anther bursting, which could cause spikelet sterility (Hasanuzzaman *et al.*, 2019). Knowing these factors could help improve agricultural planning and management, especially under climate variability and change (Makungwe *et al.*, 2021).

#### **2.7.4. Land Use and Land Cover**

According to the United States Geological Survey (USGS), land use land cover (LULC) refers to “the physical arrangement of natural and anthropogenic attributes on Earth’s surface. This involves types like forests, grasslands, wetlands, urban regions, and farmland. Land use land cover information is employed for multiple applications, such as urban development and planning, resource management, and environmental monitoring. The GlobCover 2009 land cover data was incorporated in this study (ESA, 2010).

## **2.8. Policies and Strategies on Climate Change in Liberia**

Over the past decades, Liberia has accomplished notable progress in rebuilding its agricultural sector from civil war devastation, developing policy frameworks, and making modest improvements (Longzhu *et al.*, 2025). The Liberian government has developed plans and strategies in response to climate change mitigation. For example, the establishment of the National Action Plan for Disaster Risk Reduction of Liberia 2016 to 2021 (EPA, 2021a), the formation of the Environmental Protection Management (EPM) Act of 2002, the establishment of the Forestry Reforms Law created in 2006, and the development of the National Adaptation Programme of Action (NAPA) (EPA, 2021a; NAP, 2022). These plans aimed to address climate-related issues, such as environmental protection, biodiversity conservation, and low emissions; to maintain forestry and sustainable livelihoods; and to provide adaptation, environmental, agricultural, and coastal defense (EPA, 2021a; NAP, 2020). Additionally, the government formulated the Liberia Agriculture Investment Programme (LASIP) in 2009, and Liberia's first National Communication launched in 2013, which are instrumental to emission tracking, climate change vulnerability and adaptation. Moreover, the National Climate Change Policy and Response Strategy (NPRSCC) was launched in 2018 to guide national response measures in addressing climate change (EPA, 2021a).

However, despite these policies and strategies instituted, the government still undergoes challenges to the implementation of some of these policies due to its high reliance on foreign donors and institution bodies' funds (World Bank, 2023). With support from government development partners, they implement reforms in the rice subsector, focusing on infrastructure development. For instance, support worth US\$3.5 billion was secured, with a smaller portion of over 10 percent allotted to agriculture (World Bank, 2023). Investment in agriculture, both domestically and externally, falls short of targets. However, the government's direct support for agriculture remains very low for meeting its aims to target agriculture as described in the Pro-poor Agenda for Prosperity and Development (PAPD).

## **2.9. Conceptual Framework**

The conceptual framework shown in Figure 2-1 illustrates a comprehensive model for understanding the interactions between climate variability, rice productivity, farmers' resilience

and rice growth suitability in Liberia. The framework is rooted in the Sustainable Livelihoods Framework (SLF) as described by Jackson (2020). This framework was designed to guide the research objectives and questions, providing a structured approach to understanding how climatic factors influence agricultural productivity, particularly rice yield and identify areas suitable for rice cultivation in the country. Rice undergoes unpredictable impartation processes; for instance, erratic temperature, irregular rainfall pattern, poor soil quality, pest and diseases, and farming practices. These unpredictable changes are greatly influenced by climatic factors such as temperature and rainfall, resulting in a decrease in productivity.

The model emphasizes the relationship between environmental shocks (e.g., droughts, floods, and heatwaves), institutional mechanisms, and the adaptive capacity of rural farmers. The framework further integrated rice land suitability analysis in order to provide comprehensive information on rice productivity within the study area.

By evaluating the impact of climate variability and its relationship with rice production and productivity and assessing areas that are more suitable for rice growth, this study aims to provide valuable insights into the challenges faced by smallholder farmers in Liberia. It also seeks to promote awareness of appropriate adaptation strategies to enhance farmers' resilience to climate variability and improve rice productivity. Furthermore, the study provides a foundation for informed agricultural planning and policymaking in the country.

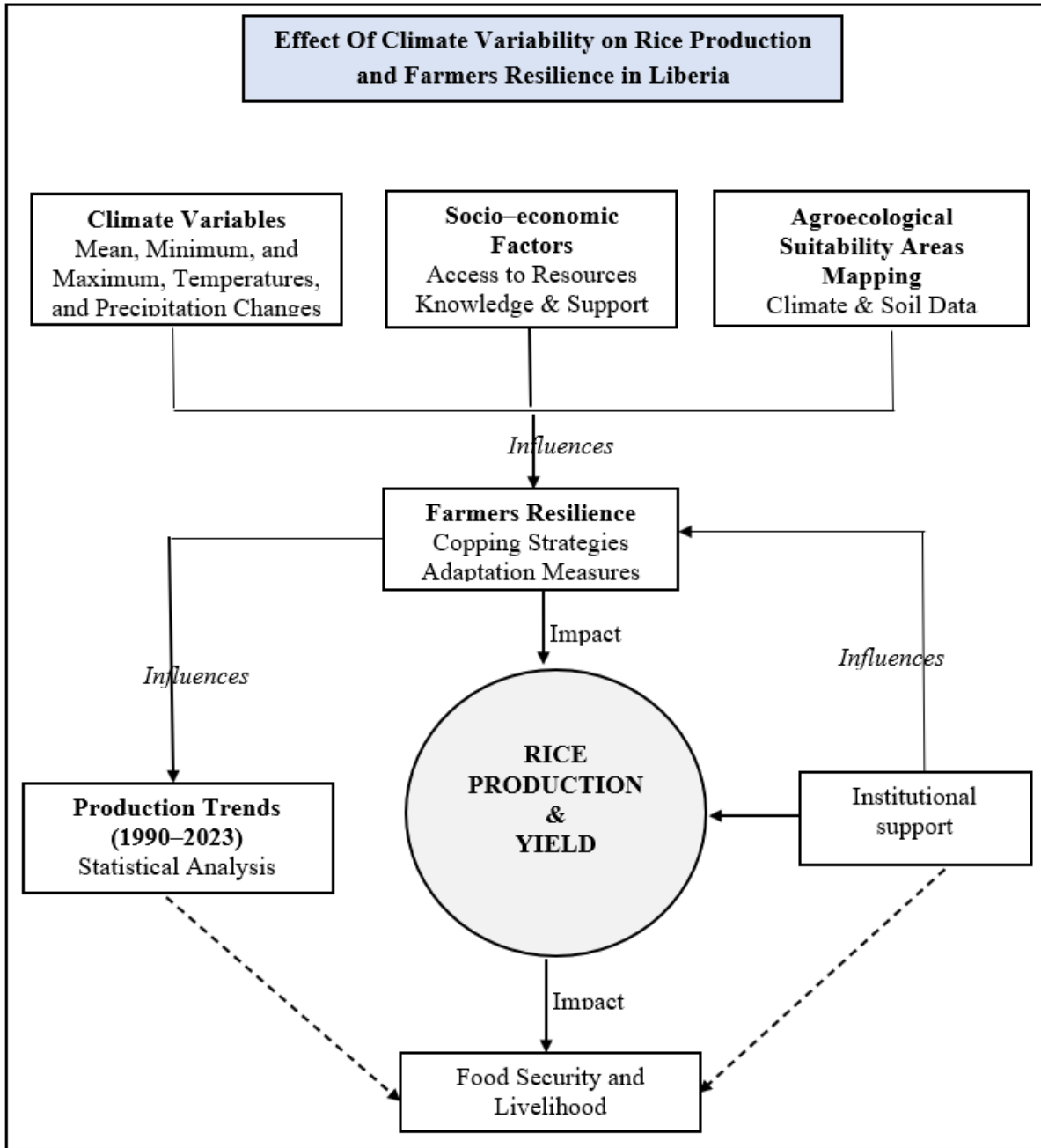


Figure 2-1. Conceptual framework

## CHAPTER III: METHODOLOGICAL FRAMEWORK

### 3.1. Overall Research Design

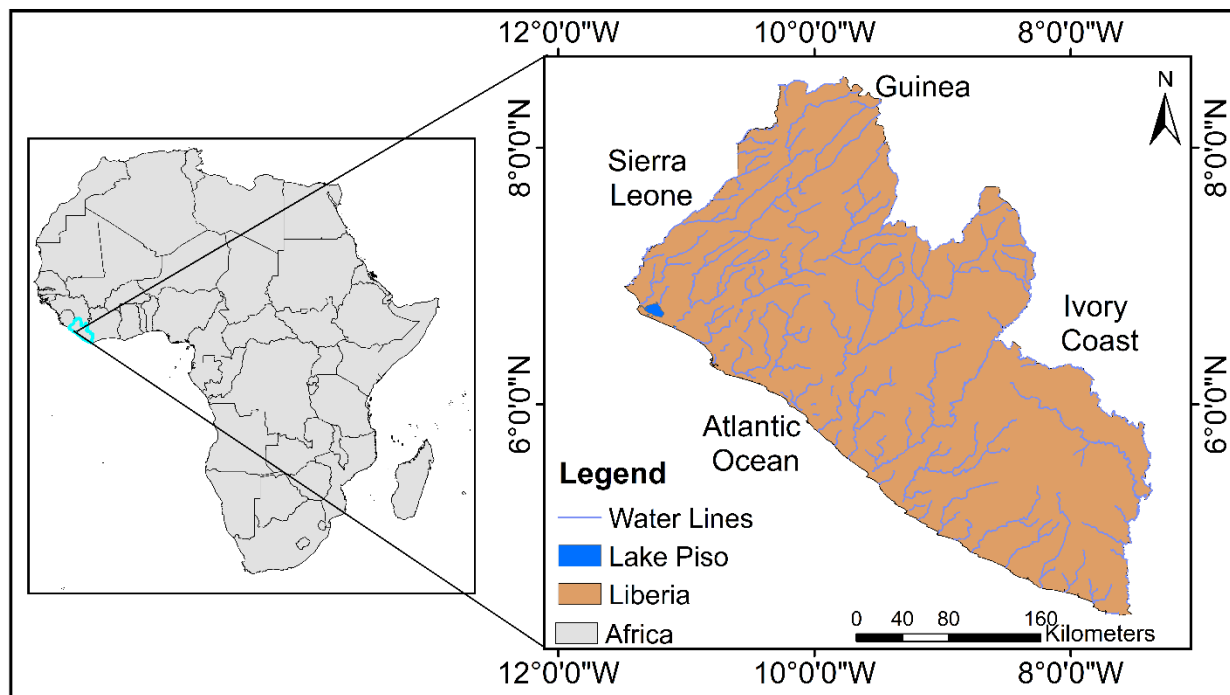
The study adopted a quantitative, observational (non-experimental) research design to investigate the relationship between climate variability and rice production from 1990–2023, and to evaluate agroecological suitability for rice cultivation in Liberia. The design is organized to integrate multiple analytical perspectives, including correlational, time-series, regression, and spatial-based approaches, in order to comprehensively address the study objectives. A correlational study framework is used to assess the strength and direction of relationships between climatic factors and rice productivity, while regression determine the impact of these climate variables on production (Oluwatimilehin & Ayanlade, 2023). On the other hand, the review of existing literature and institutional reports was used to access farmers' perceptions of climate risks and their adaptation strategies they employ to address climate change (Ampaire *et al.*, 2020). In addition, the study integrates time-series to detect trends, variability patterns, and potential climate–yield relationships (da Silva *et al.*, 2015; Jiqin *et al.*, 2023; Ondiek & Saber, 2024). Also, the research design incorporates a spatial analysis module using GIS to evaluate the spatial distribution of agroecological suitability for rice production (Joseph Kihoro, 2013; Ayehu and Besufekad, 2015; Victor and Samson, 2019; Hossen *et al.*, 2021; December *et al.*, 2022). Spatial datasets, including climate variables, topography, and soil characteristics, were processed, standardized, and integrated within a GIS environment to generate suitability maps. This spatial approach allows for the identification of geographically suitable areas and supports location-specific agricultural planning. The study relies exclusively on secondary datasets obtained from reputable global and regional sources, including climate databases and agricultural statistics. These datasets provide consistent, long-term observations potential for robust temporal and spatial analysis, although they may lack fine-scale local variability.

Due to the reliance on secondary observational data, the study does not establish causal relationships. Instead, it employs a robust, integrative research design that combines statistical analysis of Climate–rice yield associations with spatial assessment of land suitability for rice cultivation. This framework enables the identification of meaningful patterns and trends in

variables over time, providing evidence-based insights to support climate-adaptive agricultural planning and the targeted management of suitable cultivation areas in Liberia.

### 3.2. Study Setting

The study was conducted in Liberia. Liberia is bordered by Sierra Leone on the west, Guinea to the north, Côte d'Ivoire (Ivory Coast) to the east, and the Atlantic Ocean to the south (Figure 3-1). It covers a total area of 111,350 km<sup>2</sup> and has a total population of 5.3 million inhabitants (LISGIS, 2022). Liberia lies at latitudes 4° 20' to 8° 30' North and longitudes 7° 18' to 11° 30' West (EPA, 2021c). The study area has a tropical climate, characterized by a rainy season that runs from May to November and a dry season from December to April. The average annual precipitation ranges from 2,500 mm to 5,000 mm per year (EPA, 2021c), while temperatures fall between 23 °C and 33 °C (EPA, 2021a). Relative humidity reaches 90%-100% during the rainy season and 60%-90% during the dry season (World Bank, 2024). Based on the seasonal mean precipitation considered during the major rice production periods (April to September) in Liberia, precipitation ranges from 1,170 mm to 3,017 mm, while seasonal mean temperature was 23.2 °C to 25.8 °C as presented in (Figure S1) of the Supplementary Materials. The climatic conditions appeared to be more favorable for rice production despite differences among the classes. Using the Köppen-Geiger climate classification, there are three major climate types or classification in Liberia, namely: the tropical monsoon, tropical rainforest, and tropical savannah. Most of Liberia's climate is tropical monsoon (76%), followed by tropical rainforest (15%), with the remaining 9% classified as tropical savannah (Beck *et al.*, 2023); see also Supplementary Materials (Figure S2). Agriculture is the major source of livelihood for the country's population and remains a major contributor to Liberia's economic development. However, rice is one of the most cultivated crops, and its production in the study area is predominantly practiced by subsistence farmers under rainfed conditions. The average rice yields of the country scaled at approximately 1.2 t/ha with notable production in Nimba, Bong, and Lofa counties, respectively, which account for 56% of the country's rice production (CARD, 2021; Sumo *et al.*, 2023), whereas relatively lower production occurs in Margibi, Montserrado, and Grand Bassa counties, respectively (see Figure S1 available in the Supplementary Materials).



**Figure 3-1.** Map of Africa with the Study area.

### 3.3. Data Collection Methods

In this study, a secondary data approach was employed to achieve all specific objectives. The analysis was based on multiple datasets obtained from key open-access datasets, including Food and Agriculture Organization Statistics (FAOSTAT) database for rice production and yield, the ERA5 Agrometeorological Indicators was used to obtain temperature data covering the period from 1990 to 2023 (Copernicus Climate Change Service, 2020), while precipitation data was derived from Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) data (Funk *et al.*, 2015), covering the same period. In addition, climate projection data were sourced from the CORDEX (Coordinated Regional Climate Downscaling Experiment) available at: <https://esg-dn1.nsc.liu.se/search/cordex/>. Soil data were obtained from the Liberia Soil Information System (LIBSIS) database of 2023 (accessible online at <https://libsislr.com>), the Shuttle Radar Topography Mission (SRTM) accessible link: <http://earthexplorer.usgs.gov>. Land use land cover data were extracted from the GlobCover 2009 (ESA, 2010), were used to access various dataset for this study. These datasets were integrated to support both climate–rice productivity analysis and land suitability assessment. These datasets were integrated to support both climate–rice

productivity analysis and land suitability assessment. Furthermore, a comprehensive review of existing literature was conducted to gather information on farmers' perceptions of climate change impacts and the coping mechanisms they employ in response to climate change. This approach provides a robust foundation for understanding the interactions between climate variability and rice production, and for informing strategies aimed at improving rice productivity and enhancing farmers' resilience in Liberia.

### **3.4. Data Analysis Techniques**

Data analysis followed a step-by-step approach. Firstly, we pre-processed the raster dataset of the climate factors (temperature and precipitation) from ERA5 and CHIRPS that were obtained as gridded raster data and processed in ArcGIS 10.8 environment to extract seasonal average values for Liberia. The datasets were temporally aligned, and climate data were spatially processed (clipped to Liberia and aggregated to national level) for the mean, minimum, and maximum temperatures and precipitation values over the study area, representing the national-scale climatic conditions. Numerical values derived from the spatial outputs, together with production and yield data obtained from FAOSTAT, were entered into an Excel spreadsheet. Subsequently, data preprocessing and quality control were performed on the rice production and climate datasets to ensure accuracy and consistency. This included identifying missing values, inconsistencies, and outliers using statistical and graphical methods, and validating anomalies against original sources (Kwak & Kim, 2017; Sharifnia *et al.*, 2026). After cleaning, the data were used for trend, correlation, and regression analyses, improving the reliability, transparency, and reproducibility of the results.

The Mann-Kendall test (Mk test) and Sen's slope estimator were applied to identify the trend in various parameters, including production, yield, and precipitation and temperature (Jiqin *et al.*, 2023). The Spearman's rank correlation test was applied for estimating the monotonic relationship between production statistics (production and yield) and climate parameters, such as mean temperature, minimum temperature, maximum temperature, and precipitation, while the multiple linear regression (MLR) was utilized to evaluate the combined relationship or impact of climate parameters and rice productivity (Oluwatimilehin & Ayanlade, 2023). Additionally, long-term spatial maps of seasonal precipitation and temperature were generated to illustrate the spatial

variability of climatic conditions across the country as presented in Figure S1 of the Supplementary Materials.

Furthermore, climate projection data was processed to produce a spatial map in order to depict the projected change in each climate variable under the considerable time periods. Also, the study adopted a comprehensive review of existing literature, institutional reports, and reliable research findings addressing climate–agriculture interactions in Liberia and the broader sub-Saharan African region, with a focus on West Africa, to access information on farmers’ perceptions of climate risks and the coping strategies they employ to address climate change (Ampaire *et al.*, 2020). On the other hand, the MCDM method integrated with GIS technology was employed to assess Land suitability for rice production in the study area. These approaches were robustly integrated to achieve the objectives of the study.

### **3.5. Ethical Considerations**

This research is based on the ethics of integrity, reliability and accountability. The Researchers ensure that work be conducted with honesty and transparency, avoiding practices such as fabrication, falsification, and plagiarism. Upholding integrity is crucial for maintaining the credibility of research findings and the scientific community. We make sure that information provided are facts and factual and further be in the capacity to give an account of what is written. We also upheld to full assurances of privacy, anonymity and confidentiality throughout the processes of analyzing data and reporting findings. Data was not made up or transformed and results was not falsified. We maintained that analysis and findings were reported fully and accurately, irrespective of whether they contradict expected outcomes and the provision of data sources be clearly acknowledged.

### **3.6. Limitations of the Study**

This study offers a comprehensive assessment of rice production trends and climatic influences and land suitability in Liberia; however, it was constrained by various limitations. A major constraint is the absence of field-based or ground-truth datasets, including field surveys and observed yield records, which limit the analysis to correlations rather than causal relationships.

This suggests the need for future research on the physiological and morphological response of rice crops to precipitation and temperature under real field conditions. Similarly, the lack of field validation for suitability mapping due to the large national-scale extent and limited systematic production records, which makes the validation to have relied on existing literature, general land use/cover knowledge, and consistency checks from the Analytic Hierarchy Process (AHP) model rather than empirical observations. Additionally, the study's reliance on global datasets which may not fully capture local-scale variability in soils, microclimate, topography, and land cover, potentially affects the accuracy of suitability classifications. The national-level focus also limits the consideration of regional heterogeneity, including socio-demographic differences and localized geographic conditions. Furthermore, key extreme climate events, such as floods and prolonged droughts were not explicitly incorporated, despite their significant role in causing abrupt fluctuations in rice yields. Despite these limitations, the study represents an important first step toward a countrywide assessment of rice production and suitability analysis, providing valuable baseline information for agricultural planning and policy development in Liberia. Future research can build on these findings by integrating high-resolution data on climate extremes to assess their direct impacts on rice productivity; incorporating field-based data to investigate the physical impact of temperature and precipitation on productivity, while also incorporating socio-demographic factors and the geographical extent or subdivisions. Addressing these aspects will enable more precise, context-specific insights to inform climate-resilient rice production strategies and targeted policy interventions in Liberia.

## CHAPTER IV: RESEARCH ARTICLE I

### 4.1. Brief Introduction

Article one, titled: “*Effect of Climate Variability on Rice Production in Liberia*” focuses on investigating the effect of climate variability on rice production in Liberia. The research paper is made up of the combination of 4 specific objectives (objectives 1, 2, 3, and 4) of the thesis. The paper aims to determine trends in rice production and yield in Liberia from 1990 to 2023; examine patterns and changes and trends in key climate variables (precipitation and temperature during the same period; assess statistical relationship between climate variables and rice production and yield from 1990 to 2023; and to investigate the resilience and adaptation strategies employed by rice farmers in Liberia. Merging these specific objectives, resulted into a publishable article.

### 4.2. Status of Paper I

The status of the paper is publication. The manuscript was submitted to the journal called *Climate*, a SCOPUS indexed journal that is published by MDPI.

Manuscript Details: *Climate* **2026**, *14*(4), 84; <https://doi.org/10.3390/cli14040084>

### 4.3. Authors Contributions

Conceptualization, B.T.S. and C.M.M.; methodology, B.T.S., C.M.M., and J.L.M.U.; software, B.T.S. and J.L.M.U.; validation, J.L.M.U.; formal analysis, B.T.S.; investigation, C.M.M., J.L.M.U. and B.T.S.; resources, B.T.S.; data curation, B.T.S. and J.L.M.U.; writing – original draft, B.T.S.; Writing – review & editing, C.M.M., J.L.M.U., A.D.N. and L.A.; visualization, C.M.M., J.L.M.U. and B.T.S.; supervision, C.M.M.; project administration, B.T.S.; funding acquisition, B.T.S. All authors have read and agreed to the published version of the manuscript.

### 4.4. Full Article

**Title: Effect of Climate Variability on Rice Production in Liberia**

**Bondo T. Simpson**<sup>1,2,\*</sup>, **Celsa Mondlane Macandza**<sup>2,3,\*</sup>, **Jone L. Medja Ussalu**<sup>2,4</sup>, **Arsénio D. Ndeve**<sup>2,3</sup> and **Luis Artur**<sup>1,2</sup>

<sup>1</sup> Department of Economy and Agrarian Development, Faculty of Agronomy and Forestry Engineering, Eduardo Mondlane University, Julius Nyerere Avenue, n. 3453, Maputo 1102, Mozambique; bondosimpson@gmail.com

<sup>2</sup> Centre of Excellence in Agri-Food Systems and Nutrition (CE-AFSN), Eduardo Mondlane University, Praça 25 de Junho Edifício da Reitoria 5º Andar, Maputo 1102, Mozambique;

<sup>3</sup> Department of Plant Production, Faculty of Agronomy and Forestry Engineering, Eduardo Mondlane University, Maputo 1102, Mozambique; celsa.macandza@uem.mz

<sup>4</sup> Department of Rural Engineering, Faculty of Agronomy and Forestry Engineering, Eduardo Mondlane University, Maputo 1102, Mozambique; jonemedja@uem.mz

\* Correspondence: bondosimpson@gmail.com and celsa.macandza@uem.mz

## **Abstract**

Climate variability poses major challenges to agriculture worldwide amid an increasing world population and growing food demand. This study evaluates the impact of climate variability on rice production in Liberia. Rice yields and production data (1990–2023) were attained from the Food and Agriculture Organization Statistics (FAOSTAT), while temperature and precipitation were sourced from ERA5 Agrometeorological Indicators and the Climate Hazards Group InfraRed Precipitation with Station (CHIRPS). Trends and relationships were analyzed using Mann–Kendall, Sen’s slope tests, and Spearman’s rank correlation. Multiple linear regression estimates climate variables’ impact on rice productivity. The results show that mean, minimum, and maximum temperatures increased by 0.57 °C, 0.55 °C, and 0.55 °C, respectively, with precipitation variability at 180.31 mm. Climate variables showed diverse correlations with rice production. Regression results revealed a significant negative impact of minimum temperature ( $p$ -value = 0.015) on production and a positive effect of precipitation on yields ( $p$ -value = 0.036). Farmers in Liberia recognized climate impacts and adopted adaptation strategies, but resilience is hindered by limited credit access, low technology adoption, reliance on traditional practices, and inadequate extension services. Overall, the findings highlight the sensitivity of rice production in Liberia to

climate variability and underscore the need for guided adaptation and institutional support to augment farmer resilience.

**Keywords:** rainfall variability; climate variability; food insecurity; agriculture; farmer adaptation strategies; rice production; temperature trends; climate change; Liberia

## 1. Introduction

Climate variability, including alterations in climate variables such as rainfall and temperature, have significant implications, particularly on climate-sensitive sectors such as agriculture [1–4]. Rice is one of the most important crops and a staple food in many regions worldwide. Its production is highly sensitive to climate change, as it is heavily dependent on climatic factors such as temperature and precipitation for growth and development [5,6]. A study conducted by Algarni *et al.* [7] utilizes a qualitative descriptive research technique, focusing on analyzing the impact of climate change on rice production and developing effective strategies to enhance efficiency, sustainability, and global food security. The findings show a strong correlation between climate variability and declining rice yields, particularly in rainfed regions, due to water scarcity, soil degradation, and increased pest infestations. Past studies [8–10] have revealed that temperature increases during the reproductive stage of rice, especially during panicle initiation, flowering, and fertilization, may severely reduce yield and grain quality. Also, Song *et al.* [10] indicated that an increase of 1 °C in temperature above the optimum threshold reduced the yield by 8%. Another study revealed that grain yield declined by 10% for each 1 °C increase in the growing-season minimum temperature in the dry season, whereas the effect of maximum temperature on crop yield was insignificant [11]. On the other hand, recent studies found that for every 100 mm increase in precipitation above the optimal thresholds, rice yield decreased by 6.4 kg in India [12]. Similarly, Gumel *et al.* [13] employed the Decision Support System for Agrotechnology Transfer (DSSAT) Model to examine the impacts of rainfall on rice yield, and they found that an increase in daily mean rainfall of +1 mm to +2 mm above the threshold led to a decreased yield of –4.0% to –51.5% in Malaysia.

These impacts of climate change threaten food security and diet quality, thereby exposing vulnerable populations across continents to multiple forms of malnutrition, thus contributing to mortality and morbidity [14]. Furthermore, a recent scientific report employed a threshold regression approach to identify and estimate critical temperature change thresholds, while linear

mixed-effects models were used to evaluate the impacts of climate change on crop yields under varying levels of temperature increase. The findings revealed that rising temperatures negatively affect crop yields across countries, with the adverse effects intensifying once temperature increases surpass specific threshold levels. For example, in the case of wheat, a 1 °C increase in temperature results in a 6.1% reduction in yield when the temperature rise remains below 2.38 °C; however, yield losses increase to 8.2% per 1 °C warming once the threshold of 2.38 °C is exceeded. Similarly, rice yield losses per 1 °C increase in temperature rise from 1.1% to 7.1% when warming surpasses the 3.13 °C threshold. In contrast, no threshold effect was detected for maize; instead, temperature increases lead to an average yield reduction of 4.03% per 1 °C [15].

Research on rice production is crucial due to its importance for global food security, rural livelihoods, and its sensitivity to climate change [16]. Rice is the primary cereal food for over 60% of the global population; it is produced in many countries, with Asia accounting for more than 90% of its production and consumption worldwide [17]. In Africa, rice is one of the major sources of calories [6,18] and is gradually becoming a staple food and income source in many sub-Saharan African (SSA) countries [6]. In SSA, the annual rice consumption between 2009 and 2019 was 27.4 million metric tons, while average production was estimated at 15.4 million metric tons [19]. The demand for rice is continuously rising in the region due to population increase and urbanization, but production remains low to meet the demands of the consumers [20,21].

In Liberia, rice is produced by approximately 69% of all farmers and accounts for about 50% of adult caloric intake; the annual per capita consumption is estimated at around 133 kg [18]. This makes rice one of the most important crops for food security and economic livelihood in the country; however, domestic rice production is inadequate to satisfy its national demands [22]. For instance, referring to past years, production reduced by 20.55% (from 257,995 metric tons in 2018 to 170,000 metric tons in 2021), which led to substantial imports (560,000 metric tons in 2021). These imports cost over USD 100 million and accounted for approximately 65% of the total consumption [22], an enormous amount for less-developed countries such as Liberia. These reductions may be attributed to several factors [23,24].

Over the past three decades, Liberia has experienced shifts in climate patterns, including rising temperatures, irregular rainfall, and increased frequency of extreme weather events such as floods and droughts [25,26]. Given that Liberia depends solely on rainfed agriculture, these changes, as mentioned previously, have direct and indirect impacts on crop productivity,

particularly rice, which has specific climatic requirements for optimal growth. This situation is compounded by the fact that about 70% of the Liberian population depends on agriculture and forestry for their livelihoods and the overall significant contribution of agriculture to the country's economy [24,27]. It is within this context that the present study looks at the interplay between climate variability and rice production and productivity in Liberia. Hence, it is essential to assess how climate variability affects rice production to understand the issue and suggest strategies to improve resilience and food security in the country. For instance, Dorbor-soko [28] conducted a study on the assessment of the impacts of climate variability and change on rice production in Bong County, and Wuokolo [29] worked on assessing the perception of climate change and barriers to strategic adaptation for smallholder farming in Todee District in Liberia. Similarly, another work, Sarnoh [30], assessed climate risks in central and northern Liberia. The studies mentioned above examined smaller geographic areas within the country, but there has been no comprehensive study on the relationship between climate variability and rice yield in the entire country. Another study, Allen Jr. and Diallo [24], conducted a systematic review, but their focus was on assessing the impact of climate change on Liberia's agricultural sector and strategic adaptation approaches. Given the limited research on this topic, the connections between climate variability and rice production across the entire country have not been extensively explored. Most studies have concentrated on specific regions. Therefore, this study aims to evaluate the effects of climate variability on rice production in Liberia using country-specific data from 1990 to 2023.

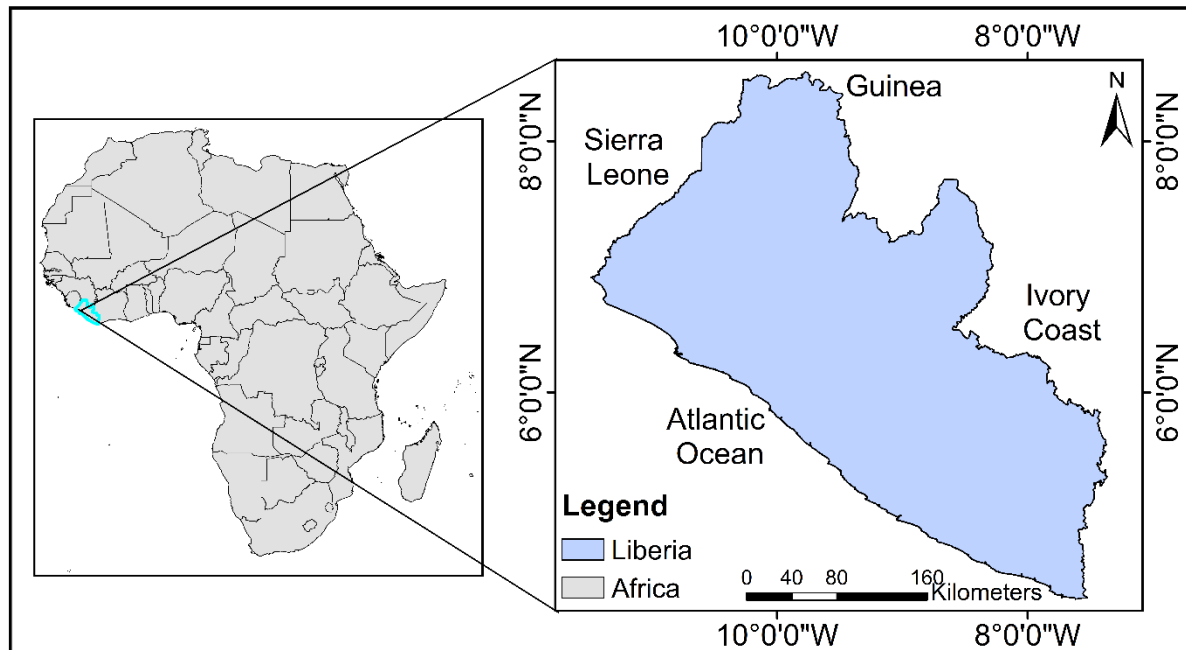
Specifically, this study aims to determine trends in rice production and yield in Liberia from 1990 to 2023, examine patterns and changes in key climate variables (precipitation and temperature), and assess the association and statistical relationship between climate variables and rice productivity. Furthermore, the study incorporates future climate projections under the RCP8.5 scenario to determine whether the increasing trends and variability observed during the historical period are likely to persist in the coming decades. The findings are intended to support the formulation of climate-resilient agricultural policies, strengthen adaptive capacity, and guide extension services. Accordingly, this study provides novel, Liberia-specific evidence that enhances understanding of how climate variability influences agricultural productivity, contributing to the broader literature on climate impacts in Liberia and across sub-Saharan Africa.

## **2. Materials and Methods**

### *2.1. Description of the Study Area*

Liberia is bordered by Sierra Leone on the west, Guinea to the north, Côte d'Ivoire (Ivory Coast) to the east, and the Atlantic Ocean to the south (Figure 1). It covers a total area of 111,350 km<sup>2</sup> and has a total population of 5.3 million inhabitants [31]. Liberia lies at latitudes 4°20' to 8°30' north and longitudes 7°18' to 11°30' west [32]. The study area has a tropical climate, characterized by a rainy season that runs from May to November and a dry season from December to April. The average annual precipitation ranges from 2500 mm to 5000 mm per year [32], while temperatures fall between 23 °C and 33 °C [33]. Relative humidity reaches 90–100% during the rainy season and 60–90% during the dry season [34]. Under the considerable study period of 1990–2023, seasonal mean precipitation for the major rice production periods (April to September) in Liberia ranges from 1170 mm to 3017 mm, while seasonal mean temperature was 23.2 °C to 25.8 °C as presented in the Supplementary Materials (Figure S1). The climatic conditions appeared to be more favorable for rice production despite differences among the classes. Using the Köppen–Geiger climate classification, there are three major climate types or classifications in Liberia, namely: the tropical monsoon, tropical rainforest, and tropical savannah. Most of Liberia's climate is tropical monsoon (76%), followed by tropical rainforest (15%), with the remaining 9% classified as tropical savannah [35]; see also Supplementary Materials (Figure S2).

Agriculture is the major source of livelihood for the country's population and remains a major contributor to Liberia's economic development. However, rice is one of the most cultivated crops, and its production in the study area is predominantly practiced by subsistence farmers under rainfed conditions. The average rice yields of the country scaled at approximately 1.2 t/ha with notable production in Nimba, Bong, and Lofa counties, respectively, which account for 56% of the country's rice production [36,37], whereas relatively lower production occurs in Margibi, Montserrado, and Grand Bassa counties, respectively (see Figure S1 available in the Supplementary Materials).



**Figure 1.** Location of the study area.

## 2.2. Study Design and Data Collection

This study adopts an integrated quantitative, spatial–temporal, and correlational research design to examine the effects of climate variability on rice production in Liberia over the period 1990–2023. The study uses a secondary data approach. It is based on datasets sourced from three major websites, namely the Food and Agriculture Organization Statistics (FAOSTAT) database, the ERA5 Agrometeorological Indicators covering a period from 1990 to 2023 [38], and the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) database referring to the same period [25]. The research design is appropriate because it integrates time-series trend analysis, geospatial data processing, and econometric modeling using multiple linear regression to examine temporal changes and the relationship between climate variability and rice yield (Figure 2). In addition, scenario-based climate projections and a structured literature synthesis were incorporated to provide broader contextual insight into potential future climate conditions and their implications for rice production. The analytical framework consists of three main components: (i) detection of historical trends in rice production and climate variables, (ii) statistical evaluation of the influence of climate variables on rice productivity, and (iii) spatial analysis combined with climate projections to assess variability and potential future changes. Given that this study relies primarily on secondary and model-based data, it cannot fully establish causal relationships.

Incorporating field-based measurements and primary data collection in future research would strengthen validation and improve causal inference. Details on the data follow below.

### 2.2.1. Rice Production Data

Data for rice productivity (paddy) (kilogram/hectare–kg/ha) and production (in Metric ton—MT) from 1990 to 2023 (34 years) were collected from FAOSTAT open data <https://www.fao.org/faostat/en/#data/QCL> (accessed on 11 March 2025). This data was sorted and prepared on an Excel sheet and then analyzed against climate datasets.

### 2.2.2. Climate Variables (Temperature and Precipitation)

Temperature data (°C) from 1990 to 2023 was obtained from ERA5 Agrometeorological Indicators, available online at <https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels> (accessed on 13 March 2025). Its horizontal resolution is 0.1° x 0.1°. Precipitation data (mm) covering the period of 1990–2023 was sourced from the CHIRPS store <https://data.chc.ucsb.edu/products/CHIRPS-2.0/> (accessed on 11 March 2025). CHIRPS integrates the Climate Hazards Precipitation Climatology (CHPclim) and in situ station data to create gridded rainfall time series with 0.05° resolution for trend analysis and seasonal drought monitoring [39,40]. Projection data on temperature and precipitation were sourced from the CORDEX (Coordinated Regional Climate Downscaling Experiment), available at <https://cds.climate.copernicus.eu/datasets/projections-cordex-domains-single-levels?tab=download> (accessed on 20 April 2025). The dataset contains a spatial resolution of 0.22° X 0.22° (~25 km). Both projection datasets (temperature and precipitation) were based on two different time periods (RCP8.5, 2031–2060, and RCP8.5, 2071–2100), were accessed in NetCDF format, and then processed in the ArcGIS 10.8 environment. All climate datasets, including temperature and precipitation, were considered based on a national-level, six-month seasonal timescale (April to September), while taking into account the key considerable period for rice production in the study area. In this study, we reviewed the current literature to collect information on farmers' perceptions of climate change impacts and the coping mechanisms they employ.

### 2.2.3. Data Processing and Quality Control

In this study, before the statistical analysis, the rice production and climate datasets underwent comprehensive preprocessing and quality control checks to ensure data accuracy and

consistency. The datasets were examined for missing values, inconsistencies, and potential outliers using descriptive statistics and graphical methods, including time-series plots and boxplots [41,42]. A cross-validation of anomalous values against the original data sources was employed to confirm their validity [42]. Furthermore, temporal alignment of climate and production datasets was considered. Spatial climate datasets were clipped to the Liberia boundary and aggregated using zonal statistics to derive national-level averages. The processed datasets were then exported for statistical analysis. The validated or cleaned dataset was subsequently used for trend analysis, correlation analysis, and multiple linear regression. These procedures enhance the reproducibility, transparency, and robustness of the study's statistical findings [42].

### *2.3. Data Analysis*

Data analysis followed a stepwise approach (Figure 2). Firstly, we preprocessed the raster dataset of the climate factors (temperature and precipitation) from ERA5 and CHIRPS, obtained as gridded raster data and processed in ArcGIS 10.8 environment to extract seasonal average values for Liberia. The raster datasets were spatially aggregated by clipping them to the study area boundary, and the mean, minimum, and maximum temperatures and precipitation values over the study area to represent national-scale climatic conditions were obtained. From the spatial outputs generated, numerical values were then inputted in an Excel spreadsheet. These data were used to plot variables including precipitation and temperatures and production and yield in order to compute various analyses such as trends, correlation, and regression analysis. Climate projection data was processed to produce a spatial map to depict the change in each variable under the considerable time periods. In addition, long-term spatial maps of precipitation and temperature were generated to illustrate the spatial variability of climatic conditions across the country as presented in Figure S1 of the Supplementary Materials. Furthermore, a comprehensive review of the existing literature, institutional reports, and reliable research findings addressing climate–agriculture interactions in Liberia and the broader sub-Saharan African region, with a focus on West Africa, was conducted to access information on farmers' perceptions of climate risks and the coping strategies they employ to address climate change [43].

#### *2.3.1. Detection of Trends*

The non-parametric Mann–Kendall test (Mk test) and Sen's slope estimator were applied to identify the trend in various parameters, including production, yield, and precipitation and

temperature [44]. The Mann–Kendall test is more favored for identifying monotonic trends in variables, as it remains unaffected by outliers [44,45]. Apart from being robust to outliers, the MK test, and its non-parametric nature, also means that it does not depend on regularly distributed data [46]. It compares all pairs of observations in the dataset, assesses the direction of the trend (increase or decrease), and then tests its statistical significance.

In order to test whether or not to reject the null hypothesis, the MK test was used, where we apply Equations (1) and (2):

**H<sub>0</sub>.** *This considers no monotonic trend present in the series.*

**H<sub>a</sub>.** *This suggests the presence of a monotonic trend in the series.*

At a 5% significance, a  $p$ -value of less than 0.05 results in the acceptance of the alternative hypothesis, indicating a trend exists in the data. Conversely, if the  $p$ -value is greater than 0.05, the null hypothesis ( $H_0$ ) is accepted, suggesting the non-existence of a trend in the data [47]. The test statistic,  $S$ , was subsequently computed as the sum of the integers:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sign}(X_j - X_i) \quad (1)$$

where  $n$  indicates the number of years,  $x_j$  and  $x_i$  are the annual values in the years  $j$  and  $k$ , respectively. The function  $\text{sign}(x_j - x_i)$  provides an indicator function that takes the value 1, 0, or  $-1$  according to the sign of the difference ( $x_j - x_i$ ) where  $j > i$ :

$$\text{sign}(X_j - X_i) = \begin{cases} -1 & \text{for } (X_j - X_i) < 0 \\ 0 & \text{for } (X_j - X_i) = 0 \\ +1 & \text{for } (X_j - X_i) > 0 \end{cases} \quad (2)$$

A positive value shows an upward (increasing) trend in the time series, while a negative value indicates a downward (decreasing) trend.

However, Sen's slope was computed, a non-parametric technique for estimating the overall slope or trend in a dataset over time. It is mostly suitable when analyzing time-series data [48]. It is a method that is more robust in trend estimation, and it is especially advantageous for data that do not assume normality or that contain outliers [45,48]. The slope estimator or  $N$  pairs is computed as follows:

$$Q_i = \frac{x_j - x_k}{j - k}, \quad \text{if } j > k \quad (3)$$

where  $x_j$  and  $x_k$  denote the annual values throughout the years  $j$  and  $k$ , respectively. Sen's slope estimator of slope is calculated as the median of the pairwise slope values ( $Q$ ). The median of the

N slope estimates was obtained by simple averaging. N values of Qi were ranked from smallest to largest, and Sen's estimator was computed as follows:

$$\left\{ \begin{array}{l} Q \left[ \frac{N+1}{2} \right] \text{ if } N \text{ was odd} \\ \frac{1}{2} (Q_{\frac{N}{2}} + Q[(N+2)/2]) \text{ if } N \text{ was even} \end{array} \right\} \quad (4)$$

In this study, we considered the trend to be statistically significant when the *p*-value was less than 0.05. Time-series analysis was employed to evaluate the trend in rice production, yield, mean seasonal rainfall, and temperatures (mean, minimum, and maximum temperatures) for the period 1990 to 2023. Several time-series plots were generated using Microsoft Excel based on the following variables: rice production, yield, precipitation, mean temperature, minimum temperature, and maximum temperature, respectively. Additionally, future climate projections under the RCP8.5 scenario were analyzed to provide context for the historical climate trend analysis and to assess whether the observed temperature and precipitation patterns may continue in the future.

### 2.3.2. Correlation Test

Spearman's rank correlation test was applied for estimating the monotonic relationship between production statistics (production and yield) and climate parameters, which in this case are mean temperature, minimum temperature, maximum temperature, and precipitation, respectively. The correlation analysis was conducted at two levels. First, we computed a general correlation test to find the relationship of rice production and yield with climatic variables from 1990 to 2023 (34 years period). Second, a particular time interval correlation test was carried out to identify the association of production and yield statistics with climatic variables corresponding to the period where rice production and yield trends displayed a significant reduction in the time series. The formula used in determining Spearman's correlation is shown below:

$$\rho = 1 - \frac{6 \sum d_i^2}{n(n^2 - 1)} \quad (5)$$

where  $d_i$  represents the differences in paired ranks; that is,  $d_i = R_{xi} - R_{yi}$ , and  $n$  is the total number of observations, which is 34 observations for the study area. The value of  $\rho$  lies between  $-1$  and  $1$ , and direct associations were indicated by positive values, whereas inverse associations were indicated by negative values.

### 2.3.3. Regression Analysis

Following the correlation analysis, multiple linear regression (MLR) was utilized to evaluate the combined relationship or impact of climate parameters and rice productivity [49]. The MLR model is defined by Equation 6.

$$Y_t = \beta_0 + \beta_1 P_{rec} + \beta_2 T_{min} + \beta_3 T_{max} + \varepsilon_t \quad (6)$$

Were

$Y_t$ : Dependent variable (rice production in t/ha or yield in kg/ha).

$P_{rec}$ : Mean precipitation (mm).

$T_{min}$ : Mean minimum temperature (°C).

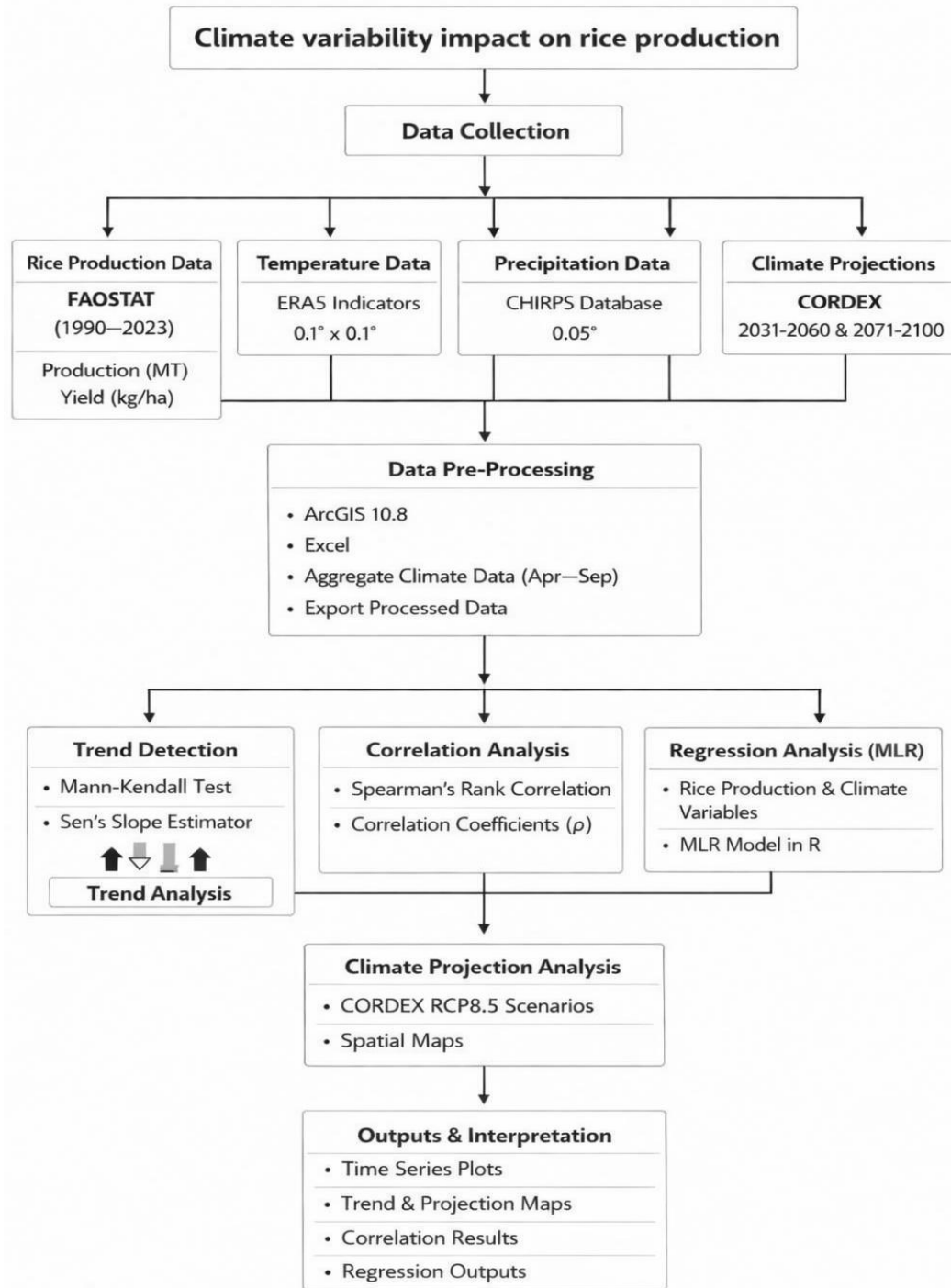
$T_{max}$ : Mean maximum temperature (°C).

$\beta_0$ : Intercept baseline (rice yield when all predictors are 0).

$\beta_1, \beta_2, \beta_3$ : Regression coefficients (effect of each predictor on rice production and yield).

$\varepsilon$ : Error term (unexplained variability).

Mean temperature was excluded from the regression analysis based on its correlation with minimum temperature and maximum temperature. Model diagnostics were conducted to ensure the validity of regression assumptions, including assessment of multicollinearity using the Variance Inflation Factor (VIF), evaluation of residuals for normality and homoscedasticity, and testing for autocorrelation with the Durbin–Watson test. The R Software (Version 4.3.1) was used to perform all statistical and regression analysis, with a significance level set at  $p < 0.05$ .



**Figure 2.** Conceptual flowchart of the study data and methods.

### 3. Results

#### 3.1. Annual Rice Production Trend

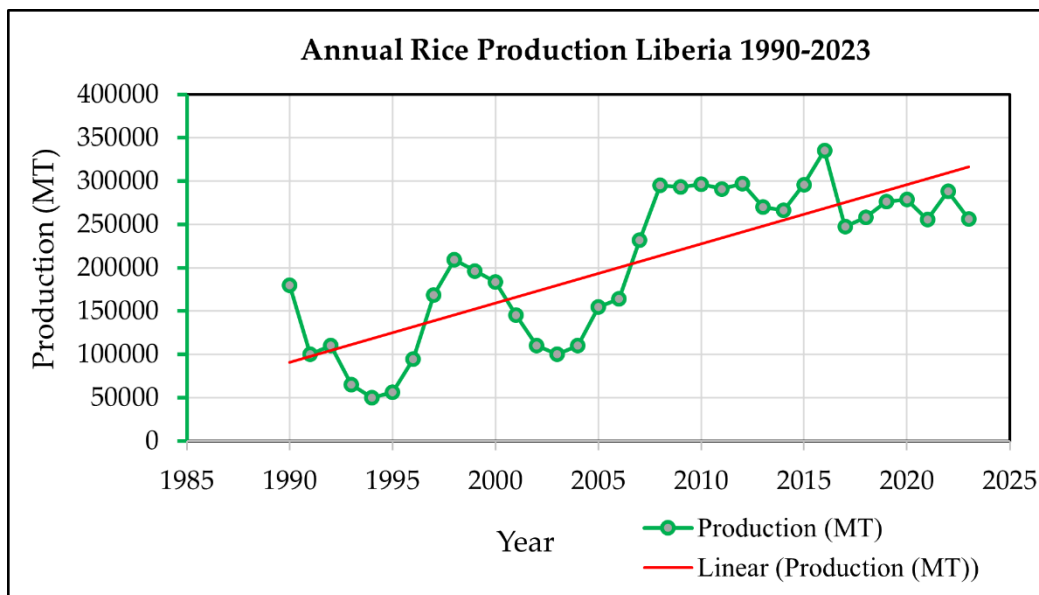
Rice production in Liberia has shown a significant increase over the past 34 years (1990–2023). The Mann–Kendall test shows that this upward trend is statistically significant ( $p$ -value <

0.001) (Table 1). Total production increased from 180,000 tons in 1990 to 256,200 tons in 2023, representing a gain of 76,200 tons over the period. The Mann–Kendall Coefficient ( $\tau = 0.510$ ) showed a moderate to strong positive trend of rice production over time (Table 1, Figure 3). This is further supported by the MK statistics ( $Z = 4.212$ ), indicating the existence of a monotonically increasing trend. Sen’s slope estimates of 6515 also confirm a substantial annual rate of increase in rice production across the study period. Despite the general positive trend, rice production exhibited notable inter-annual fluctuations during some periods (Figure 3). For instance, between 1990 and 1995, production declined noticeably, followed by an increase from 1995 to 1998. A decreasing phase occurred between 1998 and 2003, after which production recovered sharply from 2006 to 2008. From 2008 to 2012, production remained relatively stable, showing only minor fluctuations. A consistent growth phase was observed from 2014 to 2016, followed by a short-term decrease between 2016 and 2017, while 2017 to 2023 remained relatively stable (Figure 3).

**Table 1.** Mann–Kendall and Sens’s slope test results for rice production and yield.

Factors	Kendall Tau	MK-Stat (S)	p-Value	Trend	Sen’s Slope
Production	0.510	4.212	$p\text{-value} < 0.001$ ***	Yes	6515
Yield	-0.0036	-0.0148	0.9882	No	0

Significant levels:  $p < 0.001$  (\*\*\*).

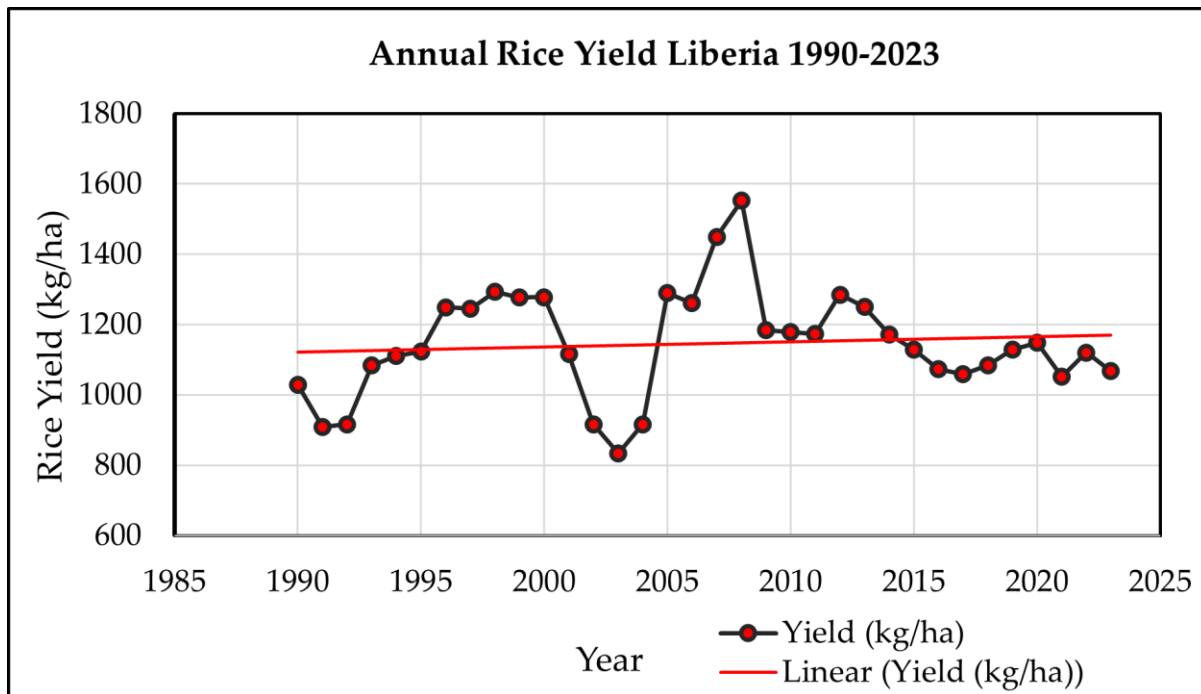


**Figure 3.** Annual variability of total rice production in Liberia from 1990 to 2023.

### 3.2. Annual Rice Yield Trends

Overall, between 1990 and 2023, rice yields have remained relatively stable, showing no statistically significant increase over time. The Mann–Kendall Tau coefficient ( $\tau = -0.0036$ ) depicts an extremely negative weak decrease (Table 1). However, the corresponding  $p$ -value ( $p$ -value = 0.9882) confirms that this correlation is not statistically significant. Similarly, the MK statistics ( $Z = -0.0148$ ) support the absence of a monotonic trend in rice yields. Sen’s slope estimates of zero further support the lack of any significant change in yield during the study period (Table 1).

Despite the overall stability, rice yields exhibited fluctuations across different sub-periods (Figure 4). Between 1990 and 1991, yield slightly decreased from approximately 1030 kg/ha to 900 kg/ha. From 1992 to 2000, yields moderately increased from 900 kg/ha to 1250 kg/ha. This was followed by a sharp decline between 2000 and 2003, when yields dropped to approximately 800 kg/ha. A strong recovery occurred from 2003 to 2008, with yields rising to 1550 kg/ha. However, a sudden drop to 1200 kg/ha was observed in 2009. From 2012 to 2017, yields experienced a gradual decline, decreasing from 1280 kg/ha to 1050 kg/ha while from 2017 to 2023, rice yield remained relatively stable (Figure 4).



**Figure 4.** Annual variability of total rice yield in Liberia from 1990 to 2023.

### 3.3. Patterns of Climatic Variables

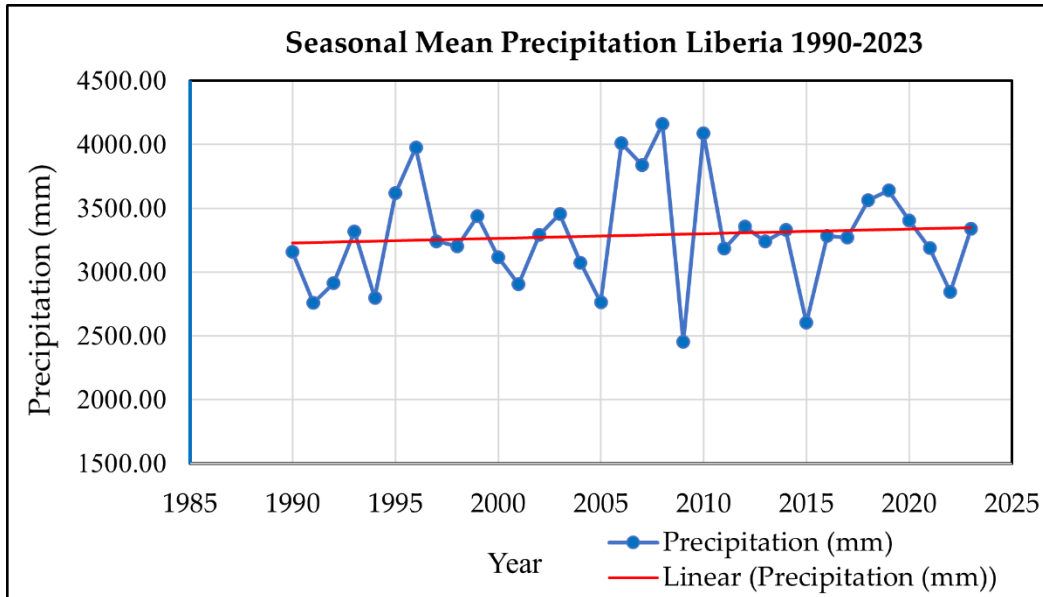
#### 3.3.1. Seasonal Precipitation Trends during the study period

Between 1990 and 2023, annual precipitation exhibited a slight but statistically non-significant increasing trend ( $p$ -value = 0.464). Over the study period, total annual rainfall increased from 3160.66 to 3340.97 (with a slight increase of 180.31 mm,  $p$ -value = 0.464). Despite this modest upward tendency, the data reveals substantial inter-annual variability. In particular, the periods between 1994 and 1996, 2005 to 2006, and 2009 to 2010 were characterized by pronounced fluctuations, including years with both exceptionally high and low rainfall anomalies (Table 2, Figure 5). During the periods of 2003 to 2005, 2011 to 2012, and 2019 to 2022, there was a slight decrease in precipitation, and with a prominent decrease from 2008 to 2009 (Figure 5). Overall, the Mann–Kendall Tau coefficient ( $\tau = 0.102$ ) indicates a very weak positive association between annual precipitation and time; values fluctuate randomly. This observation is supported by the MK statistic ( $Z = 0.830$ ) and Sen’s slope estimates of 5.144, which suggests a slight upward trend. The non-significant  $p$ -value ( $p$ -value = 0.464) confirms that no major long-term trend in precipitation occurred between 1990 and 2023.

**Table 2.** Mann–Kendall and Sen’s slope test for precipitation and temperature.

Factors	Kendall Tau ( $\tau$ )	MK-Stat ( $Z$ )	$p$ -Value	Sig.	Sen’s Slope
Precipitation	0.102	0.8301	0.464	No	5.144
Mean Temperature	0.511	4.1759	<0.001 ***	Yes	0.119
Minimum Temperature	0.509	4.1985	<0.001 ***	Yes	0.0125
Maximum Temperature	0.277	2.2704	0.023 *	Yes	0.0075

Significant levels:  $p < 0.001$  (\*\*\*),  $p < 0.05$  (\*).



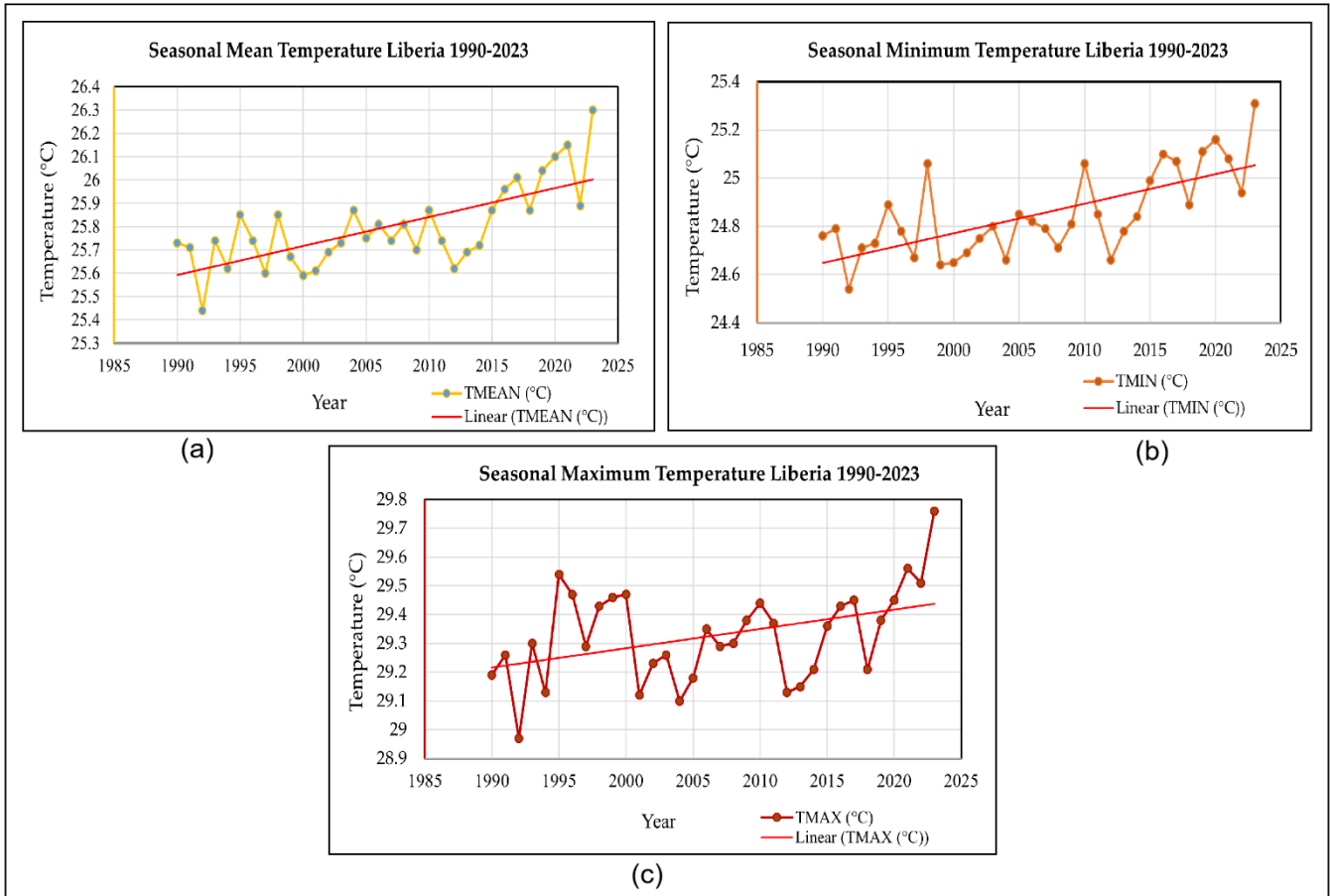
**Figure 5.** Seasonal mean precipitation variability in Liberia from 1990 to 2023.

Figure S1 in the Supplementary Materials depicts projected precipitation for the mid-century (2031–2060) with that of the end-century (2071–2100). These projection results of precipitation, for instance, RCP8.5 2031–2060, revealed a variability with a lower value of 937.51 mm and a highest of 4072.29 mm (see Figure S3a, Supplementary Materials), while RCP8.5 2071–2100 demonstrated a variation from 843.98 mm to a highest value of 3801.95 mm, respectively, as shown in the Supplementary Materials (Figure S3b). The long-term average variability in seasonal precipitation from mid-century to the end of the century is expected to range from  $-93.56$  mm to  $-240.34$  mm, as depicted in the Supplementary Materials (Figure S3a,b).

### 3.3.2. Temperature Trends

From 1990 to 2023, mean, minimum, and maximum seasonal temperatures all showed an overall increasing trend. The mean temperature rose from  $25.73$  °C to  $26.30$  °C, representing an increase of  $0.57$  °C ( $p$ -value  $< 0.001$ ) (Figure 6a). Similarly, the minimum temperature increased from  $24.76$  °C to  $25.31$  °C (an increase of  $0.55$  °C,  $p$ -value is  $< 0.001$ ) (Figure 6b), while the maximum temperature rose from  $29.19$  °C to  $29.76$  °C (an increase of  $0.55$  °C,  $p$ -value =  $0.023$ ) (Figure 6c). The Mann–Kendall Tau coefficients for mean, minimum, and maximum temperatures were  $0.511$ ,  $0.509$ , and  $0.277$ , respectively, indicating weak to strong increasing trends over the study period. These findings suggest that the upward trend was more pronounced in the mean and minimum temperatures, followed by the maximum temperatures. Although the increases were

relatively small in absolute terms, Sen’s slope estimates of these variables are as follows: mean temperature (0.119), minimum temperature (0.0125), and maximum temperature (0.0075). This further confirms the presence of gradual warming across all temperature indicators during the study period (Figure 6a–c).



**Figure 6.** Seasonal mean temperatures: (a) mean, (b) minimum, and (c) maximum temperature variability in Liberia from 1990 to 2023.

Figure S4 within the Supplementary Materials shows projection results of temperature for the mid-century (2031–2060) and end-century (2071–2100). Results of the RCP8.5 for temperature during 2031–2060 revealed significant increasing changes ranging from 24.20 °C to 27.25 °C at the middle of the century, with an estimated increase of 3.03 °C (Figure S4a of the Supplementary Materials), and Figure S4b of the Supplementary Materials demonstrates that the 2071–2100 RCP8.5 interpolation demonstrated a change from 25.95 °C to 28.74 °C in temperature, indicating an absolute increase of 2.7 °C during the time period. This means that the

combined projected change in temperature from 2031 to 2100 is expected to reach 4.54 °C as shown in the Supplementary Materials (Figure S4a,b).

### 3.4. Seasonal Temperature and Precipitation Impact on Rice Productivity

#### 3.4.1. Correlation Between Climate Variables and Rice Productivity

Correlation analysis for 1990 to 2023 suggests that climate variables in Liberia (precipitation and mean, minimum, and maximum temperatures) did not significantly affect rice production, as *p*-values were 0.956, 0.082, 0.531, and 0.908, respectively. However, there may be some inter-variability or minor impacts under various time periods. Precipitation shows a non-statistically significant negative relationship with production and a positive association with yields (Table 3).

Similarly, rice yield (tons/hectare) also shows no statistically significant associations with climatic factors (*p*-value > 0.05). Although there is an observed weak positive correlation with precipitation (*r* = 0.259), this may signify that higher rainfall tends to slightly favor rice yield, even though not strongly enough to be statistically significant. Rice yield also shows a negative correlation with mean and minimum temperatures (Table 3), suggesting that higher temperatures may negatively affect yield in the study region, even though the association is not statistically significant, as the *p*-value is greater than 0.05.

**Table 3.** Correlation (*r*) between rice production (MT), yield (ton/ha), and climate variables—precipitation (mm), mean, minimum, and maximum temperatures (°C) (*p* < 0.05, *n* = 34)—during the period of 1990–2023.

Rice	Precipitation		Temperature					
			Mean		Minimum		Maximum	
	Correlation	<i>p</i> -Value	Correlation	<i>p</i> -Value	Correlation	<i>p</i> -Value	Correlation	<i>p</i> -Value
Production	-0.010	0.956	-0.303	0.082	-0.111	0.531	0.021	0.908
Yield	0.259	0.139	-0.284	0.104	-0.205	0.246	0.112	0.527

Considering the correlation results across different timescales for both rice production and yield revealed that most climate parameters exhibited a statistically non-significant relationship with rice productivity over the various periods analyzed. An exception was observed for the minimum and maximum temperatures during the 1998–2003 period, which showed a highly significant

correlation with production ( $p$ -value  $< 0.001$ ) (Table 4). For rice yield, significant associations were identified for mean and minimum temperatures during 2000–2003 and for precipitation during 2003–2005, with  $p$ -value less than 5%. Additionally, during the period 2012 to 2023, mean temperature ( $p$ -value = 0.004), minimum temperature ( $p$ -value = 0.036), and maximum temperature ( $p$ -value = 0.002) exhibited significant correlations with rice yield (Table 4).

**Table 4.** Correlation ( $r$ ) results between rice production (MT), yield (ton/ha), and climate variables—precipitation (mm), mean, minimum, and maximum temperatures ( $^{\circ}$ C)—under different time intervals ( $p < 0.05$ ).

Factors	Per Interval	Precipitation		Temperature						
		Time	Correlatio	Mean	Minimum	Maximum	Correlatio	Correlatio	Correlatio	
		n	$p$ -Value	Correlatio	$p$ -Value	Correlatio	$p$ -Value	Correlatio	$p$ -Value	
		n		n		n		n		
TI-I. Production										
	1990–1995		–0.314	0.544	–0.429	0.397	–0.371	0.469	–0.543	0.266
	1995–1998		–0.8	0.2	–0.105	0.895	0.2	0.8	–0.8	0.2
	1998–2003		–0.314	0.544	0.2	0.704	1	<0.001 ***	1	<0.001 ***
	2003–2008		0.383	0.309	–0.100	0.797	–0.233	0.546	0.533	0.139
TI-II. Yield										
	2000–2003		–0.80	0.20	–10	<0.001 ***	–10	<0.001 ***	0.20	0.80
	2003–2005		–10	<0.001 ***	0.50	0.667	0.50	0.667	–0.5	0.633
	2012–2023		0.154	0.633	–0.760	0.004 **	–0.608	0.036 *	–0.796	0.002 **

TI-I, production, and TI-II, yield, under different time intervals; significant levels:  $p < 0.001$  (\*\*\*),  $p < 0.01$  (\*\*),  $p < 0.05$  (\*).

### 3.4.2. Regression Results of Climate Variables Impact on Rice Production

The regression model relating rice production and climate variables indicated that climate variables influence rice production in Liberia, explaining 26.16% of the total variation ( $R^2 = 0.2616$ ,  $p$ -value = 0.026). Among the climatic variables analyzed, minimum temperature was the

only factor that showed a statistically significant negative effect on rice production ( $\beta = 2.676$ ;  $p$ -value = 0.015), indicating that higher minimum temperatures are associated with a reduction in rice production in Liberia (Table 5).

**Table 5.** Regression results of climate variables—precipitation (mm), mean minimum temperature, mean maximum temperature ( $^{\circ}\text{C}$ ), and rice production (MT), ( $p < 0.05$ ,  $n = 34$ ).

<b>Predictor</b>	<b>Coefficient</b>	<b>Std. Error</b>	<b>t-Stat</b>	<b>p-Value</b>
Intercept	-5.077	2.462	-2.062	0.048 *
Precipitation	9.335	33.31	0.280	0.781
Mean TMini	-2.676	1.031	2.593	0.015 *
Mean TMax	-4.767	1.164	-0.410	0.685

$p < 0.05$  (\*),  $R^2 = 0.2616$ .

On the other hand, the regression results of rice yield against climate parameters revealed a positive relationship between the observed and predicted values ( $R^2 = 0.231$ ) (Table 6). Approximately 15.4% of the variation in rice yield was explained by the independent variables, as indicated by the adjusted  $R^2$  of 0.154 and a model  $p$ -value of 0.046, which is less than 0.05, thus confirming the statistical significance of the model. Considering the various climatic variables evaluated, the analysis revealed that only precipitation displayed a statistically significant positive effect on rice yield ( $p$ -value = 0.036), as shown in Table 6, suggesting that higher rainfall contributes to increased rice productivity in Liberia.

**Table 6.** Regression results of climate variables—precipitation (mm), mean, minimum, and maximum temperatures ( $^{\circ}\text{C}$ ), and rice yield (ton/ha) ( $p < 0.05$ ,  $n = 34$ ).

<b>Predictor</b>	<b>Coefficient</b>	<b>Std. Error</b>	<b>t-Stat</b>	<b>p-Value</b>
Intercept	-37.482	4485.479	-0.084	0.934
Precipitation	0.134	0.061	2.201	0.036 *
Mean TMini	-327.594	189.915	-1.743	0.092
Mean TMax	275.450	211.997	1.299	0.204

$p < 0.05$  (\*),  $R^2 = 0.231$ .

## 4. Discussion

### 4.1. Trends in Annual Rice Production

The Mann–Kendall and Sen’s slope test results demonstrate that rice production has shown a significant increasing trend over the study period (1990–2023) despite the variation in production across different time intervals. This noticeable increase in production in the study area aligns with regional agricultural reports and studies that have documented a gradual increase in rice output in West Africa due to the expansion of cultivation and government programs promoting rice self-sufficiency [50,51]. Likewise, refs. [19,21] indicated that the increase in production in the SSA region is largely driven by the expansion of rice-harvested areas and not referring to as yield. For instance, between 2000 and 2020, the harvested area rose from 6.9 million ha to 16.6 million ha, while the increase in rice yield was relatively low, increasing from 1.7 to 2.1 t ha<sup>-1</sup> [21], supporting the fact that the increase in rice productivity is dissimilar to the increased actual yield. The observed fluctuations in rice production in Liberia cannot be attributed solely to changes in cultivated area, but rather to the interaction between multiple biophysical and socio-economic factors. Extreme climatic events, including droughts and seasonal flooding, periodically constrain production in both upland and lowland predominantly rainfed systems, leading to substantial year-to-year variability [52]. In addition, policy changes affecting the distribution of improved seeds, agricultural extension services, and input subsidy programs may influence production in specific periods [28,53]. Variations in rice cultivation areas, driven by land availability, labor constraints, and broader socio-economic conditions, further contribute to inter-annual fluctuations [53]. Together, these interacting factors provide important context for understanding the pronounced increases or declines observed in certain years, despite the overall upward trend in rice production.

### 4.2. Analysis of Trends in Annual Rice Yield

Despite increases in total rice production in Liberia, rice yields have remained stagnant, indicating no significant trend. This implies that the observed rise in total rice production is predominantly driven by land expansion rather than improvements in productivity per unit area [21]. Recent studies noted that Liberia’s average national rice yield has remained low in recent decades, at around 1.2 metric tons per hectare, which is considerably lower than yield reported in several other West African countries, including 3.0 t/ha in Côte d’Ivoire, 2.7 t/ha in Ghana, 3.4 t/ha in Mali, and 4 t/ha in Benin, respectively [37,54]. Several interacting biophysical, structural and agronomic factors contribute to the persistent stagnation in yields. These include climate

variability and the predominance of traditional rainfed farming, limited adoption of improved rice varieties, and the low use of modern agricultural inputs such as improved seed, fertilizers, mechanization, and irrigation. In addition, limited access to farm credit agricultural support services constrain farmers' ability to adopt productivity-enhancing technologies [18,24,37]. Fertilizer application in Liberia averages less than 5 kg per hectare, which is significantly below the sub-Saharan African average of approximately 20 kg per hectare [55,56]. Low fertilizer input limits soil nutrient availability, preventing rice crops from achieving their yield potential. In addition, baseline surveys indicate that only about 19–20% of farmers cultivate improved rice varieties, while fertilizer use among smallholders is reported at less than 5% [55,57]. Recent studies have also revealed the limited use of improved seed (about <5%) and a low level of access to extension services (<10%) by farmers in the country [58]. These low adoption rates are attributed to restricted access to quality seeds, limited extension services, and lack of awareness of the benefits of modern technologies [57]. Reports from the World Bank, ref. [59], and the World Food Programme (WFP), ref. [60], indicate that improvements in rice yield in Liberia and other West African countries have been constrained by several challenges, including limited access to improved rice varieties, irrigation technologies, inadequate use of fertilizers, and inadequate extension services. Farmers often rely on traditional practices and local seed varieties, which are less responsive to modern yield-enhancing technologies, thus limiting productivity growth per hectare [21,61]. Furthermore, climate variability—particularly irregular rainfall and temperature extremes—affects critical rice growth stages, limiting yield potential even under favorable climatic conditions [62,63]. Overall, the stagnation in rice yields reflects a combination of biophysical, socio-economic, and institutional constraints, highlighting that increases in total rice production have not translated into proportional improvements in yield per hectare.

### *4.3. Trends in Climatic Variables*

#### *4.3.1. Analysis of Trends in Precipitation*

The results of the Mann–Kendall test showed a non-significant upward trend in precipitation during the study period, reflecting high variability in rainfall patterns. Although rainfall during the growing season showed a slight increase, this change was not statistically significant. However, the absence of a statistically significant trend in seasonal rainfall totals does not necessarily imply stability or reliability in rainfall distribution. For example, intra-seasonal variability, including delayed onset of rains, mid-season dry spells, and early cessation, remains a

critical constraint on planting date decisions and ensuring stable crop development [64]. Such irregularities are often masked by long-term trend analysis but exert significant influence on productivity outcomes [65]. This finding aligns with previous studies' results, which indicate that rural agricultural communities' increasing understanding of changes in local climate conditions, particularly regarding rainfall onset, duration, and distribution, as well as changes in temperature patterns, directly affect rice planting and harvesting dates [28,33]. Studies across West Africa [64] have shown that intra-seasonal rainfall variability has greater implications for yield stability than annual rainfall totals. Moreover, interpolated projection of precipitation under different scenarios of RCP8.5 2031–2060 and RCP8.5 2060–2100 revealed a strong variability in precipitation, indicating an average projected decrease in precipitation by  $-93.56$  mm to  $-240.34$  mm as shown in the Supplementary Materials (Figure S3a,b). These variabilities would hinder farmers' production practices, including changes in planting calendar, crop type, and management practices, which may result in low productivity [66]. Thus, while current rainfall levels in Liberia remain relatively stable, their temporal distribution may be posing significant risks for food production. This study, therefore, underscores the temporal variability of key climatic variables, including precipitation and temperature.

#### 4.3.2. Analysis of Temperature Trends Over the Study Period

Results from the Mann–Kendall test revealed an overall statistically significant increasing trend in temperature, which may hold critical implications for rice production. Kendall's Tau coefficient suggests a general tendency for temperature to increase over time and is highly steady. Continued increases in temperature could have adverse impacts on rice production in the country, a trend that has also been perceived by local farmers in northern Liberia [28,29]. These findings in rising temperatures are consistent with the Liberia National Adaptation Plan document [67], which highlighted that Liberia's mean air temperature will increase by  $0.4$  °C to  $1.3$  °C from 2010 to 2050, based on Regional Climate Models (RCMs). Similarly, the Sixth Assessment Report (AR6) of the United Nations Intergovernmental Panel on Climate Change (IPCC) documented that the global surface temperature has increased by  $1.1$  °C during the past decades (2011–2020) compared to 1850–1900, with further increases of  $1.5$  °C expected by 2021–2040 [1]. Additionally, temperature projections for Liberia under RCP8.5 suggest a continued increase in mean air temperature over two future periods, 2031–2060 and 2071–2100, highlighting the potential for escalating thermal stress on rice production if current trends persist. These projected changes in

temperature varied in both time series, including the periods 2031 to 2060 and 2071 to 2100. The projected changes from 2031 to 2060 are expected to reach 3.03 °C, as highlighted in the Supplementary Materials (Figure S4a), and 2.7 °C during the period 2071 to 2100 (see Figure S4b in the Supplementary Materials), whereas the overall increase from 2031 to 2100 is expected to reach 4.54 °C as shown in the Supplementary Materials (Figure S4a,b). The estimated increase in temperature and variability in precipitation under the RCP8.5 scenario suggests that the climatic trends observed during the historical period may exist, which could influence future rice production conditions in Liberia. These findings support the broader evidence that temperatures are rising globally and regionally, which may hold critical implications for Liberia's predominant rainfed rice production system in the future.

However, referring to previous years, existing studies have revealed that this increasing trend has been perceived by farmers across the study area, and they have further employed various adaptive strategies, including the use of short-duration varieties, adjusting planting schedules, diversifying crops, and basic soil-water management [29,30]. Furthermore, this finding aligns with similar studies underlining the conspicuous increasing trends in temperatures across various regions worldwide [44,68]. For instance, Asfaw *et al.* [69] reported inter-annual variability in rainfall, with mean and minimum temperatures showing significant increasing trends over time, whereas the maximum temperature trend was not significant. They recommend that agricultural sector strategies be designed to account for the declining and erratic rainfall patterns and the increasing temperature trends.

Regional studies support these findings, indicating an increase in production. In Moyamba District, southern Sierra Leone, Yila *et al.* [70] found that temperature exhibited a noticeable increasing trend over the study period, negatively affecting crop production. Similarly, research across West Africa indicated that rising mean temperatures would likely affect rice productivity by accelerating rice phenology, shortening the grain-filling period, and increasing evapotranspiration, thereby heightening the vulnerability of Liberia's largely rainfed rice systems [8,71]. Moreover, the increase in minimum and maximum temperatures beyond the normal threshold may pose a risk to crop performance. For example, high temperatures are particularly harmful, as they increase plant respiration, limit carbohydrate availability for grain filling, and reduce spikelet fertility, ultimately lowering yield potential [72]. Specifically, temperatures above 35°C at the flowering stage have been shown to cause spikelet sterility and severe yield reduction

in rice [9]. However, countries are already facing considerable economic impacts, which are likely to worsen as global warming increases the frequency of extreme events [66].

Given Liberia's dependence on rainfed production systems, such exposure may increase the likelihood of crop failure. Overall, the findings indicate that although temperature did not show a statistically significant impact on rice production during the study period (1990–2023), the observed warming trend suggests that continued increases in temperature may pose potential risks to rice production in Liberia in the future. Therefore, it is essential to implement various adaptation measures such as adjusting planting date, use of short-duration local rice varieties, crop diversification, soil and water conservation, and adopting heat-tolerant varieties in order to boost productivity [71,73–75]. Such strategies align with adaptation behaviors observed in other West African countries, notably Nigeria, Ghana, and Sierra Leone, where smallholder farmers modify agricultural practices to cope with rainfall variability and temperature extremes [70,76,77].

#### *4.4. Impact of Seasonal Temperature and Precipitation on Rice Productivity*

##### *4.4.1. Discussion of the Relationship Between Climate Variables and Rice Productivity*

The study findings indicate that, over the 34 years, no statistically significant relationships were identified between rice production and the accessed climate variables. Nonetheless, production exhibited moderate negative correlations with precipitation, as well as with the mean and minimum temperatures. By contrast, rice yield displayed moderate and more consistent associations with temperature-related variables. These patterns suggest that overall production and productivity are likely influenced more strongly by non-climatic factors such as land expansion, soil quality, access to quality seed, agronomic practices, and policy interventions rather than by climate conditions alone. Supporting this interpretation, ref. [19,78] reported that low yields in rainfed environments constitute a major constraint, such as sub-optimal natural resource and crop management practices commonly adopted by smallholder farmers. These include inadequate water management and limited use of fertilizers, herbicides, and machineries for rice production, noting that rainfed production systems account for approximately 70% of the global harvested rice area. Gül *et al.* [79] demonstrated that non-climatic factors such as area under rice cultivation, fertilizer use, labor force, and water resources affect rice production and have substantial impact on yield. Furthermore, a study conducted by Coulibaly *et al.* [80] identified key barriers such as low adoption of improved varieties and irrigation technologies, limited access to climate information,

low access to extension services, inadequate access to finance and inputs, and overreliance on traditional knowledge that hinder a farmer's adaptation and can result in low productivity levels.

Analysis across multiple timescales revealed fluctuating relationships between climate variables (temperatures and precipitation) and rice yields. Rice yield displayed a strong and negative correlation with precipitation during specific periods, for instance, from 1998 to 2003 for production, and from 2003 to 2005 for yield, suggesting that excessive rainfall and flooding likely constrained rice growth and productivity during these intervals. These results are pertinent, especially the case where rice production in Liberia is mainly based on upland and lowland systems, both of which are largely rainfed and highly sensitive to climate variability. Upland rice, which dominates cultivation, relies heavily on seasonal rainfall, while lowland rice grown in valley bottoms and floodplains also depends on precipitation for water availability. Adequate rainfall is essential during key growth stages—such as germination, tillering, panicle initiation, and grain filling—to maintain soil moisture and support crop development [81]. Insufficient rainfall during these stages can cause water stress and reduced yields, whereas adequate precipitation enhances plant growth and grain formation, explaining the positive relationship between precipitation and rice yields observed in this study. These patterns align with findings reported for other regions of West Africa [21]. The statistically significant negative relationship between precipitation and yield during 2003–2005 further indicates that excessive and insufficient rainfall can contribute to yield reduction [12,82]. However, significant negative correlations were observed for minimum and maximum temperatures within 1998 to 2003 for production, and for mean, minimum, and maximum temperatures within 2000–2003 and 2012–2023 for yield. These results underscore the adverse effects of temperature extremes during these periods, which are consistent with evidence presented in the AR6 Synthesis Report [1]. The report highlights that climate variables, particularly temperature and precipitation, have varying and significant associations with agricultural production and productivity globally and across regions. Previous studies have similarly demonstrated that climate variables, particularly temperature and precipitation, exert major influences on crop productivity, including rice [6,49,83]. Similar findings have been reported in other West African countries. In Côte d'Ivoire, rainfall variability has been shown to significantly influence rice farming performance and farmers' economic outcomes [84]. Also, studies conducted in Ghana indicate that variations in rainfall patterns and temperature significantly affect agricultural productivity and contribute to yield fluctuations across seasons [9]. Regional studies

covering Sierra Leone and Guinea also report substantial variability in rice yields across climatic zones, driven by interactions between climatic conditions and farm management practices [85]. At the broader regional scale, climate change has already contributed to measurable reductions in crop productivity in West Africa, highlighting the increasing influence of temperature and rainfall variability on agricultural systems [86].

In this study, the findings show that temperature and precipitation exhibited significantly different associations with rice production and yield across different timescales, compared with the entire study period (1990–2023), during which no significant relationship was observed. In tropical rice-growing environments such as Liberia, where baseline temperatures are already relatively high, further increases in nighttime temperature may intensify respiration losses and reduce grain-filling efficiency, thereby negatively affecting rice productivity. To mitigate these constraints, it is crucial to effectively deploy a diverse set of technologies such as water preservation technologies in rainfed and irrigated lowland rice, site-specific nutrient management practices, tools to support decision-making (crop growth simulation models), and labor-saving technologies developed in recent decades [21,87].

#### 4.4.2. Regression of Climate Variables Against Rice Production and Yield

Based on the regression results for production, minimum temperature emerged as the only climate variable that significantly influenced rice production in Liberia during the study period. Minimum temperature exhibited a significant negative effect, indicating that a 1 °C increase in minimum temperature is associated with a 2.676 MT decrease in rice production. This suggests that elevated minimum temperature (nighttime temperatures) may impair crop performance, possibly due to increased respiration rates that lead to energy loss, disruption of physiological recovery processes, and heightened stress during sensitive growth stages such as flowering and grain filling [88,89]. This finding is particularly critical in the context of climate change, as minimum temperatures are increasing at a faster rate than maximum temperatures [75,90]. Another study revealed that elevated temperatures pose serious risks to crop production and productivity [88]. Similarly, refs. [64,93] noted that increased temperatures adversely impact the growth and development of rice plants, particularly during processes such as germination, tillering, flowering, and grain filling stages.

Overall, the findings suggest that temperature-related stresses, especially those associated with minimum temperature, play a more critical role in determining rice production outcomes than

precipitation [82,91]. This highlights the crop's sensitivity during flowering and grain-filling stages [92]. Similar patterns have been reported across western and southern regions of Africa, where temporal fluctuations in temperature account for a substantial proportion of yield variability [93,94]. The regression analysis further revealed that, although climate variables collectively exert a moderately significant influence on rice yield in Liberia, the  $R^2$  value of 15.4% indicates that the majority of yield variation is likely driven by non-climatic factors. These may include soil fertility, production systems and management practices, pest pressure, technological adoption, and broader socio-economic conditions. The regression analysis identified precipitation as the only climatic factor that significantly influenced rice yield during the full study period, when accounting for other climatic and soil variables, even though the simple bivariate correlation was not statistically significant. This finding aligns with [28] and [30], who, in their studies, emphasized the direct and indirect implications of rainfall on Liberia's rice production system. The positive association underscores the central role of rainfall in Liberia's predominantly rainfed rice production systems [30,95]. This positive relationship between precipitation and rice yield observed in this study is therefore consistent with the ecological characteristics of rainfed agricultural systems, where crop performance strongly depends on rainfall distribution and seasonal water availability. In tropical environments such as Liberia, rainfall variability can significantly influence yield outcomes by affecting water availability during critical growth stages and supporting physiological processes such as photosynthesis, nutrient transport, and panicle development [1,88]. Similarly, research across West Africa and other tropical regions is closely linked to the variability and distribution of seasonal rainfall [86].

These findings provide valuable insights for formulating appropriate agricultural policies and practices that enhance adaptive capacity, inform extension services, support climate-resilient agricultural development, and guide policy frameworks addressing climate hazards to enhance food security.

## **5. Conclusions and Policy Recommendations**

This study examined the effects of climate variability on rice production in Liberia over the period 1990 to 2023. The results indicate a consistent increasing trend in temperature variables (mean, minimum, and maximum), alongside pronounced rainfall variability. These patterns align with farmers' perceptions of delayed rainfall onset and irregular distribution. The findings further reveal that the relationships between climate variables and rice production and yield vary across

different timescales, suggesting that climate factors exert context-specific influences depending on the timing and magnitude of temperature and precipitation changes.

Although climate variability contributes to fluctuations in rice output, regression results show that climate variables explain only a modest proportion of the observed variation (26.16% for total production and 15.4% for yield). Minimum temperature was found to have a statistically significant negative effect on rice production, while precipitation positively and significantly influences yield. Spatial analysis further demonstrates changes in seasonal temperature and precipitation patterns across the study area, indicating uneven exposure to climate risks. Future projections under RCP8.5 suggest continued increases in temperature and substantial variability in precipitation during both mid-century (2031-2060) and end-century (2071-2100) periods, with important implications for future rice productivity.

Despite an overall increase in total rice production, yields have remained essentially stagnant over the study period. This indicates that non-climatic factors, such as limited access to improved seed varieties, irrigation infrastructure, fertilizers, credit, and low extension services, may be constraining productivity. Therefore, climate variability alone does not fully explain the persistently low rice yields in Liberia; rather, a combination of climatic, agronomic, and socio-economic factors drives the productivity gap and continued reliance on imports.

In response or to reduce future substantial losses due to the consistent variation in climate factors, farmers in Liberia should consistently adopt adaptation practices even though evidence from the existence literature indicates that farmers have adopted several adaptation strategies, including adjusting planting dates, using short-duration varieties, crop diversification, and basic soil and water conservation practices. However, these responses are still rudimentary and largely informal, which are constrained by limited institutional and financial support, increasing farmers' vulnerability to climate variability.

To enhance resilience and ensure sustainable rice production, several policy measures are recommended. First, strengthening localized climate information systems is essential to provide timely and accessible forecasts, alongside improving the capacity of national meteorological services to disseminate user-friendly climate information. Second, investment in agricultural research and development should prioritize the dissemination of short-duration, drought-tolerant, and flood-resistant rice varieties suited to diverse agroecological zones. Third, improving access to agricultural inputs through targeted subsidies, microfinance schemes, and farmer cooperatives

is necessary to reduce production constraints. Fourth, extension services should be strengthened to support the scaling and refinement of existing farmer-led adaptation practices through technical guidance and institutional backing from government agencies and non-governmental organizations.

Finally, policy interventions should incorporate socio-economic dimensions of farmer resilience, including gender, education, and market access, to ensure that adaptation strategies are inclusive and context-specific. By integrating these approaches, Liberia can transition from reactive coping mechanisms to a more proactive, climate-resilient rice production system capable of enhancing food security and reducing import dependence.

#### *Limitations of the Study and Future Directions*

This study offers a comprehensive assessment of rice production trends and climatic influences in Liberia; however, it was constrained by various limitations, including firstly, the absence of a field-based or ground-truth dataset, which makes it limited to correlation. Thus, in the absence of causation, conclusions are based on assumptions. This justifies the need for future research on the physiological and morphological response of rice crops to precipitation and temperature. Secondly, although the study analyzes production and climate at a national level, it does not include other important extreme climate events such as floods, prolonged droughts, and cyclones, which can induce abrupt fluctuations in rice yields. Additionally, due to the national geographical extent, the study did not take into consideration the socio-demographics and geographical differences between regions. Hence, future research can build on these findings by integrating high-resolution data on climate extremes to assess their direct impacts on rice productivity, incorporate field-based data to investigate the physical impact of temperature and precipitation on productivity, while also incorporating socio-demographic factors and the geographical extent or subdivisions. Addressing these aspects will enable more precise, context-specific insights to inform climate-resilient rice production strategies and targeted policy interventions in Liberia.

#### **6. Patents**

Not applicable. This study is solely based on secondary datasets that are publicly available as referenced in the data availability section and did not involve direct experimentation with animals or humans.

**Supplementary Materials:** The following supporting information can be downloaded at: <https://www.mdpi.com/article/doi/s1>, Figure S1: Spatial variability of precipitation and temperature with major and minor rice production areas; Figure S2: Liberia climate classes based on Köppen classification; Figure S3: Climate projection of precipitation; Figure S4: Climate projection of temperature. All other information and materials supporting the findings of this study are provided within the text of the article.

**Author Contributions:** Conceptualization, B.T.S. and C.M.M.; methodology, B.T.S., C.M.M. and J.L.M.U.; software, B.T.S. and J.L.M.U.; validation, J.L.M.U.; formal analysis, B.T.S.; investigation, C.M.M., J.L.M.U. and B.T.S.; resources, B.T.S.; data curation, B.T.S. and J.L.M.U.; writing—original draft, B.T.S.; writing—review and editing, C.M.M., J.L.M.U., A.D.N. and L.A.; visualization, C.M.M., J.L.M.U. and B.T.S.; supervision, C.M.M.; project administration, B.T.S.; funding acquisition, B.T.S. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research and Article Processing Charge (APC) were funded by the Centre of Excellence in Agri-Food Systems and Nutrition (CE-AFSN), Eduardo Mondlane University, Praça 25 de Junho Edifício da Reitoria 5º Andar, Maputo 1102, Mozambique, tel. 849551721, Maputo, Mozambique. Email: [ceasfn@uem.mz](mailto:ceasfn@uem.mz), VAT: 500003545, Grant info: World Bank: E089-MZ.

**Data Availability Statement:** All datasets and materials supporting the findings of this study are provided within the article and are publicly available online : <https://www.fao.org/faostat/en/#data/QCL> (accessed on 11 March 2025); <https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels> (accessed on 13 March 2025); <https://data.chc.ucsb.edu/products/CHIRPS-2.0/> (accessed on 11 March 2025); and <https://cds.climate.copernicus.eu/datasets/projections-cordex-domains-single-levels?tab=download> (accessed on 20 April 2025).

**Acknowledgments:** The authors would like to fully acknowledge the financial support received through the Centre of Excellence in Agri-Food Systems and Nutrition (CE-AFSN), Eduardo Mondlane University, Mozambique, for the achievement of this study.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## Abbreviations

CHIRPS	Climate Hazards Group InfraRed Precipitation with Station
CORDEX	Coordinated Regional Climate Downscaling Experiment
DSSAT	Decision Support System for Agrotechnology Transfer
EPA	Environmental Protection Agencies
FAO	Food and Agriculture Organization
FAOSTAT	Food and Agriculture Organization Statistics
GDP	Gross Domestic Product
IPCC	Intergovernmental Panel on Climate Change
Mk	Mann–Kendall
NAP	National Adaptation Plan
MLR	Multiple Linear Regression
RCMs	Regional Climate Models
SSA	Sub-Saharan Africa
WFP	World Food Programme

## 7. References

1. IPCC Summary for Policymakers:IPCC. (2023). Summary for Policymakers: Synthesis Report. Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, 1–34. S; 2023; pp. 1–34. <https://doi.org/10.59327/IPCC/AR6-9789291691647.001>.
2. Yuan, X.; Li, S.; Chen, J.; Yu, H.; Yang, T.; Wang, C.; Huang, S.; Chen, H.; Ao, X. Impacts of Global Climate Change on Agricultural Production: A Comprehensive Review. *Agronomy* **2024**, *14*, <https://doi.org/10.3390/agronomy14071360>.
3. Mulungu, K.; Kangogo, D. Striving to Be Resilient: The Role of Crop-Poultry Integrated System as a Climate Change Adaptation Strategy in Semiarid Eastern Kenya. *Heliyon* **2022**, *8*, e11579, <https://doi.org/10.1016/j.heliyon.2022.e11579>.

4. Reyes, F.; Gosme, M.; Wolz, K.J.; Lecomte, I.; Dupraz, C. Alley Cropping Mitigates the Impacts of Climate Change on a Wheat Crop in a Mediterranean Environment: A Biophysical Model-Based Assessment. *Agric.* **2021**, *11*, <https://doi.org/10.3390/agriculture11040356>.
5. Ayanlade, A.; Radeny, M.; Morton, J.F.; Muchaba, T. Rainfall Variability and Drought Characteristics in Two Agro-Climatic Zones: An Assessment of Climate Change Challenges in Africa. *Sci. Total Environ.* **2018**, *630*, 728–737, <https://doi.org/10.1016/j.scitotenv.2018.02.196>.
6. Adjah, K.L.; Asante, M.D.; Toure, A.; Aziadekey, M.; Amoako-Andoh, F.O.; Frei, M.; Diallo, Y.; Agboka, K. Improvement of Rice Production under Drought Conditions in West Africa: Application of QTLs in Breeding for Drought Resistance. *Rice Sci.* **2022**, *29*, 512–521, <https://doi.org/10.1016/j.rsci.2022.06.002>.
7. Algarni *et al.* Analyzing the Impact of Climate Change on Rice Production and Strategies for Enhancing Efficiency, Sustainability, and Global Food Security. *International J. Innov. Res. Sci. Stud.* **2025**, 1946–2957.
8. Wassmann and Dobermann Climate Change Adaptation through Rice Production in Regions with High Poverty Levels Reiner. An open access J. Publ. by SESSO Period. **2012**, *1*, 2–24.
9. Jagadish, S.V.K.; Murty, M.V.R.; Quick, W.P. Rice Responses to Rising Temperatures - Challenges, Perspectives and Future Directions. *Plant Cell Environ.* **2015**, *38*, 1686–1698, <https://doi.org/10.1111/pce.12430>.
10. Song, Y.; Wang, C.; Linderholm, H.W.; Fu, Y.; Cai, W.; Xu, J.; Zhuang, L.; Wu, M.; Shi, Y.; Wang, G.; *et al.* The Negative Impact of Increasing Temperatures on Rice Yields in Southern China. *Sci. Total Environ.* **2022**, *820*, 153262, <https://doi:10.1016/j.scitotenv.2022.153262>.
11. Peng, S.; Huang, J.; Sheehy, J.E.; Laza, R.C.; Visperas, R.M.; Zhong, X.; Centeno, G.S.; Khush, G.S.; Cassman, K.G. Rice Yields Decline with Higher Night Temperature from Global Warming. *Proc. Natl. Acad. Sci. U. S. A.* **2004**, *101*, 9971–9975, <https://doi:10.1073/pnas.0403720101>.
12. Maiti, A.; Hasan, M.K.; Sannigrahi, S.; Bar, S.; Chakraborti, S.; Mahto, S.S.; Chatterjee, S.; Pramanik, S.; Pilla, F.; Auerbach, J.; *et al.* Optimal Rainfall Threshold for Monsoon Rice Production in India Varies across Space and Time. *Commun. Earth Environ.* **2024**, *5*, 1–8, <https://doi:10.1038/s43247-024-01414-7>.
13. Gumel, D.Y.; Abdullah, A.M.; Sood, A.M.; Elhadia, R.E.; Jamalani, M.A.; Youssefa, K.A.A.B. Assessing Paddy Rice Yield Sensitivity to Temperature and Rainfall Variability in Peninsular Malaysia Using DSSAT Model. *Int. J. Appl. Environ. Sci.* **2017**, *12*, 1521–1545 .

14. Mannar, V.; Micha, R. Global Nutrition Report; Development Initiatives: Bristol, UK, 2020.
15. Tran, B.L.; Tseng, W.C.; Chen, C.C. Climate Change Impacts on Crop Yields across Temperature Rise Thresholds and Climate Zones. *Sci. Rep.* **2025**, *15*, 23424.
16. Kyaw, A.M.M.; Kim, B.H.S. Climate Change, Adaptation, and Economic Outcomes in Rice Farming: Empirical Findings from Myanmar's Delta Region. *Agric. Food Econ.* **2025**, *13*, 1–18, <https://doi.org/10.1186/s40100-025-00414-1>.
17. Robertson, N.; Oinam, B. Rice Suitability Mapping Using the Analytic Hierarchy Process Approach in a River Catchment. *Glob. J. Environ. Sci. Manag. (GJESM)* **2023**, *9*, 141–156, <https://doi.org/10.22034/gjesm.2023.01.11> .
18. Pope, E.M.; Opile, W.; Ngode, L.; Emmy, C. Assessment of Upland Rice Production Constraints and Farmers' Preferred Varieties in Liberia. *Int. J. Res. Innov. Soc. Sci.* **2023**, *VII*, 1175–1189, <https://doi.org/10.47772/IJRISS>.
19. Ibrahim, A.; Saito, K.; Kokou, A.; Johnson, J.M.; Diagne, M.; Fagnombo, D.J.; Felix, F.; Sylvia, B.O.; Martial, H. Seizing Opportunity towards Sustainable Rice Cultivation in Sub-Saharan Africa. *Environ. Sustain. Indic.* **2022**, *15*, 100189, <https://doi.org/10.1016/j.indic.2022.100189>.
20. Daszkiewicz, T. Food Production in the Context of Global Developmental Challenges. *Agric.* **2022**, *12*, <https://doi.org/10.3390/agriculture12060832>.
21. Saito *et al.* Status Quo and Challenges of Rice Production in Sub-Saharan Africa. *Plant Prod. Sci.* **2023**, *26*, 320–333, <https://doi.org/10.1080/1343943X.2023.2241712>.
22. Pluato *et al.* Impact of Post-Harvest Losses on the Profitability of Rice Production Amongst Smallholder Farmers in Liberia. *Agric. Res. Technol. Open Access J.* **2024**, *28*, <https://doi.org/10.19080/artoaj.2024.28.556414>.
23. Tarway-twalla, A.K. Agricultural Productivity , Climate Change and Smallholder Farmer ' s Entrepreneurship : A Case Study of the Central and Western Regions of Liberia By Monrovia , Liberia. **2013**.
24. Jr, A.D.A.; Diallo, K. Agricultural Dynamics in Liberia : Current Issues and Solutions. *Int. J. Res. Innov. Soc. Sci.* **2025**, *IX*, 7430–7437, doi:<https://dx.doi.org/10.47772/IJRISS.2025.910000604>  
Received:
25. Funk, C.; Peterson, P.; Landsfeld, M.; Pedreros, D.; Verdin, J.; Shukla, S.; Husak, G.; Rowland, J.; Harrison, L.; Hoell, A.; *et al.* The Climate Hazards Infrared Precipitation with Stations - A New

- Environmental Record for Monitoring Extremes. *Sci. Data* **2015**, 2, 1–21, <https://doi.org/10.1038/sdata.2015.66>.
26. CCKP Liberia Country Profile-WEB; 2021; Vol. 3. Available online: [https://climateknowledgeportal.worldbank.org/sites/default/files/2021-07/15917-WB\\_Liberia%20Country%20Profile-WEB.pdf](https://climateknowledgeportal.worldbank.org/sites/default/files/2021-07/15917-WB_Liberia%20Country%20Profile-WEB.pdf) (accessed on 18 July 2024).
  27. CBL Central Bank of Liberia Annual Report 2022; 2023. Available online: <https://www.cbl.org.lr/sites/default/files/documents/2023ANNUALREPORT.pdf> (accessed on 18 October 2024).
  28. Dorbor-soko, L.M. Assessment of the Impacts of Climate Variability and Change on Rice Production in Bong County, Liberia, 2024. Available online: <https://erepository.uonbi.ac.ke/handle/11295/167192> (accessed on 15 September 2025).
  29. Dorbor Wuokolo, J. Perception of Climate Change and Barriers to Strategic Adaptation for Smallholder Farming in Todee District, Liberia, Chulalongkorn University, 2023. Available online: [https://www.researchgate.net/publication/367392196\\_Perception\\_of\\_Climate\\_Change\\_and\\_Barriers\\_to\\_Strategic\\_Adaptation\\_for\\_Smallholder\\_Farming\\_in\\_Todee\\_District\\_Liberia](https://www.researchgate.net/publication/367392196_Perception_of_Climate_Change_and_Barriers_to_Strategic_Adaptation_for_Smallholder_Farming_in_Todee_District_Liberia) (accessed on 18 September 2025).
  30. Sarnoh Assessment of Climate Risks in Central and Northern Liberia Yusuff Mohammed Sarnoh, University of Glasgow, 2024. Available online: <https://theses.gla.ac.uk/84580/> (accessed on 22 October 2025).
  31. LISGIS Thematic Report on Population Size , Distribution and Structure 2022 Liberia Population and Housing Census. **2022**. Available online: <https://lisgis.gov.lr/censusreport/thematic/ThematicReportonPopulationSizeDistributionandStructure.pdf> (accessed on 3 April 2024).
  32. EPA Republic of Liberia Liberia ’ s First Adaptation Communication to the United Nations Framework Convention on Climate Change (UNFCCC); 2021. Available online: [https://unfccc.int/sites/default/files/resource/First\\_Adaptation\\_Communication\\_AdCom\\_LIBERIA.pdf?glarity\\_translate=1](https://unfccc.int/sites/default/files/resource/First_Adaptation_Communication_AdCom_LIBERIA.pdf?glarity_translate=1) (accessed on 18 July 2025).
  33. EPA Liberia’s Revised Nationally Determined Contribution (NDC). *Minerva. Int. Verzeichnis Wissenschaftlicher Institutionen* **2021**, 307–307. Available online: <https://epa.gov.lr/wp->

- content/uploads/2024/10/Liberias-Updated-NDC\_RL\_FINAL-002.pdf (accessed on 28 July 2024).
34. World Bank Liberia Country Climate Development Report; 2024. Available online: <https://documents1.worldbank.org/curated/en/099032024143525952/pdf/P1798481a4fb560431a86a1bb83f1117b00.pdf> (accessed on 18 November 2024).
  35. Beck, H.E.; McVicar, T.R.; Vergopolan, N.; Berg, A.; Lutsko, N.J.; Dufour, A.; Zeng, Z.; Jiang, X.; van Dijk, A.I.J.M.; Miralles, D.G. High-Resolution (1 Km) Köppen-Geiger Maps for 1901–2099 Based on Constrained CMIP6 Projections. *Sci. Data* **2023**, *10*, 1–16, <https://doi.org/10.1038/s41597-023-02549-6>.
  36. CARD Data Collection Survey on Rice Related Programs / Projects in the CARD Member Countries ( with Competitiveness Analysis of Local Rice to Imported Rice; 2021. Available online: [https://riceforafrica.net/wp-content/uploads/2023/12/Mozambique\\_competitiveness-analysis\\_20210808.pdf](https://riceforafrica.net/wp-content/uploads/2023/12/Mozambique_competitiveness-analysis_20210808.pdf) (accessed on 22 December 2024).
  37. Sumo, T.V.; Ritho, C.; Irungu, P. Determinants of Smallholder Rice Farmers’ Willingness-to-Pay for Private Extension Services in Liberia: The Case of Gibi District. *Sustain.* **2023**, *15*, <https://doi.org/10.3390/su151914300>.
  38. Copernicus Climate Change Service Agrometeorological Indicators from 1979 to Present Derived from Reanalysis. Copernicus Climate Change Service (C3S), Climate Data Store (CDS). Available online: <https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels> (accessed on 13 March 2025).
  39. Ayehu and Besufekad Land Suitability Analysis for Rice Production: A GIS Based Multi-Criteria Decision Approach. *Am. J. Geogr. Inf. Syst.* **2015**, *4*, 95–104, doi:10.5923/j.ajgis.20150403.02.
  40. Harrison, L.; Landsfeld, M.; Husak, G.; Davenport, F.; Shukla, S.; Turner, W.; Peterson, P.; Funk, C. Advancing Early Warning Capabilities with CHIRPS-Compatible NCEP GEFS Precipitation Forecasts. *Sci. Data* **2022**, *9*, 1–13, <https://doi.org/10.1038/s41597-022-01468-2>.
  41. Kwak, S.K.; Kim, J.H. Statistical Data Preparation: Management of Missing Values and Outliers. *Korean J. Anesthesiol.* **2017**, *70*, 407–411, <https://doi.org/10.4097/kjae.2017.70.4.407>.
  42. Sharifnia, A.M.; Kpormegbey, D.E.; Thapa, D.K.; Cleary, M. A Primer of Data Cleaning in Quantitative Research: Handling Missing Values and Outliers. *J. Adv. Nurs.* **2026**, *82*, 970–975, <https://doi.org/10.1111/jan.16908>.

43. Ampaire, E.L.; Acosta, M.; Huyer, S.; Kigonya, R.; Muchunguzi, P.; Muna, R.; Jassogne, L. Gender in Climate Change, Agriculture, and Natural Resource Policies: Insights from East Africa. *Clim. Change* **2020**, *158*, 43–60, <https://doi.org/10.1007/s10584-019-02447-0>.
44. Jiqin, H.; Gelata, F.T.; Chaka Gameda, S. Application of MK Trend and Test of Sen’s Slope Estimator to Measure Impact of Climate Change on the Adoption of Conservation Agriculture in Ethiopia. *J. Water Clim. Chang.* **2023**, *14*, 977–988, <https://doi.org/10.2166/wcc.2023.508>.
45. Chang, K.L.; Schultz, M.G.; Lan, X.; McClure-Begley, A.; Petropavlovskikh, I.; Xu, X.; Ziemke, J.R. Trend Detection of Atmospheric Time Series: Incorporating Appropriate Uncertainty Estimates and Handling Extreme Events. *Elementa* **2021**, *9*, 1–28, [doi:10.1525/elementa.2021.00035](https://doi.org/10.1525/elementa.2021.00035).
46. Ondiek, R.A.; Saber, M. Spatial – Temporal Analysis of Impacts of Climate Variability on Maize Yield in Kenya. *Agric.* **2024**, 1–20, [doi:https://doi.org/10.3390/agriculture14081415](https://doi.org/10.3390/agriculture14081415).
47. Dawood, M.; Rahman, A. ur; Rahman, G.; Nadeem, B.; Miandad, M. Geo-Statistical Analysis of Climatic Variability and Trend Detection in the Hindu Kush Region, North Pakistan. *Environ. Monit. Assess.* **2024**, *196*, <https://doi.org/10.1007/s10661-023-12175-9>.
48. da Silva, R.M.; Santos, C.A.G.; Moreira, M.; Corte-Real, J.; Silva, V.C.L.; Medeiros, I.C. Rainfall and River Flow Trends Using Mann–Kendall and Sen’s Slope Estimator Statistical Tests in the Cobres River Basin. *Nat. Hazards* **2015**, *77*, 1205–1221, <https://doi.org/10.1007/s11069-015-1644-7>.
49. Oluwatimilehin; Ayanlade Climate Change Impacts on Staple CropAs: Assessment of Smallholder Farmers’ Adaptation Methods and Barriers. *Clim. Risk Manag.* **2023**, *41*, 100542, <https://doi.org/10.1016/j.crm.2023.100542>.
50. FAO Rice Production Report; 2018; Vol. XXI. Available online: [https://dn790003.ca.archive.org/0/items/assguilhermeferri\\_gmail\\_RICE/RICE.pdf](https://dn790003.ca.archive.org/0/items/assguilhermeferri_gmail_RICE/RICE.pdf) (accessed on 4 September 2025).
51. Soullier, G.; Demont, M.; Arouna, A.; Lançon, F.; Mendez del Villar, P. The State of Rice Value Chain Upgrading in West Africa. *Glob. Food Sec.* **2020**, *25*, 100365, <https://doi.org/10.1016/j.gfs.2020.100365>.
52. FAO Climate Change and Food Security: Risks and Responses; 2015. Available online: <http://www.fao.org/3/a-i5188e.pdf> (accessed on 10 March 2026).

53. EPA National Policy and Response Strategy on Climate Change Final Document-Min\_0; 2018. Available online: <https://www.undp.org/liberia/publications/national-policy-and-response-strategy-climate-change> (accessed on 23 February 2025).
54. Saysay, J.L.; Gabagambi, D.M.; Mlay, G.I.; Mined, I.J. Technical Efficiency in Rice Production Among Smallholder Farmers in Central Liberia : A Stochastic Production Frontier Analysis. *J. Econ. Sustain. Dev.* **2018**, *9*, 47–53.
55. World Bank Improving Service Delivery in Liberia’s Agriculture Sector; 2022. Available online: <https://documents1.worldbank.org/curated/en/099755001262239106/pdf/P1752640ae486b0a089630a7454908775f.pdf> (accessed on 8 March 2026).
56. Mabaya, E., Mulbah, Q., Mienwipia, A., Waithaka, M., Mugoya, M., Tihanyi, K., Kanyenji, G. Liberia Country Report; 2021;
57. MOA Baseline Survey in the Rice Sector Development Hubs of Liberia Final Report Smallholder Agricultural Productivity Enhancement and Commercialization (SAPEC) Project. **2017**. Available online: <https://www.moa.gov.lr/document/smallholder-agricultural-productivity-enhancement-commercialization-sapec/baseline-survey> (accessed on 10 March 2026).
58. Sumo, T. V.; Ritho, C.; Irungu, P. Effect of Farmer Socio-Economic Characteristics on Extension Services Demand and Its Intensity of Use in Post-Conflict Liberia. *Heliyon* **2022**, *8*, e12268, doi:10.1016/j.heliyon.2022.e12268.
59. World Bank Liberia Smallholder Agriculture Transformation and Agribusiness Revitalization Project; 2013. Available online: <https://documents1.worldbank.org/curated/en/539361545925964964/pdf/project-appraisal-document-pad-smallholder-agriculture-transformation-and-agribusiness-revitalization-project-star-p-p160945-12192018-63681026525344785.pdf> (accessed on 14 October 2025).
60. WFP Resilient Food Systems in Western Africa: WFP Contribution to Food Systems Transformation in Western Africa; 2023. Available online: <https://docs.wfp.org/api/documents/WFP-0000153294/download/> (accessed on 12 November 2025).
61. Africa Rice Center and Central Agricultural Research Institute, Seeds4Liberia Project: Rice Seed Value Chains in Liberia: Mapping and SWOT Analysis; 2025. Available online: <https://cgspace.cgiar.org/server/api/core/bitstreams/dbdbc416-7478-4d25-889f-d656e20d7794/content> (accessed on 12 November 2025).

62. Yu, J.; Du, T.; Zhang, P.; Ma, Z.; Chen, X.; Cao, J.; Li, H. Impacts of High Temperatures on the Growth and Development of Rice and Measures for Heat Tolerance Regulation : A Review. **2024**, 1–24.
63. Gwambene *et al* Climate Change and Variability Impacts on Agricultural Production and Food Security for the Smallholder Farmers in Rungwe, Tanzania. *Environ. Manage.* **2023**, 71, 3–14, <https://doi.org/10.1007/s00267-022-01628-5>.
64. Sultan, B.; Gaetani, M. Agriculture in West Africa in the Twenty-First Century: Climate Change and Impacts Scenarios, and Potential for Adaptation. *Front. Plant Sci.* **2016**, 7, 1–20, <https://doi.org/10.3389/fpls.2016.01262>.
65. Habte, A.; Worku, W.; Mamo, G.; Ayalew, D.; Gayler, S. Rainfall Variability and Its Seasonal Events with Associated Risks for Rainfed Crop Production in Southwest Ethiopia. *Cogent Food Agric.* **2023**, 9, <https://doi.org/10.1080/23311932.2023.2231693>.
66. Timité, N.; Kouakou, A.T.M.; Bamba, I.; Barima, Y.S.S.; Bogaert, J. Climate Variability in the Sudanian Zone of Côte d’Ivoire: Weather Observations, Perceptions, and Adaptation Strategies of Farmers. *Sustain.* **2022**, 14, <https://doi.org/10.3390/su141610410>.
67. NAP Liberia National Adaptation Plan 2020 - 2030; 2022. Available online: [https://unfccc.int/sites/default/files/resource/LIBERIA\\_%20NAP\\_%20FINAL\\_%20DOCUMENT.pdf](https://unfccc.int/sites/default/files/resource/LIBERIA_%20NAP_%20FINAL_%20DOCUMENT.pdf) (accessed on 22 July 2024).
68. Joseph, M.; Moonsammy, S.; Davis, H.; Warner, D.; Adams, A.; Timothy, T.D. Heliyon Modelling Climate Variabilities and Global Rice Production : A Panel Regression and Time Series Analysis. *Heliyon* **2023**, 9, e15480, <https://doi.org/10.1016/j.heliyon.2023.e15480>.
69. Asfaw, A.; Simane, B.; Hassen, A.; Bantider, A. Variability and Time Series Trend Analysis of Rainfall and Temperature in Northcentral Ethiopia: A Case Study in Woleka Sub-Basin. *Weather Clim. Extrem.* **2018**, 19, 29–41, <https://doi.org/10.1016/j.wace.2017.12.002>.
70. Yila, K.M.; Gboku, M.L.S.; Lebbie, M.S.; Kamara, L.I. Changes in Rainfall and Temperature and Its Impact on Crop Production in Moyamba District, Southern Sierra Leone. *Atmos. Clim. Sci.* **2023**, 13, 19–43, [doi:10.4236/acs.2023.131003](https://doi.org/10.4236/acs.2023.131003).
71. Lobell *et al.* Historical Effects of Temperature and Precipitation on California Crop Yields. *Clim. Change* **2007**, 81, 187–203, <https://doi.org/10.1007/s10584-006-9141-3>.

72. Jasmine, K. Liberia Country Food and Agriculture Delivery Compact. Penambahan Natrium Benzoat Dan Kalium Sorbat Dan Kecepatan Pengadukan Sebagai Upaya Penghambatan Reaksi Inversi Pada Nira Tebu **2014**.
73. Altieri, M.A.; Nicholls, C.I.; Henao, A.; Lana, M.A. Agroecology and the Design of Climate Change-Resilient Farming Systems. *Agron. Sustain. Dev.* **2015**, *35*, 869–890, <https://doi.org/10.1007/s13593-015-0285-2>.
74. Gautam, Y.; Andersen, P. Rural Livelihood Diversification and Household Well-Being: Insights from Humla, Nepal. *J. Rural Stud.* **2016**, *44*, 239–249, <https://doi.org/10.1016/j.jrurstud.2016.02.001>.
75. IPCC Scientific Review of the Impact of Climate Change on Plant Pests—A Global Challenge to Prevent and Mitigate Plant Pest Risks in Agriculture, Forestry and Ecosystems; FAO on Behalf of the IPCC Secretariat: Rome, Italy, 2021. <https://doi.org/10.4060/cb4769en>.
76. Tambo, J.A.; Abdoulaye, T. Smallholder Farmers' Perceptions of and Adaptations to Climate Change in the Nigerian Savanna. *Reg. Environ. Chang.* **2013**, *13*, 375–388, <https://doi.org/10.1007/s10113-012-0351-0>.
77. Ndamani, F.; Watanabe, T. Farmers' Perceptions about Adaptation Practices to Climate Change and Barriers to Adaptation: A Micro-Level Study in Ghana. *Water (Switzerland)* **2015**, *7*, 4593–4604, doi:10.3390/w7094593.
78. Saito, K.; Senthilkumar, K.; Ali, I.; Johnson, J.; Rodenburg, J.; Senthilkumar, K.; Ali, I.; Johnson, J. Status Quo and Challenges of Rice Production in Sub-Saharan Africa. *Plant Prod. Sci.* **2023**, *26*, 320–333, <https://doi.org/10.1080/1343943X.2023.2241712>.
79. Onușluel Gül, G.; Gül, A.; Najar, M. Historical Evidence of Climate Change Impact on Drought Outlook in River Basins: Analysis of Annual Maximum Drought Severities through Daily SPI Definitions. *Nat. Hazards* **2022**, *110*, 1389–1404, <https://doi.org/10.1007/s11069-021-04995-0>.
80. Coulibaly, J.Y.; Gbetibouo, G.A.; Kundhlande, G.; Sileshi, G.W.; Beedy, T.L. Responding to Crop Failure: Understanding Farmers' Coping Strategies in Southern Malawi. *Sustain.* **2015**, *7*, 1620–1636, doi:10.3390/su7021620.
81. Abbas, S.; Mayo, Z.A. Impact of Temperature and Rainfall on Rice Production in Punjab, Pakistan. *Environ. Dev. Sustain.* **2021**, *23*, 1706–1728, <https://doi.org/10.1007/s10668-020-00647-8>.

82. Birkmann, J.; Liwenga, E.; Pandey, R.; Boyd, E.; Djalante, R.; Gemenne, F.; Leal Filho, W.; Pinho, P.; Stringer, L.; Wrathall, D., *Livelihoods and Sustainable Development*; 2023; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2023.
83. Jagadish , S.V.K.; Murty, M.V.R.; Quick, W.P. Rice Responses to Rising Temperatures—Challenges, Perspectives and Future Directions. *Plant Cell Environ.* **2015**, 38, 1686–1698. <https://doi.org/10.1111/pce.12430>.
84. Béké, T.E.; Sobia, A. The Economic Impact of Climatic Variations on Ivorian Rice Farming. *J. Agric. Stud.* **2020**, 8, 88, doi:10.5296/jas.v8i2.14798.
85. Niang, A.; Becker, M.; Ewert, F.; Dieng, I.; Gaiser, T.; Tanaka, A.; Senthilkumar, K.; Rodenburg, J.; Johnson, J.M.; Akakpo, C.; *et al.* Variability and Determinants of Yields in Rice Production Systems of West Africa. *F. Crop. Res.* **2017**, 207, 1–12, <https://doi.org/10.1016/j.fcr.2017.02.014>.
86. Sultan, B.; Defrance, D.; Iizumi, T. Evidence of Crop Production Losses in West Africa Due to Historical Global Warming in Two Crop Models. *Sci. Rep.* **2019**, 9, 1–15, <https://doi.org/10.1038/s41598-019-49167-0>.
87. Tripathi, R.; Kumar, A.; Guru, P.; Debnath, M.; Mohapatra, S.D.; Mohanty, S.; Shahid, M.; Nayak, A.K. Precision Farming Technologies for Water and Nutrient Management in Rice : Challenges and Opportunities. *Oryza* **2021**, 58, 126–142, doi:<https://doi.org/10.35709/ory.2021.58.spl.5> Precision.
88. Hatfield, J.L.; Prueger, J.H. Temperature Extremes: Effect on Plant Growth and Development. *Weather Clim. Extrem.* **2015**, 10, 4–10, <https://doi.org/10.1016/j.wace.2015.08.001>.
89. Su, Q.; Rohila, J.S.; Ranganathan, S.; Karthikeyan, R. Rice Yield and Quality in Response to Daytime and Nighttime Temperature Increase – A Meta-Analysis Perspective. *Sci. Total Environ.* **2023**, 898, 165256, <https://doi.org/10.1016/j.scitotenv.2023.165256>.
90. Rahman, M.A.; Kang, S.C.; Nagabhatla, N.; Macnee, R. Impacts of Temperature and Rainfall Variation on Rice Productivity in Major Ecosystems of Bangladesh. *Agric. Food Secur.* **2017**, 6, 1–11, <https://doi.org/10.1186/s40066-017-0089-5>.
91. Zhao, C.; Liu, B.; Piao, S.; Wang, X.; Lobell, D.B.; Huang, Y.; Huang, M. Temperature Increase Reduces Global Yields of Major Crops in Four Independent Estimates. *PNAS* **2017**, 1–6, doi:10.1073/pnas.1701762114.
92. Baruah, U.; Das, S.; Kalita, P.; Saikia, M.; Bhoulal, S.; Pal, S.; Das, R. High-Night Temperature-Induced Changes in Chlorophyll Fluorescence, Gas Exchange, and Leaf Anatomy Determine

Grain Yield in Rice Varieties. *J. Plant Growth Regul.* **2023**, *42*, 5538–5557, <https://doi.org/10.1007/s00344-023-10934-z>.

93. Jalloh, A.; Nelson, G.C.; Thomas, T.S.; Zougmore, R.B.; Roy-Macauley, H. *West African Agriculture and Climate Change: A Comprehensive Analysis*; International Food Policy Research Institute: Washington, DC, USA, 2013; ISBN 9780896292048.
94. Nhamo, L.; Matchaya, G.; Mabhaudhi, T.; Nhlengethwa, S.; Nhemachena, C.; Mpandeli, S. *Cereal Production Trends under Climate Change : Impacts and Adaptation Strategies in Southern Africa. Agric.* **2019**, 1–16, <https://doi.org/10.3390/agriculture9020030>.
95. MOA Liberia Agriculture Pilot Survey Final Report Ministry of Agriculture; 2019. Available online: [https://www.moa.gov.lr/sites/default/files/documents/Liberia%20Agriculture%20Pilot%20Survey%20%20Report%202019\\_MOA.pdf](https://www.moa.gov.lr/sites/default/files/documents/Liberia%20Agriculture%20Pilot%20Survey%20%20Report%202019_MOA.pdf) (accessed on 3 August 2024).

**Disclaimer/Publisher’s Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

## CHAPTER V: RESEARCH ARTICLE II

### 5.1. Brief Introduction

The second article titled: “*Geospatial Multi-Criteria Decision-Making for Land Suitability Analysis for Rice Cultivation in Liberia*” is made of one specific objective (objective 5) of the thesis. It aims to identify agricultural land suitable for rice cultivation in Liberia using a GIS-based MCDM and AHP, while considering ten key factors: precipitation, temperature, elevation, slope, soil texture, soil pH, soil organic carbon, nitrogen, phosphorus and potassium. The manuscript was submitted to the Journal called “Discover Sustainability,” which is a SCOPUS indexed journal that is published in Springer Nature.

### 5.2. Status of Paper II

Currently, the manuscript has been accepted for publication by Discover Sustainability in Springer Nature. Article details: *Discov Sustain* (2026). <https://doi.org/10.1007/s43621-026-03217-6>

### 5.3. Author Contributions

B.T.S. and J.L.M.U. proposed the study objectives, methodology, performed the data analysis, wrote original draft and reviewed the manuscript. C.M.M. and A.N. supervised, critically revised the manuscript. All authors approved the last version of manuscript to be published.

### 5.4. Full Research Paper

**Title: Geospatial Multi-Criteria Decision-Making for Land Suitability Analysis for Rice Cultivation in Liberia**

**Bondo T. Simpson<sup>1,2</sup>, Jone L. Medja Ussalu<sup>1,2, \*</sup>, Celsa Mondlane Macandza<sup>1,2</sup>, and Arsénio Ndeve<sup>1,2</sup>**

- 1 Centre of Excellence in Agri-Food Systems and Nutrition (CE-AFSN), Eduardo Mondlane University, Mozambique; bondosimpson@gmail.com
  - 2 Faculty of Agronomy and Forestry Engineering, Eduardo Mondlane University, Maputo, Mozambique; jonemedja@gmail.com, celsamacandza@gmail.com, Ndevegod@gmail.com
- \* Correspondence: [jonemedja@gmail.com](mailto:jonemedja@gmail.com)

## **Abstract**

Achieving food security and sustainable resource management has become the main goal for many developing countries. Rice is a staple crop in Liberia, and its demand is increasing while yield remains low. Rapidly changing climate patterns and persistent low yields necessitate a systematic, data-driven identification of the most resilient and productive agricultural areas for rice, contributing to food security. Currently, there is a gap on empirical and national-scale rice suitability assessment for Liberia. This study aims to identify suitable areas for rice cultivation in Liberia, based on climate, geomorphologic and geochemical factors. We used a GIS-based Multi-Criteria Decision-Making (MCDM) approach, applying the Analytic Hierarchy Process (AHP) to derive expert-weighted criteria layers (climate, geomorphologic, and geochemical) for the final suitability map. Results show that 5.57% of Liberia is highly suitable, 44.57% suitable, 42.41% semi-suitable, and 7.45% unsuitable. Primary limiting factors for rice suitability in Liberia include: pH, slope, and soil texture. Most suitable areas are found in the central, northern, and southeastern regions, including counties such as Lofa, Bong, Nimba, Gbarbolu, Grand Gedeh, and River Gee. These findings indicate that 50.14% of the land presents favorable conditions for rice cultivation in Liberia, including potential land (42.41%) that can be harnessed using agricultural technologies. This study provides important aids for agricultural land accessibility and planning and further provides a critical baseline for the government and stakeholders to strategically target land-use planning, input subsidies, and enhance rice production through expansion of land in the suitable areas indicated hereof, thereby, directly supporting national food security goals.

**Keywords:** Analytic Hierarchy Process; GIS; Multi-Criteria Decision-Making; rice cultivation; land suitability; Liberia.

## 1. Introduction

Rice is one of the major cultivated food sources worldwide [1]. It is a primary food and income source in many Sub-Saharan African countries including Liberia [2,3]. Its demand is continuously rising, due to the population growth, however production remains low to meet the demand of the consumers [3,4,5], leading to food insecurity and malnutrition in many low-income countries with food deficits [6].

In Liberia, rice plays a major role in the daily diet. It is preferred because it is easy to store and prepare compared to other staple food [2,5]. The country accounts for 50% of adult caloric intake, with nearly 133 kg annual per capita consumption [3]. This makes rice to be one of the most important crops for food security and economic livelihood that is produced by 69% of farmers in the country [7]. Rice consumption in Liberia has increased over the past years, reaching approximately 560,000 metric tons in 2021, with annual increase of 4.6% [8]. Liberia struggles to meet its annual rice needs, importing over 90% of its rice, costing over USD 100 million annually [9]. The country's average rice yields is approximately between 1.1 to 1.2 tons/ha, considerably below the regional average of 4-6 tons/ha, putting food security at risk [3,10,11]. Therefore, enhancement of rice productivity would contribute to reducing hunger and poverty indices, bring relief, domestic food safety, and financial stability growth [12,13].

The importance of rice in Liberia extends even far; it serves as a platform for income generation [7]. The chain of values linked to rice cultivation involves a range of tasks, encompassing growing, processing, allocation, and selling, generating job prospects and revenue sources throughout the journey. Its accessibility and cost have traditionally affected the nation's socio-political environment in the past, like in 1979, where high rice tariffs resulted in major riots, highlighting its essential importance in the Liberian society.

Due to the country's demand for rice, the Liberian government launched the National Agriculture Development Plan (NADP) 2024-2030, also known as "Feed Yourselves" Agenda, intending to enhance food security. With this regard, the Liberian government has identified counties with potential for rice production, such as, Lofa, Bong, and Nimba. However, these areas have not been thoroughly assessed for their suitability. To achieve optimal rice production, it is crucial to identify the most appropriate locations, through a land suitability analysis. Suitability is determined by the combination of different factors, such as climate and land/soil characteristics, assessing how well the local match or satisfy the needs of the crop [14].

This study aims to identify agricultural land suitable for rice cultivation in Liberia, using a Geographic Information System (GIS)- based Multi-Criteria Decision-Making method, based on ten key factors: precipitation, temperature, elevation, slope, soil texture, soil pH, soil organic carbon, nitrogen, phosphorus and potassium. GIS and remote sensing have been widely used by many researchers for assessing land suitability for crop production in many parts of the world [3,15,16,17,18]. Some studies across neighboring and sub-Saharan Africa regions have employed similar approach to determine land potential for crop production, such as, in Nigeria [15,19], Ethiopia [18], Kenya [20], and Ghana [21]. In particular, an extensive land suitability analysis in Liberia is still a gap. This is the first GIS- and remote sensing-based study for assessing land suitability for rice crop cultivation in Liberia.

Findings include partial suitability assessment to identify optimal and limiting factors to rice productivity in Liberia. Additionally, future suitability against climate change is also assessed. In general, Liberia presents a climate-resilient agriculture, being constrained by other factors such as soil texture, pH and slope. This study provides important baselines for stakeholders and policy makers to make evidence-based decisions on their interventions in addressing the current challenge in rice crop productivity, contributing to increased rice production and yield, and therefore, contribution to food security.

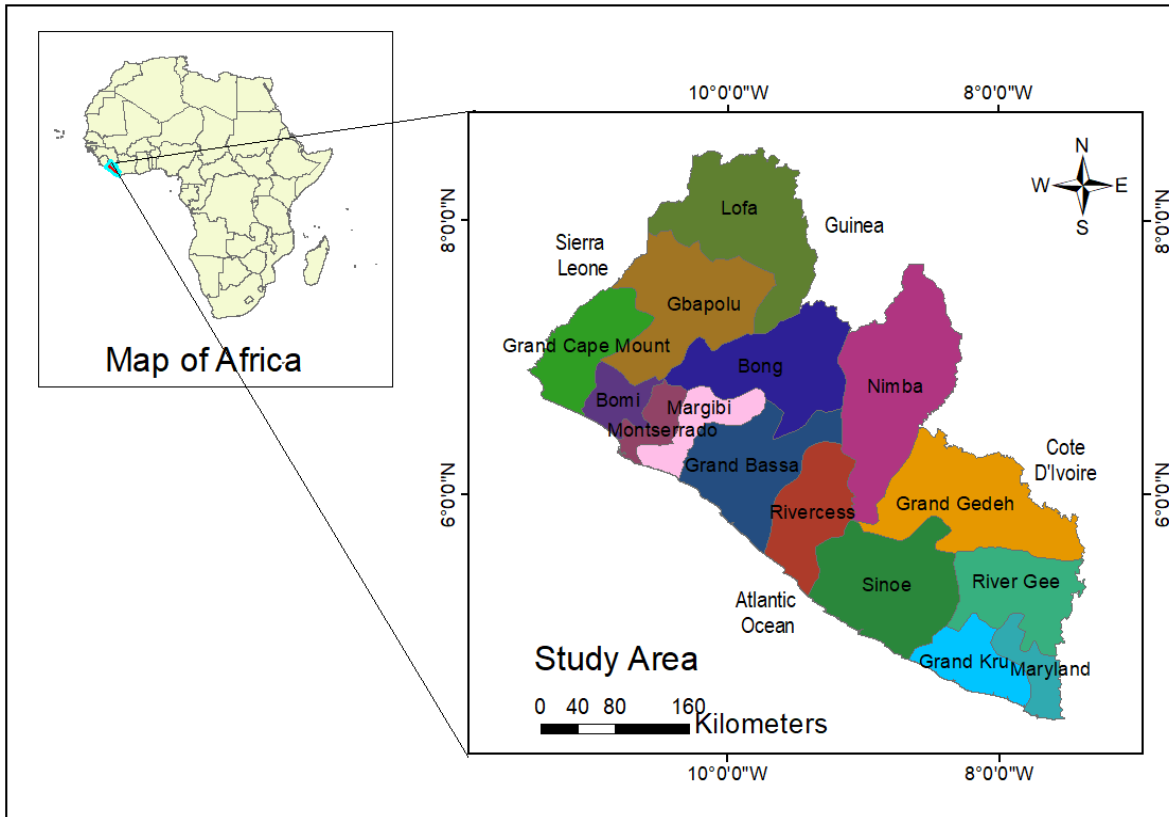
## **2. Materials and Methods**

### *2.1. Characterization of the study area*

The study area, Liberia, is located in the upper Guinea rainforest region of West Africa, bordered by Guinea to the north, Sierra Leone to the west, Côte d'Ivoire (Ivory Coast) to the east, and the Atlantic Ocean to the south. Liberia is one of the smallest countries in the west African region (Figure 1), and its total area covers 111,350 km<sup>2</sup>, with a population of 5.3 million [22]. The country lies between the latitudes 4° 20' N and 8° 30' N and longitudes 7° 18' W and 11° 30' W [23].

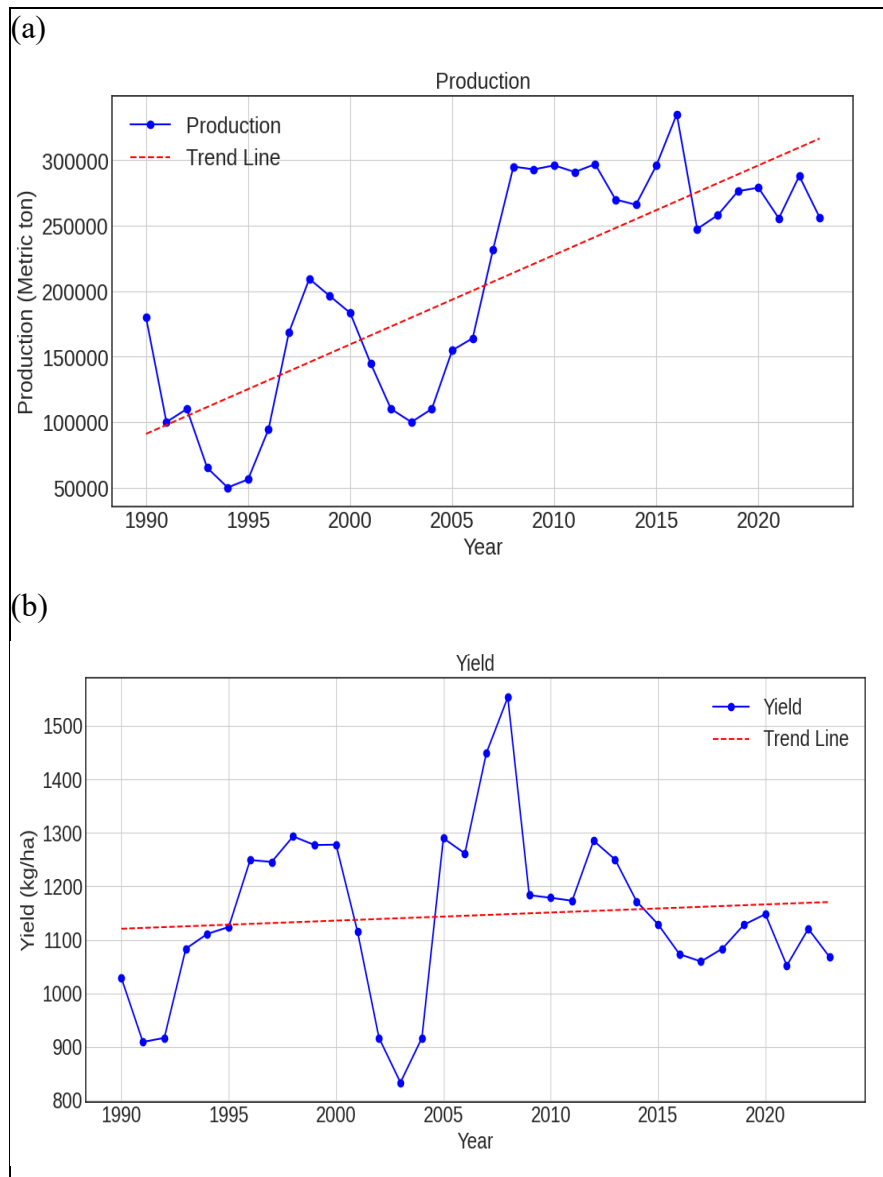
Major part of the country is characterized by mixed vegetation and savanna. Agriculture is the major socioeconomic activity in Liberia, involving over 70 percent of the population [24]. Rice is produced by 69% of farmers and accounts for about 50% of adult caloric intake; the annual per capita consumption is estimated at around 133 kg [3]. Rice production is mostly practiced by small-holder farmers under rainfed conditions. The average rice yields of the country is approximately

1.2 t/ha, with notable production in Nimba, Bong, and Lofa counties, which account for 56% of the country's rice production (CARD, 2021; Sumo *et al.*, 2023).



**Fig. 1** The study area, Liberia and its county divisions

Figure 2 presents the historical variability of rice production and yield from 1990 to 2023, processed using national data provided by FAOSTAT open data (<https://www.fao.org/faostat/en/#home>). Based on this data, the total production in Liberia increased from 180,000 t/ha in 1990 to 256,200 t/ha in 2023 representing a gain of 76,200 t/ha in 33 years, while the yield remains nearly constant and its average converge to the value presented above, reported in literature.



**Fig. 2** Variability of the time series of rice (a) production and (b) yield, from 1990 to 2023. Data provided by FAOSTAT open data (<https://www.fao.org/faostat/en/#home>).

### 2.1.1. Climate

Liberia presents a tropical and humid climate, subdivided in three sub-groups namely: monsoon, savanna, and equatorial climate [25,26]. Liberia temperature is typically within the range from 23°C to 33°C throughout the year [27] and the mean temperature for the country is 25.7° [26]. On the other hand, the average annual precipitation in Liberia is 2500 mm, with some spatial differences between regions [28]. Rainfall along the coastal areas exceeds 4,000 mm per year and reduces to 1,300 mm in the country's interior. For instance, in Monrovia, precipitation

reaches 5,000 mm annually, with the pick in June and July, where monthly precipitation reaches about 1000 mm [29,30]. Daily relative humidity along the coastal belt remains high (>80%), decreasing to nearly 20% inland during the dry season [25].

### 2.1.2. Geomorphology

Liberia's geomorphology is shaped by a combination of ancient geological formations and fluvial processes, resulting in diverse landforms across the country. Landscape is characterized by four distinct regions, which include coastal plains, rolling hills, plateaus and coastline, and northern highland [27]. The coastal area has an upland extension of 32 to 40 km and consists of moderately rolling hills or low plains with an altitude not exceeding 15 m [27]. Rolling hills reach 90 m and are mostly used for agricultural purposes. The plateau extends over 120 km, with heights up to 300 m, while mountains rise to 600 m, including the Mano River mountains [26,27]. The northern highlands feature significant ranges with Mount Wutivi reaching 1,440 meters, and these areas are also rich in minerals and biodiversity [27]. Mount Nimba nearby Yekepa reaches about 1,752 meters above sea level, but it is not completely within Liberia as Mount Nimba shares a border with Guinea and Côte d'Ivoire [27].

Soil texture plays a key role in rice cultivation, as it is the level of coarseness of the soil, and rice being a tropical crop, requires a soil texture that can retain water for a longer period [15]. The study area is generally characterized by 4 major soil types, with sub-classes (the combination of these soil types). These soil types include clayey (60–70%), sandy (10–15%), loamy (7–10%), and silty (5–8%). The clayey soil covers most parts of Liberia (upland and interior regions) due to the widespread presence of heavily weathered, iron-riched Ferralsols (clay), which is mostly found in counties including Lofa, Bong, Nimba, and Sinoe (Figure 4a). The sandy class is mostly found in the south and south-central parts of Liberia. Soil texture is a limiting factor for rice crop production in Liberia, as poor soils are found even in the major rice producing counties. Lofa in particular, is predominantly covered by Ultisols, typically acidic and with limited nutrient availability, while Bong and Nimba are largely Oxisols, which are deeply weathered, low in nutrient fertility, and highly prone to nutrient depletion without inputs [3].

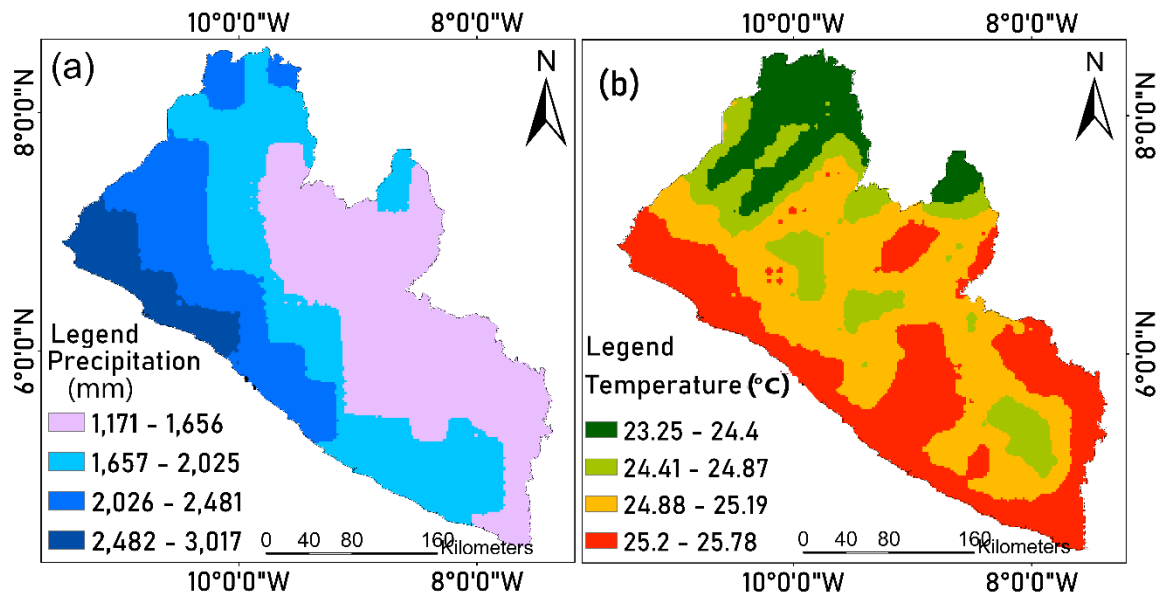
## 2.2. Data for suitability analysis

Climate, soil, topographical and land use land cover data were used for achieving the purpose of this study. These data were obtained from various sources with varying resolutions as

depicted in Table 1. Ten factors were considered for the suitability analysis, namely: temperature, precipitation, elevation, slope, soil texture, soil pH, soil organic carbon (SOC), nitrogen, phosphorus and potassium. In general, there is not a rule of thumb for the number of factors to include in the multi-criteria decision-making (MCDM) method. In our case, the inclusion of the 10 factors was determined by their influence or contribution to rice crop development based on previous studies [12,22,23] and by data availability and quality.

### 2.2.1. Climate data

Climate information consisted of air temperature and precipitation, which have a direct interference in agriculture, and they can affect either positively or negatively the growth, development, and yield of agricultural crops [31]. Rice is typically cultivated in tropical and subtropical regions, and based on its tropical characteristics, it grows well in a climate with relatively high temperatures between 20° to 40°C and annual rainfall levels ranging from 1250 mm to 2000 mm [15,19]. Data of precipitation and temperature from 1980 to 2023 were obtained from Copernicus Climate Change Service (C3S), consisting of AgrERA5 reanalysis (Agrometeorological Indicators), with a spatial resolution of 0.1° x 0.1° [32] (available online at <https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels>). For the purpose of this study, we have considered the seasonal data from April to September, for both temperature and precipitation, which is the rice growing season in Liberia. Figure 3 shows the spatial variability of long-term averages of precipitation and temperature over this season. For assessing future implication of climate change on land suitability, we have considered projections of precipitation and temperatures derived from the Coordinated Regional Climate Downscaling Experiment, phase 5 (CORDEX5), the most updated CORDEX phase for Africa, available by the moment of this study, covering the period of 2006 - 2100, accessed at <https://esg-dn1.nsc.liu.se/search/cordex/>. Instructions for downloading the data can be found at <http://www.csag.uct.ac.za/cordex-africa/how-to-download-cordex-data-from-theesgf/>. We have downloaded the CORDEX for Africa with spatial resolution of 0.22ox0.22o. For the purpose of this study, we have assessed the worst greenhouse gas emission scenario RCP8.5. Available data consisted of a total of 6 simulations from the ensemble “r1i1p1” (6 ensemble members), as a result of the combination of two regional models (CCLM and REMO) and three driving models (MOHC-HadGEM2-CC, NCC-NorESM1-M, and MPI-M-MPI-ESM-LR). The ensemble mean was averaged over Liberia for two future periods: mid-21st century (2031-2060) and the end of 21st century (2071-2100).



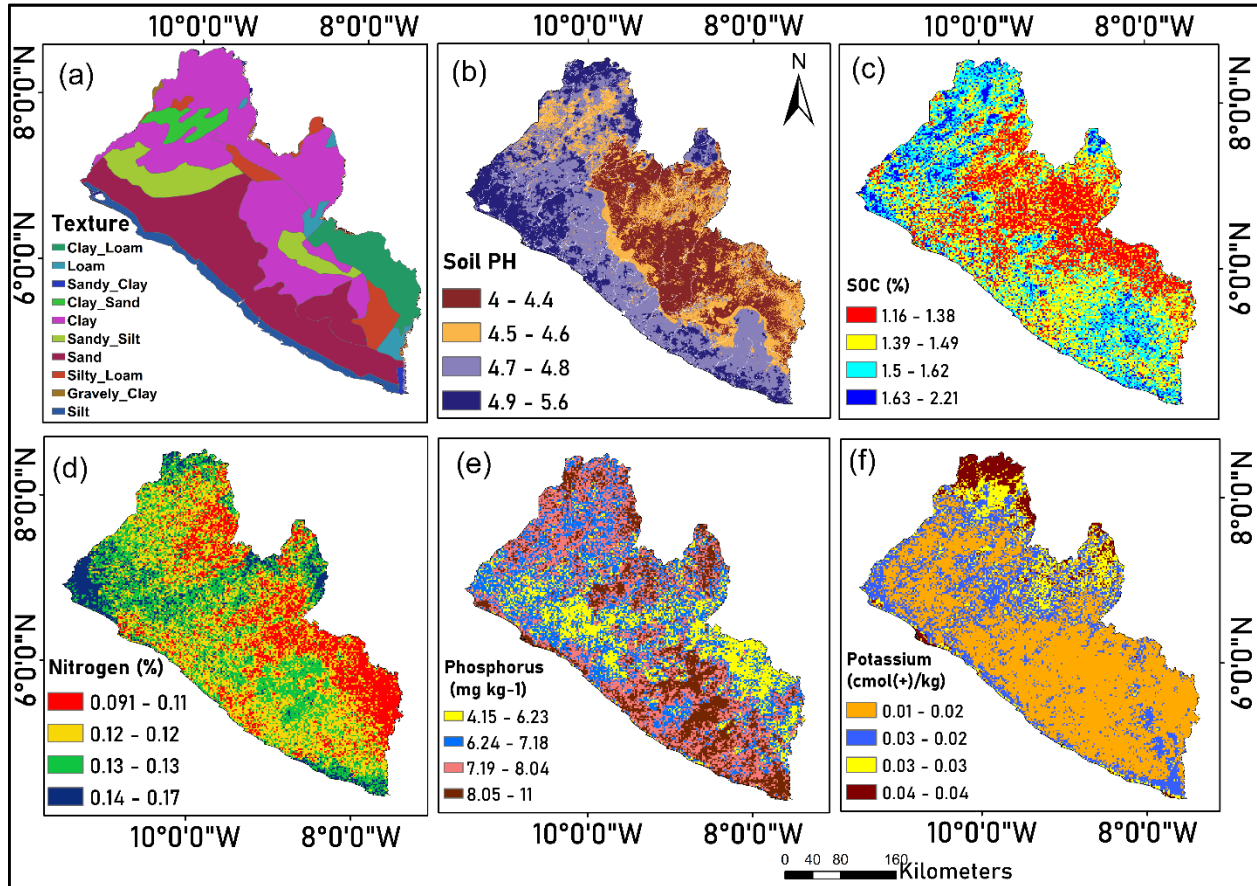
**Fig. 3** Spatial variability of (a) precipitation in mm and (b) temperature in °C, averaged during the rice growing season (April to September) in Liberia

### 2.2.2. Soil data

Data on soil physical properties (soil texture) was sourced from FAO (Food and Agricultural Organization) world soil map, and chemical properties including pH, nitrogen, phosphorus, and potassium were obtained from the Liberia Soil Information System (LIBSIS) database of 2023 (accessible online at <https://libsislr.com>). Figure 4 shows the soil data considered for this study.

Soil texture plays a key role in rice cultivation, as it is the level of coarseness of the soil, and rice being a tropical crop, requires a soil texture that can retain water for a longer period [15]. Liberia is generally characterized by 4 major soil types, with sub-classes (the combination of these soil types). These soil types include clayey (60–70%), sandy (10–15%), loamy (7–10%), and silty (5–8%). The clayey soil covers most parts of Liberia (upland and interior regions) due to the widespread presence of heavily weathered, iron-riched Ferralsols (clay), which is mostly found in counties including Lofa, Bong, Nimba, and Sinoe (Figure 4a). The sandy class is mostly found in the south and south-central parts of Liberia. Soil texture is a limiting factor for rice crop production in Liberia, as poor soils are found even in the major rice producing counties. Lofa in particular, is predominantly covered by Ultisols, typically acidic and with limited nutrient availability, while Bong and Nimba are largely Oxisols, which are deeply weathered, low in nutrient fertility, and

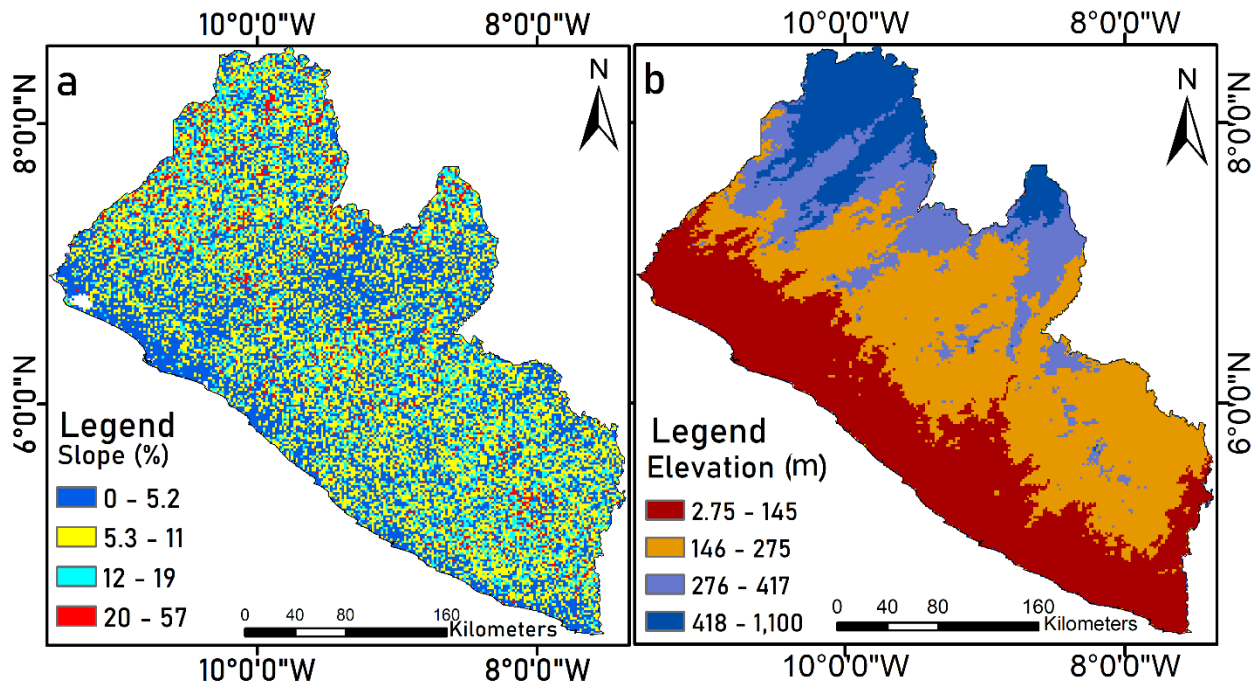
highly prone to nutrient depletion without inputs [3,32]. Both soil types (Ultisols and Oxisols) are classified under the USDA Soil Taxonomy system and are common in humid tropical and subtropical regions [32].



**Fig. 4** Geomorphological maps for soil parameters in Liberia: (a) soil texture, (b) pH, (c) soil organic carbon, (d) nitrogen, (e) phosphorus, and (f) potassium

### 2.2.3. Topographic data

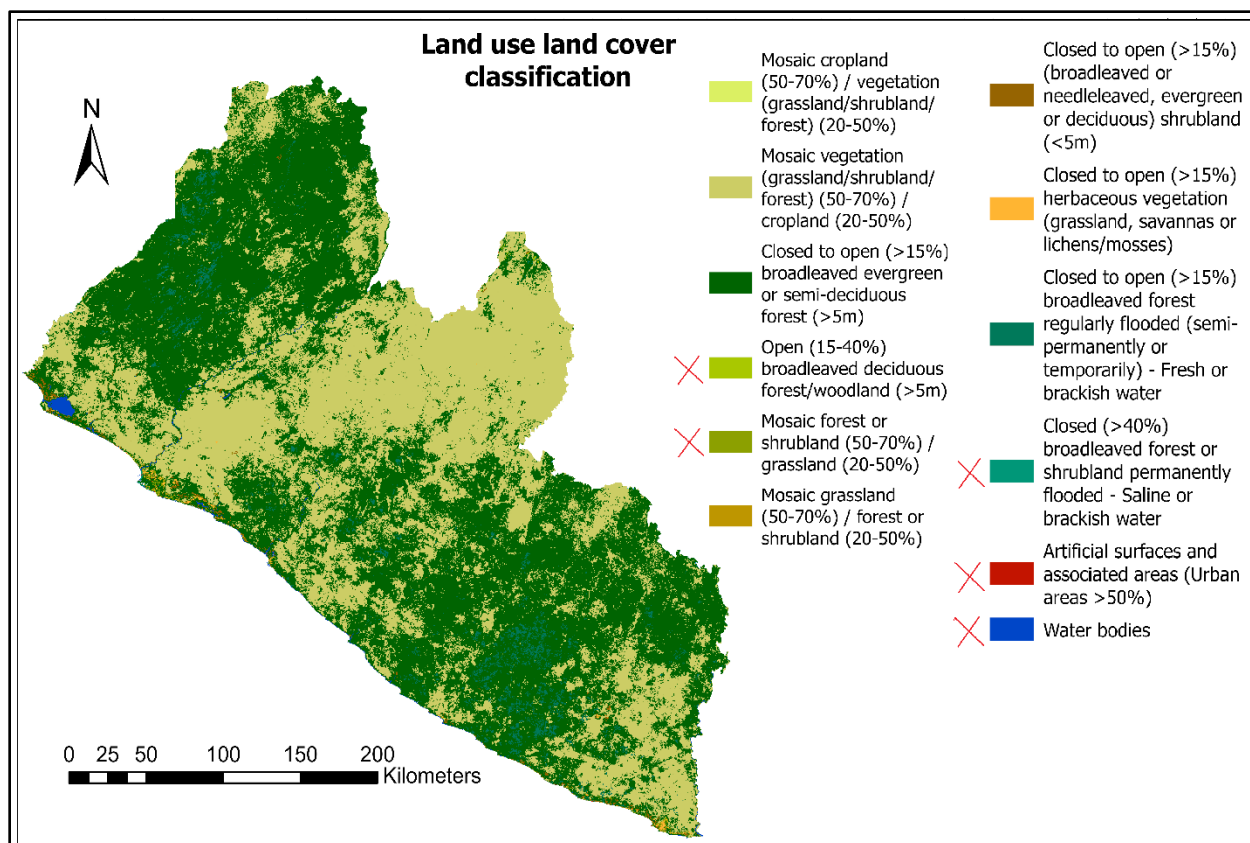
Topographic data such as elevation and slope were accessed through the Shuttle Radar Topography Mission (SRTM) which is among the most commonly utilized Digital Elevation Model (DEM) data sources [33]. In this study, the 30 m spatial DEM data from STRM was utilized and is available from the United States Geological Survey (USGS) through the link <http://earthexplorer.usgs.gov>. Figure 5 shows the spatial variability of elevation and slope in Liberia.



**Fig. 5** Topographical characterization of Liberia: (a) slope (%) and (b) elevation (m)

#### 2.2.4. Land use land cover data

The land use land cover (LULC) data was used at the end of the suitability analysis for masking out areas covered by permanent water bodies, settlements and dense forests, as shown in Figure 6. LULC data was extracted from the GlobCover 2009, which is a global land cover map based on ENVISAT's Medium Resolution Imaging Spectrometer (MERIS) Level 1B data acquired in full resolution mode with a spatial resolution of approximately 300 meters [34]. Table 1 summarizes all data types and their respective sources.



**Fig. 6** Land use land cover map for Liberia. Data extracted from [34]. Land cover classes marked by red “X” were masked out from the final suitability map

**Table 1** Data types and their sources

Data	Format	Data source	Web link
Temperature and Precipitation	Raster	ERA5	<a href="https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels">https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels</a>
Elevation and slope	Raster	SRTM	<a href="http://earthexplorer.usgs.gov">http://earthexplorer.usgs.gov</a>
Soil texture	Shapefile	FAO	<a href="https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/faounesco-soil-map-of-the-world/en/">https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/faounesco-soil-map-of-the-world/en/</a>
Chemical properties	Shapefile	LIBSIS	<a href="https://libsislr.com">https://libsislr.com</a>
Land use land cover	Raster	ESA	<a href="http://due.esrin.esa.int/page_globcover.php">http://due.esrin.esa.int/page_globcover.php</a>

### 2.3. Data processing and analysis

GIS technology was employed to gather, analyze and visualize spatial data. Various suitability map layers were created [12], based on the criteria presented in Table 2. The preparation of the map layers involved interpolation of gridded data to get the same spatial resolution, which was fixed at 0.01x0.01o (~1 km) using Ordinary Kriging, a native ArcGIS interpolation method, which performs relatively well for sparse data [35].

### 2.3.1. Multi-Criteria Decision-Making

The study employed Multi-Criteria Decision-Making (MCDM) method integrated with Geographical Information System (GIS) technology. Land suitability assessment is done in a way that key consideration is given to local requirements and conditions are adequately represented in the ultimate decisions [36]. As such, this research adopted FAO’s method of land classification as described by [14] to evaluate areas that are suitable for rice cultivation. Partial suitability map layers were produced based on the thresholds of suitability levels for each factor presented in Table 2.

**Table 2** Criteria for suitability rating for rice development

<b>Factors</b>	<b>Very Suitable</b>	<b>Suitable</b>	<b>Semi Suitable</b>	<b>Not Suitable</b>	<b>Sources</b>
Rainfall within growing season (mm)	1000 – 2000	2000 – 3500	>3500	< 1000	[19,35]
Temperature within growing season (°C)	22 - 27	27 - 32	32 - 37	< 22 and > 37	[36]
Slope (%)	0 -2	2 - 5	5 - 8	> 8	[36]
Elevation (m)	0 - 400	400 - 800	800 - 1400	> 1400	[36]
Soil Texture	C, SC, SCL	S, CL	SL, L	Sandy	[19,36,37]
Nitrogen (%)	> 0.3	0.2 – 0.3	0.1 – 0.2	< 0.1	[37]
Phosphorus (mg kg <sup>-1</sup> )	10 - 12	7 – 10 and 12 - 15	5 – 7 and 15 - 18	<5 and >18	[36]
Soil Organic Carbon (%)	> 3	2 - 3	1 - 2	< 1	[36]
Potassium (mg kg <sup>-1</sup> )	200 - 250	150 – 200 250 - 300	100 - 150	<100 and >300	[36]

---

				<4.5 and	
pH	5.5 – 6.5	4.5 – 5.4	7.6 – 8.5	>8.5	[38]

---

### 2.3.2. Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) is a widely recognized and reliable technique for multi-criteria decision-making, used in both, its original and optimal forms [37,40]. A key step in many decision-making processes is accurately assessing relevant data, often involving the evaluation of the relative importance, or weights for each criterion of a decision problem [14]. In assessing the suitability of crops, especially rice, not all factors are equally significant; as such, it is important to evaluate their relative importance. As previously referred in subsection 2.2, ten factors including rainfall, temperature, elevation, slope, soil texture, soil organic carbon, soil pH, nitrogen, phosphorus, and potassium were considered for the AHP application. The AHP method developed by Wind and Saaty [41] employs a Pairwise Comparison Matrix (PCM) to assess two factors at a time [41]. According to the Wind and Saaty's scale, the available values for the pairwise comparisons are members of the set: {1, 2, 3, 4, 5, 6, 7, 8, 9, 1/2, 1/3, 1/4, 1/5, 1/6, 1/7, 1/8, 1/9} (Table 3). In this study the relative importance assigned to each factor for the pairwise comparison matrix was judged by all four authors and through literature consultations. For example, a rating of 5 depicts that in relation to the column factor, the row factor is strongly important. Conversely, a rating of 1/5 indicates that relative to the column factor, the row factor is less important. Equal importance between column and row factors is rated as 1, as described in Table 3. AHP determines the weights ( $w_i$ ) of factors using the Eigenvector related to the highest Eigenvalue and further normalize the sum of the modules to one (Equation 1).

$$\sum_{i=1}^n w_i = 1. \quad (1)$$

The fundamental input is the two-way comparison matrix,  $A$ , of  $n$  criteria, created based on the scaling ratios from [39], is specified in Equation 2.

$$A = [a_{ij}], \quad i, j = 1, 2, 3, \dots, n, \quad (2)$$

where matrix  $A$  has the elements  $a_{ij}$  and generally has the property of reciprocity, expressed mathematically as:

$$a_{ij} = \frac{1}{a_{ji}}. \quad (3)$$

After generating this matrix, it is further normalized as matrix B:

$$B = [B_{ij}], \quad i, j = 1, 2, 3 \dots, n, \quad (4)$$

where B is the normalized matrix of A, with the elements  $b_{ij}$  denoted as:

$$b_{ij} = \frac{a_{ij}}{\sum_{i=1}^n a_{ij}}, \quad i, j = 1, 2, 3 \dots, n. \quad (5)$$

Finally, each weight value  $w_i$  is calculated as:

$$w_i = \frac{\sum_{j=1}^n b_{ij}}{\sum_{i=1}^n \sum_{j=1}^n b_{ij}}, \quad i, j = 1, 2, 3 \dots, n. \quad (6)$$

**Table 3.** Degree of importance of the AHP scale for pairwise comparison. Source: [39]

Value of importance	Description
1	Equal importance
3	Moderate importance of one over another
5	Strong or essential importance
7	Very strong importance
9	Extreme importance
2, 4, 6, 8	Intermediate values between the two adjacent judgments
Reciprocals	Values for inverse comparison

When applying the AHP method, it is vital that the weights obtained from the matrix of pairwise comparisons are consistent [40]. The consistency of the assessments is determined by the Consistency Ratio (CR). CR value should be less than 0.1 for the pairwise comparison matrix to be considered accurate [41,42].

$$CR = \frac{CI}{RI}, \quad (7)$$

$$CI = \frac{\lambda_{max} - n}{n - 1}, \quad (8)$$

where, CI is the Consistency Index,  $\lambda_{max}$  is the maximum Eigen value of the matrix, RI is a random index, representing the average of the resulting consistency index depending on the order of the matrix produced by [39], as shown in Table 4. In this study, CR of 0.07 was obtained, indicating

that the applied AHP model is accurate and consistent, thus, appropriate relative weights of factors were determined.

**Table 4.** Random Index (RI). Source: [39]

Matrix	order	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.58	

The two-way comparison matrix (A) and the normalized matrix (B) are shown in Table 5 and Table 6, respectively. Weights determined by Equation 6 are also presented in Table 6.

**Table 5.** Pairwise comparison matrix (A) of selected factors: Slope (SLP), elevation (ELV), soil texture (STEX), soil organic carbon (SOC), soil acidity or alkalinity (pH), temperature (TEM), rainfall (RF), nitrogen (N), phosphorus (P) and potassium (K)

Criteria	Pairwise comparison matrix (A)									
	SLP	ELV	TEM	RF	pH	N	P	K	SOC	STEX
SLP	1	1/2	1/5	1/5	1/3	1/3	1/3	1	1/5	3
ELV	2	1	1/5	1/5	1/4	1/3	1/3	1/2	1/3	3
TEM	5	4	1	1/5	2	2	2	2	3	4
RF	5	5	2	1	2	2	2	2	3	5
pH	4	3	1/2	1/2	1	1/3	1/3	1/3	1/2	2
N	3	3	1/2	1/2	3	1	1	1	1/3	2
P	3	3	1/2	1/2	3	1	1	1	1/3	2
K	3	3	1/2	1/2	3	1	1	1	1/3	2
SOC	5	5	1/4	1/3	2	3	3	3	1	3
STEX	1/3	1/3	1/4	1/5	1/4	1/3	1/3	1/3	1/3	1

**Table 6.** Normalized pairwise comparison matrix (B) and calculated weights ( $w_i$ ) for the selected factors: Slope (SLP), elevation (ELV), soil texture (STEX), soil organic carbon (SOC), soil acidity or alkalinity (pH), temperature (TEM), rainfall (RF), nitrogen (N), phosphorus (P) and potassium (K)

Criteria	Normalized pairwise comparison matrix (B) and weights ( $w_i$ )											Rank
	SLP	ELV	TEM	RF	pH	N	P	K	SOC	STEX	Weight	
SLP	0.032	0.018	0.034	0.048	0.020	0.029	0.029	0.082	0.021	0.111	0.043	7
ELV	0.064	0.036	0.034	0.048	0.015	0.029	0.029	0.041	0.036	0.111	0.044	6
TEM	0.160	0.144	0.169	0.048	0.119	0.176	0.176	0.164	0.320	0.148	0.163	2
RF	0.160	0.180	0.339	0.242	0.119	0.176	0.176	0.164	0.320	0.185	0.206	1
pH	0.128	0.108	0.085	0.121	0.059	0.029	0.029	0.027	0.053	0.074	0.070	5
N	0.096	0.108	0.085	0.121	0.178	0.088	0.088	0.082	0.036	0.074	0.096	4
P	0.096	0.108	0.085	0.121	0.178	0.088	0.088	0.082	0.036	0.074	0.096	4
K	0.096	0.108	0.085	0.121	0.178	0.088	0.088	0.082	0.036	0.074	0.096	4
SOC	0.160	0.180	0.042	0.081	0.119	0.265	0.265	0.247	0.107	0.111	0.157	3
STEX	0.011	0.012	0.042	0.048	0.015	0.029	0.029	0.027	0.036	0.037	0.029	8
CR=0.07	Maximum Eigen Value = 10.99									$\Sigma = 1$		

### 2.3.3. Preparation of final land suitability map

The final land suitability map of the study area was produced by applying a weighted linear combination of the ten partial suitability maps obtained for each factor using the criteria from Table 2. The weighted linear combination is denoted by Equation 9. The ArcGIS-based raster calculator was used for this process.

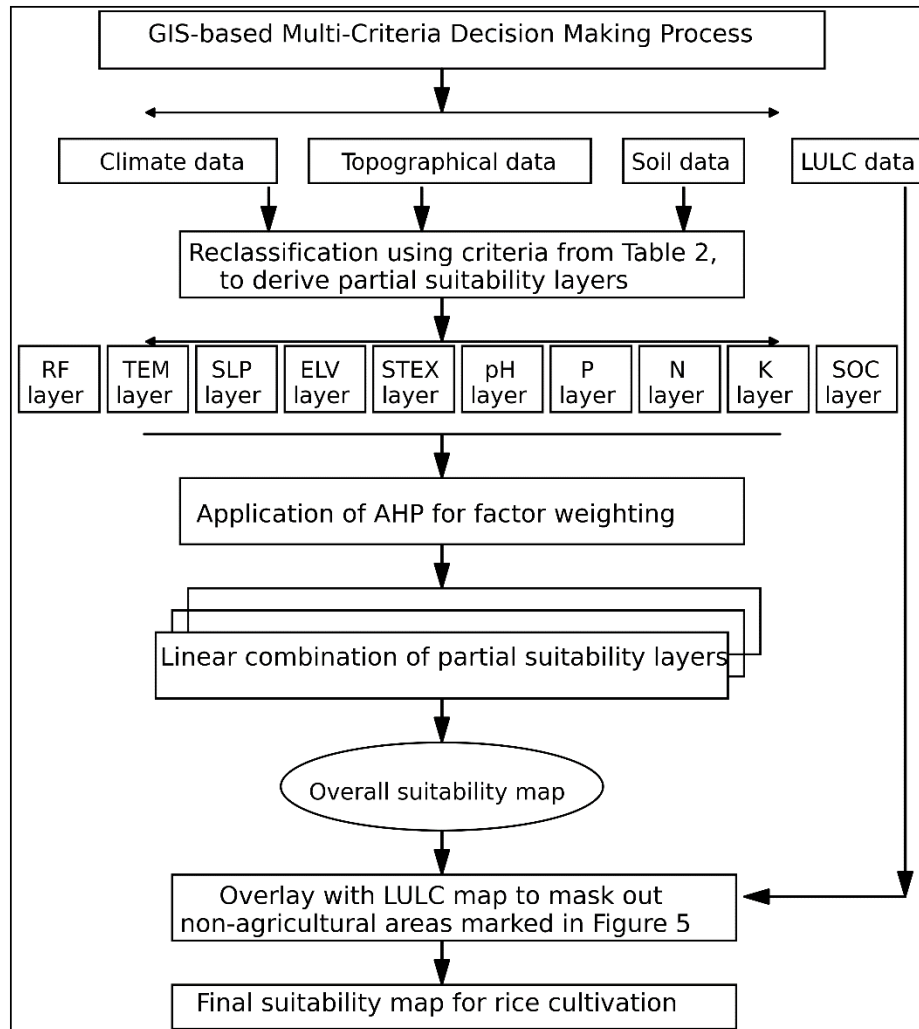
$$S = \sum_{i=1}^n (R_i * w_i) , \quad (9)$$

where,  $S$  is final land suitability map;  $R_i$  is the partial suitability regarding the  $i$ -th factor;  $w_i$  is the weight assigned to the  $i$ -th factor, derived from the AHP; and  $n$  is the total number of factors.

Applying the weights from Table 6, the Equation 9 can be expanded to the equation 10:

$$S = (RF * 0.206) + (TEM * 0.163) + (SOC * 0.157) + (STEX * 0.029) + (ELV * 0.044) + (pH * 0.070) + (SLP * 0.043) + (N * 0.096) + (P * 0.096) + (K * 0.096) \quad (10)$$

Figure 6 outlines all the process to come up with the final land suitability map.



**Fig. 7** Workflow outlining the methodology applied for land suitability

### 3. Results

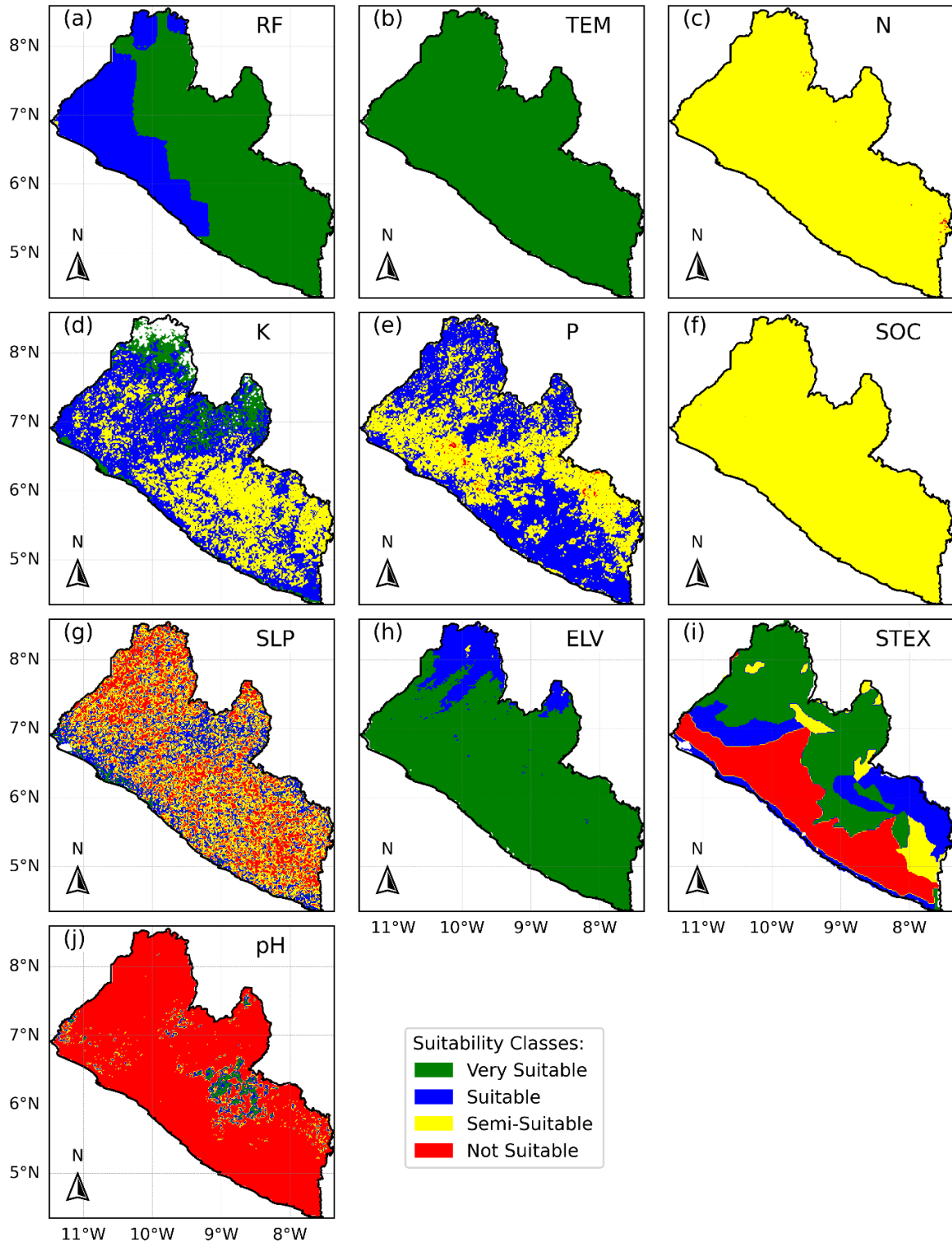
This study applied the GIS-based MCDM and AHP for agricultural land suitability analysis to identify areas that are suitable for rice cultivation in Liberia. Ten factors were considered for this purpose. A weighted linear combination was used to overlay partial suitability layers and determine the overall suitability map of the country.

#### 3.1. Partial suitability

Figure 8 presents the reclassified maps with different suitability levels for each factor. Precipitation, which is the highly weighed factor, showed two suitability levels, which are very suitable (nearly 75% of Liberia) and suitable (approximately 25%) as observed from Figure 8a. This implies that the entire country is favorable for rice cultivation with respect to precipitation,

or it would be if we assume that all other factors are also optimal. However, among the ten factors, only two others were found to be optimal in Liberia, which are, the air temperature that showed a single class of very suitable for rice cultivation (Figure 8b) and the elevation which is very suitable to suitable (Figure 8h).

Great suitability variation is observed from the remaining factors. For instance, as observed in Figure 4a-f, soil properties such as soil texture, pH, soil organic carbon, nitrogen, phosphorus, and potassium present greater spatial variations. Soil texture ranges from clay loam to silt, while the remaining factors present the following ranges: pH (4.0–5.6), soil organic carbon (1.16–1.21%), nitrogen (0.091– 0.17%), phosphorus (4.15–11 mg/kg), and potassium (0.01–0.04 cmol(+)/kg). In particular, soil organic carbon and nitrogen, which are important inputs for crop development, are critical, falling in the semi-suitable class for the whole country (Figure 8c,f), indicating potential implication on rice cultivation. Slope, soil texture and pH presented significant areas that are unsuitable for rice cultivation (Figure 8g,i,j), implying that rice productivity in Liberia is mostly constrained by these three factors, with pH being the most limiting factor as attested by Figure 8j.



**Fig. 8** Partial land suitability maps derived from each factor: (a) precipitation, (b) temperature, (c) nitrogen, (d) potassium, (e) phosphorus, (f) soil organic carbon, (g) slope, (h) elevation, (i) soil texture, and (j) pH.

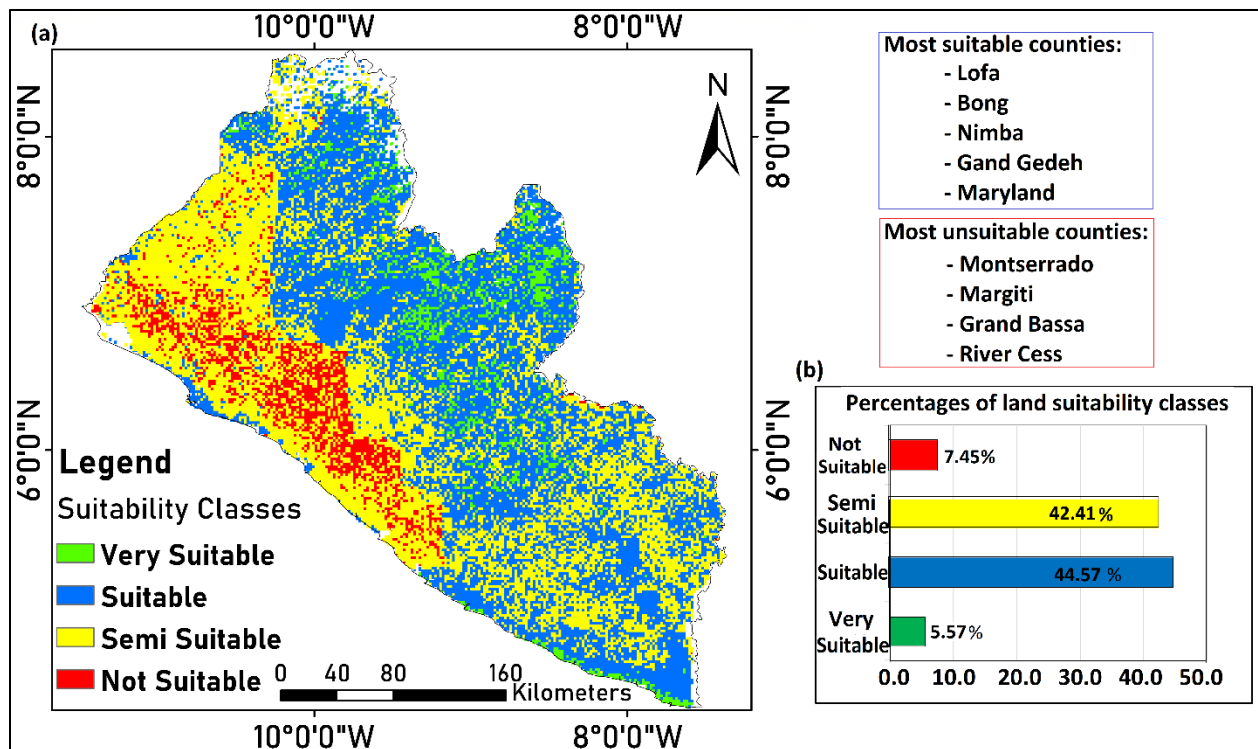
### 3.2. Final suitability map

The overall suitability analysis identified four suitability classes in Liberia: very suitable, suitable, semi-suitable, and not suitable, as presented in Figure 9a. Their corresponding percentages within the country's area are presented in Figure 9b. Considering the different categories of suitability in the country, 5.57% of the land is very suitable, and can be found mostly in the northeastern regions, with more emphasis to Bong and Nimba, where the combination of the ten considered factors provides optimal conditions for rice production, suggesting that these areas could be fundamental for intensive rice cultivation.

About 44.57% of land was classified as suitable, covering the northeastern and coastal southeastern regions, with more emphasis to Lofa, Bong, Nimba, and parts of Grand Gedeh, Sinoe and Maryland. These areas generally meet the minimum conditions for rice cultivation, presenting no relevant limitations that can significantly affect rice cultivation. With the adoption of improved management practices and improved rice varieties, these lands can provide high yields.

Semi-suitable areas correspond to approximately 42.41% of the country, mostly found in the western part (parts of Grand Cape Mount and Gbarpolu) and partially in the eastern (parts of Grand Gedeh, Sinoe, River Gee and Grand Kru). These regions are affected by improper/poor conditions such as higher slopes, more acidic soils, and predominantly sandy soils. Although these factors minimize the natural productivity of the land, targeted interventions (e.g., soil fertility management, adequate land preparation, irrigation, and improved rice varieties) could reduce these limitations, and make these areas feasible for production.

Lastly, 7.45% of the country is considered not suitable for rice production, mostly in the southwestern areas (Riversess, Grand Bassa, Montserrado, Margiti, Bomi and parts of Grand Cape Mount). These areas consist of ecologically unfit ecosystems for supporting rice growth, influenced by acid soils, higher slopes, sandy soils, and combination of other poor soil properties such as soil organic carbon, nitrogen, phosphorus, and potassium. Expansion of rice cultivation in these areas may not only be unproductive and unsustainable but may also increase environmental degradation, contributing to biodiversity loss.

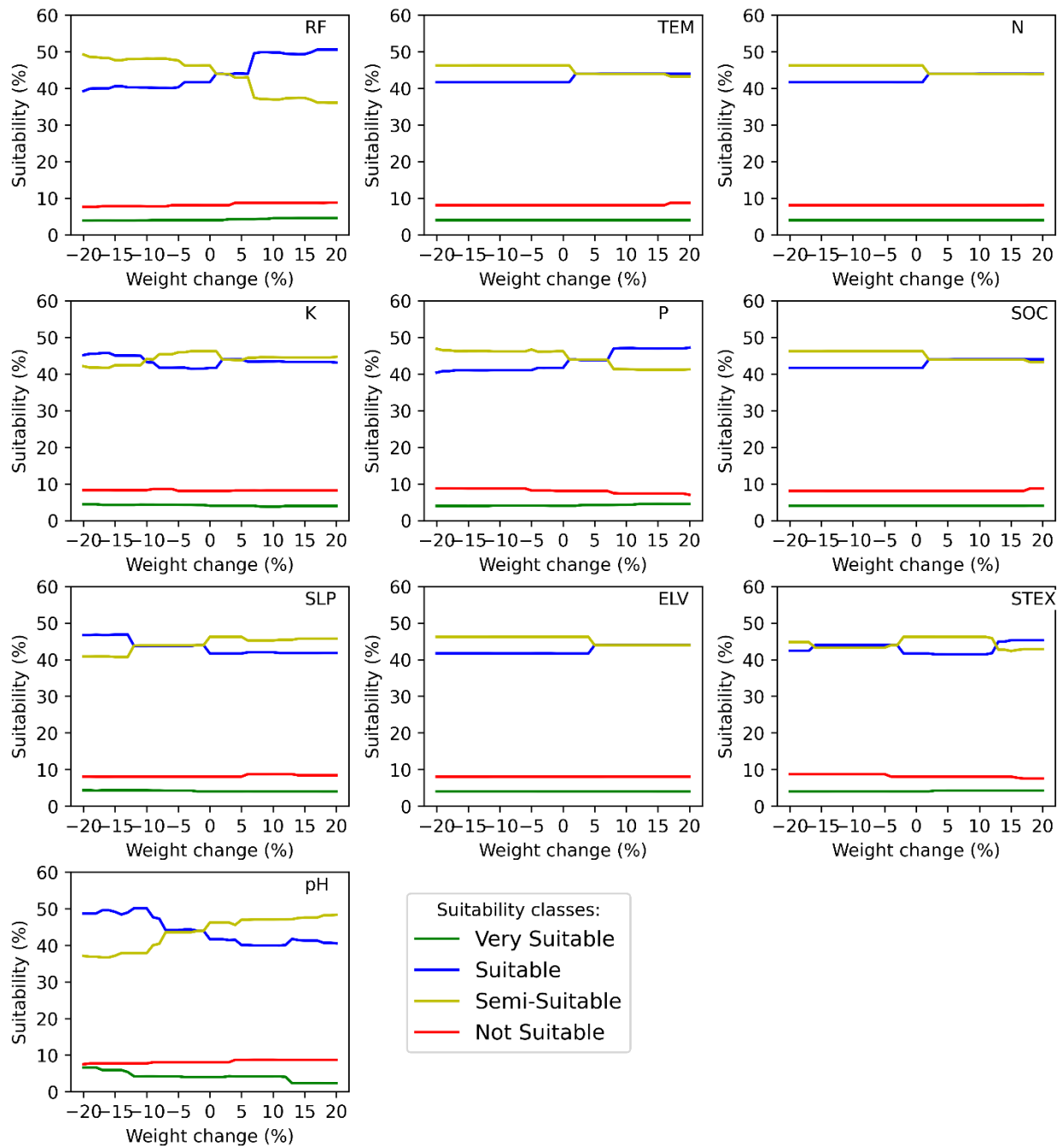


**Fig. 9** (a) Final rice cultivation suitability map for Liberia, and (b) percentages of suitability classes

### 3.3 Sensitivity analysis

Sensitivity analysis was conducted in this study to investigate the influence of shifting the weights of factors to the overall suitability result [16,31]. Sensitivity analysis is typically conducted using three ways: changing the relative importance of factors, changing the value of the parameters, and changing the weights of the factors. In this study, the sensitivity analysis has been carried out based on changing weights of the factors following the “what-if” approach [31]. It offers the possibility of identifying the key factor that influences the initial decision the most. In this study, factors were assigned weights obtained through the AHP pairwise comparison. Each weight was perturbed +/- 20%, with a moving step of 1%, resulting in 40 simulations per factor, and a total of 400 simulations for the ten factors. For each weight perturbation the others were readjusted so that the sum of all weights is maintained equal to 1. Figure 10 presents the sensitivity results, which indicate a relative stability of the model, with slight classes’ changes. Notable sensitivity is observed for precipitation and pH, where shifting of the semi-suitable and suitable classes appear more pronounced. For precipitation, suitability shifts from semi-suitable to suitable when the weight change becomes above 5%, while for pH, it shifts from suitable to semi-suitable

when the weight change becomes above -10%. More stable factors are: temperature, nitrogen, soil organic carbon, and elevation.



**Fig 10.** Sensitivity analysis of the 10 factors used in the study. 40 simulations were computed per factor, with weight perturbation from -20% to +20%, and a moving step of 1%.

## 4. Discussion

### 4.1. Land suitability

Climate variables (temperature and precipitation) are the two most contributing factors for accessing rice land suitability compared to the others due to their important role played in rice growth and development. Liberia is a tropical humid region, with abundant precipitation, what implies that it is not a limiting factor for rice cultivation in Liberia due to its adequate availability. Air temperature also falls in the optimal range. During the rice growing season in Liberia (April to September), long-term seasonal temperature ranges from 23 to approximately 26°C, and precipitation from approximately 1000 mm to 3500 mm (Figure 3a, b). These seasonal averages are favorable for rice cultivation according to [19,35].

High annual rainfall and consistently warm temperatures support rainfed rice cultivation and reduce dependence on irrigation during the main growing season [43], suggesting that Liberia's agriculture is generally climate-resilient. However, potential future risks associated with climate change or climate extremes (anomalies within its variability) should be considered. Irregular rainfall patterns, prolonged dry spells, and extreme precipitation events may disrupt cropping calendars and adversely affect yields [44,45], while heat waves associated with rising temperatures could increase evapotranspiration and heat stress, especially in upland systems [46]. Therefore, the country should still consider the importance of adaptive management strategies, including improved water management, climate-resilient rice varieties, and enhanced agronomic practices, to sustain rice productivity under changing climatic conditions [47].

The other factors presented different levels of suitability within the country, as observed from Figure 8c-j. These factors interfered in the overall environmental conditions for suitability, and their variation across regions led to different land suitability levels for rice growth, where soil texture (sandy soils), pH (acid soils), and slope (ranging from 0 to 57%) appear to be the critical factors affecting suitability. In particular, sandy soils and higher slopes struggle to retain water, an important factor for rice growth [48]. Rice is mostly productive between 0-6% slopes and become unsuitable for above 8% slopes [49]. On the other hand, although elevation was found to be optimal factor for land suitability, [50] indicated that for every 100 meters increase in mountain altitude, the time frame for vegetation and flowering in plants is delayed by 4-6 days. Moreover, rice crop mostly flourishes under the elevation up to approximately 500 meters, mainly in lowlands [50]. These regions usually possess suitable temperature and water supply [48].

Results from the final suitability map indicate that Liberia has good potential for rice production. Putting together the two suitability classes classified as very suitable and suitable, totalizes about 50.14% of areas with optimal conditions for expanding rice production with minimal efforts, highlighting the country's capacity to increase domestic rice production and reduce importations, which currently correspond to over 60% of national rice consumption [11,28].

While there is a lack of empirical peer-reviewed studies for land suitability for rice cultivation in Liberia, our findings are in line with those reported by CARD (2021) project [24], which conducted a study on the local rice competitiveness in 15 selected counties of Liberia, funded by Japan International Cooperation Agency. The study revealed that rice production in Liberia, is mostly produced in counties such as Lofa, Bong, Nimba, Gbarpolu, Grand Bassa, and Grand Gedeh [24], some of which were also identified as suitable for rice cultivation by our study. Additionally, the Nimba land assessment project (2021–2023) implemented by LIBSIS under the support of FAO and MOA, included in their activities, the production of a rice land suitability map for the county to serve as a pilot for the country. Findings revealed that approximately 30-40% of Nimba County is deemed moderately to highly suitable for rice production. These agreements with the existing knowledge provide more confidence and a comprehensive assessment of the spatial distribution of the country's potential for rice production.

Similar studies carried out in other Sub-Saharan African and neighboring countries, with comparable climate conditions, and characterized by more fertile soils, have shown to support relatively higher rice productivity [20,35,41], highlighting the effects of the Liberian poor soil conditions identified in this study. Recent studies have shown that Liberia's average national rice yield has remained low in recent decades, at around 1.2 metric tons per hectare, which is considerably lower than in other west African countries, 3.0 t/ha in Côte d'Ivoire, 2.7 t/ha in Ghana, 3.4 t/ha in Mali and 4 t/ha in Benin [10,11]. Several underlying factors account for this stagnation in yield. These include traditional farming systems, the use of low-yield varieties, limited use of modern inputs such as improved seed, fertilizers, mechanization, and limited access to farm credit [10,11,51]. Reports from World Bank [52] and the World Food Programme (WFP) [53] indicate that yield improvements in Liberia and other West African countries have been constrained by limited access to improved rice varieties, irrigation technologies, fertilizers, and extension services. Farmers often rely on traditional practices and local seed varieties, which are less responsive to modern yield-enhancing technologies, thus limiting productivity per hectare [5].

Using GIS-based MCDM and AHP approach for assessing potential land for rice cultivation, [15] conducted a study in Oye-Ekiti, Nigeria, and found a relatively high potential for rice cultivation, classifying suitability into three categories: Highly suitable (18%), moderately suitable (70%), and marginally suitable (12%); having pointed inadequate water supply and low nutrients capacity as a constraint in some areas such as Eruwa, Oyo, and Shaki, where irrigation is needed to supplement rainfall for better yields. [54] used slightly different classification names in their land suitability assessment in Cote d'Ivoire (Poro region) and found 59.13% optimal, 12.38% suitable, 19.23% moderately favorable, and about 10% unsuitable; indicating constraints such as the combination of unfavorable ecological conditions, poor soil quality, competing land uses, and constraints in human and animal resources for rice cultivation. Additionally, in Denguele (North West of Côte d'Ivoire), [55] classified 74.04% of the total area of the region as very good and good. In Amhara region, Ethiopia, [14] found 23.15% highly suitable, 49.28% moderately suitable, 24.44% marginally suitable, and 3.13% not suitable, having pointed the same suitability constraints as in our study, such as, soil pH and slope, including rainfall deficit at some locations. A study carried out in Mwea region, Kenya [17] presented two suitability categories of moderately suitable (23.08%) and highly suitable (77.92%) for rice cultivation.

The above studies highlight the great potential of African countries for rice cultivation. However, despite this high potential rice is still not substantially produced in many African countries, including Liberia. For instance, [17] reported that by their study period, only 12% of suitable land was under rice cultivation. This is also the case of Liberia, where only a small portion (less than 10%) is currently under cultivation [51,56], despite the existence of a significant area of the country with optimal conditions for rice production, as indicated by this study.

Beyond the total suitable area in Liberia (50.14%), our study also found a considerable proportion of semi-suitable land, corresponding to nearly 42.41%, revealing the existence of potential areas for productivity enhancement through targeted management interventions, or that can be harnessed using agricultural technologies. While these areas face certain agronomic constraints, such as soil texture, pH and slope, they are not fundamentally unproductive. With appropriate policies and investments such as land leveling, optimized fertilizer application, improved irrigation systems, and adoption of adaptive rice varieties, this land could add important contribution to national food production, thus, supporting national agriculture development plans

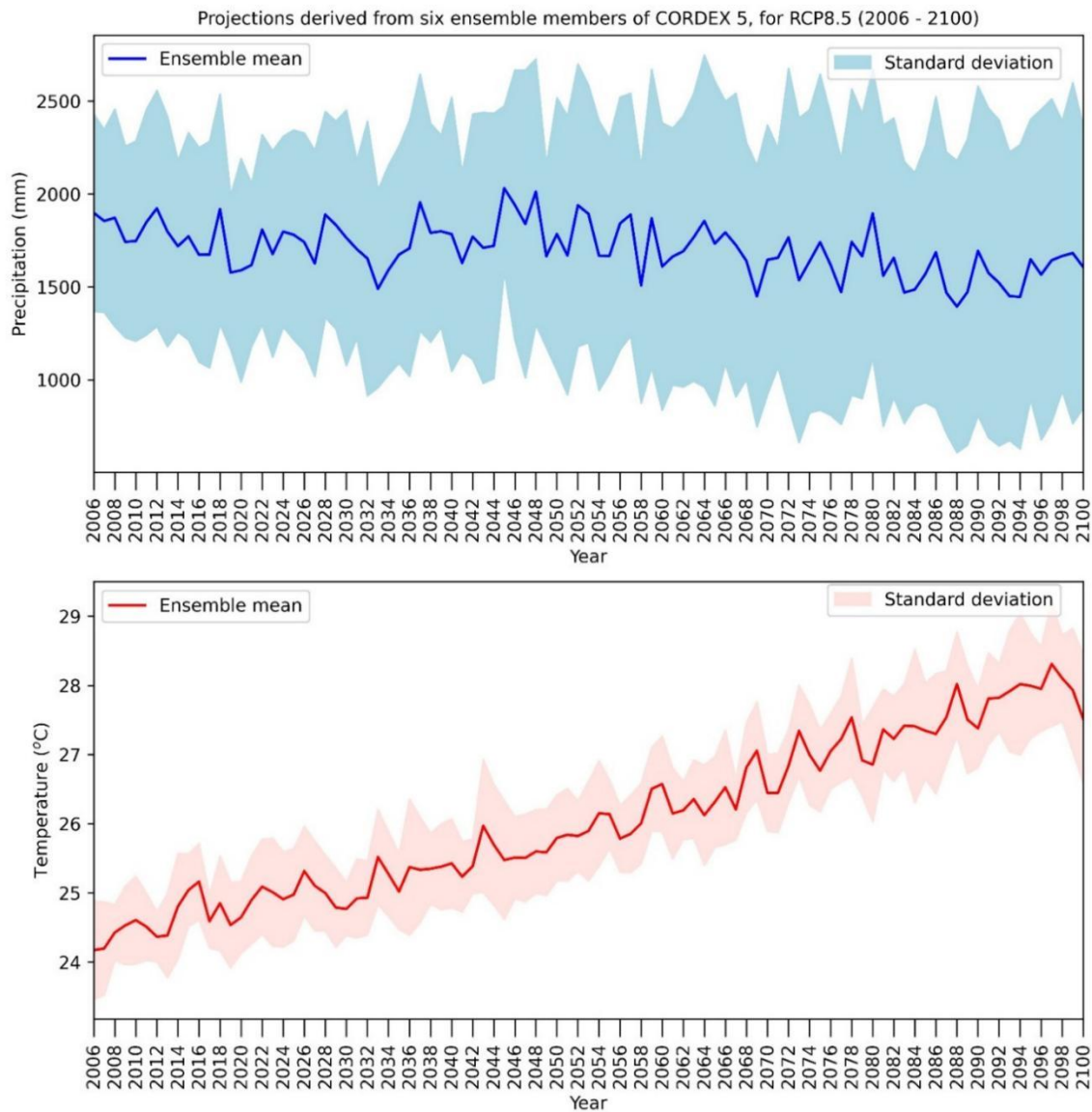
(NADP), including the objectives of the NADP 2024-2030 “Feed Yourselves” Agenda, aimed at enhancing food security.

Furthermore, these interventions could contribute to fostering domestic production, leading to socio-economic stability, given that, despite the existence of favorable conditions in Liberia, only small fraction of this arable land is currently under cultivation, estimated in less than 30% [51]. Major constraints pointed in literature for the limited agricultural production include factors such as post-war-conflict, inadequate infrastructure, limited access to inputs, land tenure insecurity, limited extension services, vulnerability to extreme climate events, lack of mechanization, inadequate credit facilities, poor market access and weak value chains, as well as deforestation and environmental degradation [7,51]

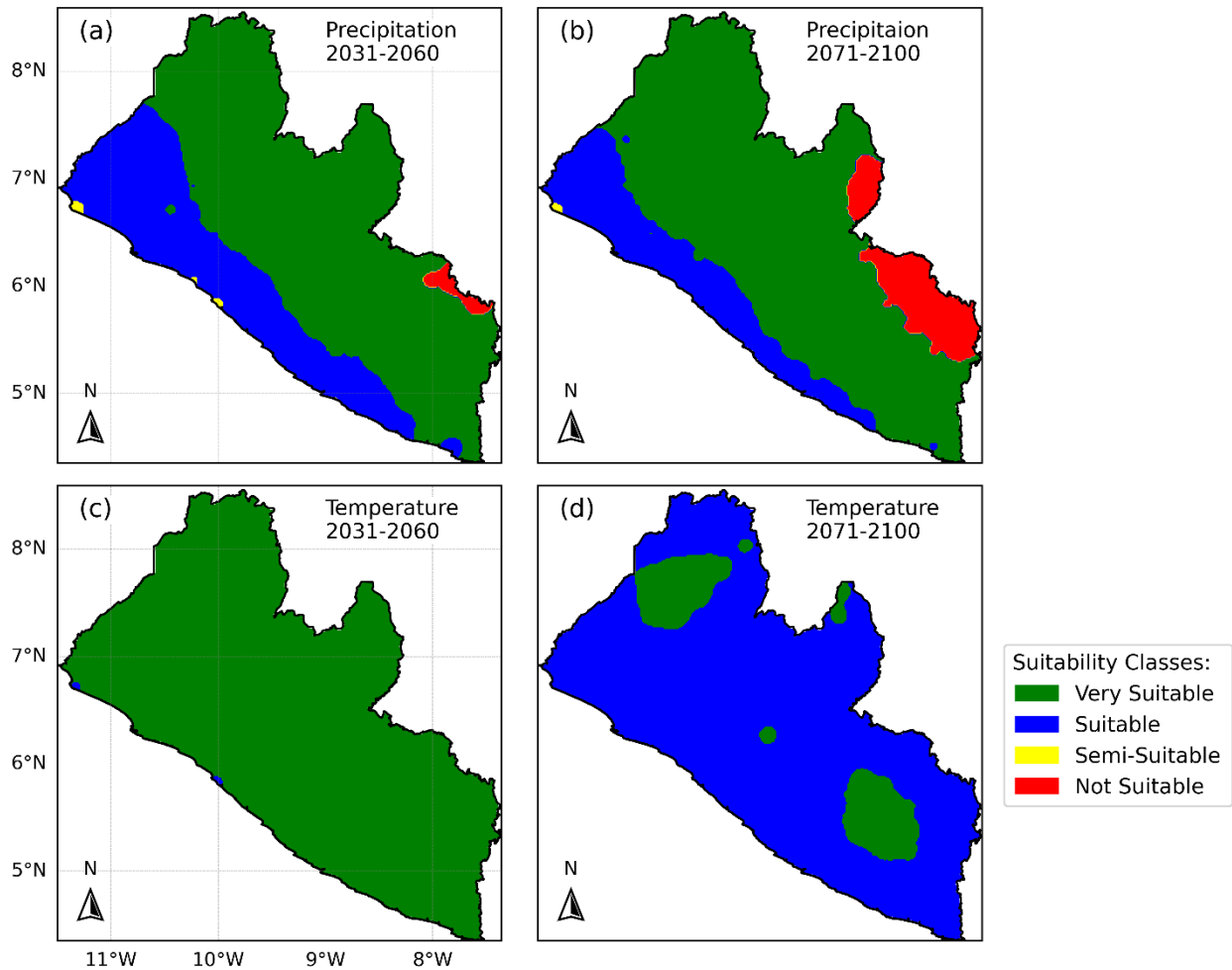
#### 4.2. Climate change implications to land suitability

Agriculture is a climate-sensitive sector. Changes in climate variables, such as rainfall and temperature, have significant implications on crop production and yield [57–60]. This study found that the current precipitation and temperature patterns are generally favorable for rice cultivation in Liberia, categorizing the country as suitable to very suitable for precipitation and very suitable for temperature, implying that land suitability for rice cultivation in Liberia is not constrained by the current climate state. However, at the worst climate change scenario, simulations from the regional climate model CORDEX 5 in Liberia indicated that temperatures are expected to rise significantly by the end of the 21<sup>st</sup> century, while precipitation change is not statistically significant, although a slightly decrease is expected (Figure 11). These findings suggest that the land suitability map obtained in this study is not static. It is more likely to change in future as attested by Figure 12, compromising rice production in some regions of Liberia, especially in the northeast part, where unsuitability is indicated by precipitation. Although the average of future temperature is still indicated as suitable (Figure 12c,d), it is important to consider the extremes within the future warmer climate variability, which may have negative impacts on rice crop production. Past studies [61–63] have revealed that temperature increases during the reproductive stage of rice, especially during panicle initiation, flowering, and fertilization, may severely reduce yield and grain quality. [62] found that an increase of 1°C of temperature above the optimum threshold reduced the yield by 8%. Other several studies conducted over the Sub-Saharan Africa reported that climate variability and change have resulted in a reduction in crop yields, altered planting seasons, and increased vulnerability of smallholder farmers to food insecurity [64–66].

Higher minimum temperatures may impair crop performance possibly due to increased respiration rates, which can lead to energy loss, disruption of physiological recovery process and stress on sensitive growth stages such as flowering and grain filling [1,67]. Similarly, [68] and [69] acknowledged that increased temperature affects the growth and development of rice plants, particularly during germination, flowering and grain filling stages. Overall, the results suggest that temperature disparities particularly minimum temperature, plays more critical role in rice production than precipitation [70,71]. This highlights the crop’s sensitivity to temperature during flowering and grain-filling stages [72].



**Fig. 11.** CORDEX 5 projections of precipitation (upper panel) and air temperature (lower panel) averaged over Liberia, using six ensemble members, for the RCP8.5 scenario, from 2006 to 2100



**Fig. 12.** Future land suitability in relation to future CORDEX 5 projections of precipitation (a,b) and temperatures (c,d) averaged over Liberia from six ensemble members, at the worst scenario RCP8.5, by 2031-2060 and 2071-2100, respectively

## 5. Conclusions and recommendations

This study aimed at developing rice land suitability map, which holds important applications for developing sustainable land use, agricultural planning, and shaping environmental policies aligned with local natural characteristics.

Our findings indicated that about 50.14% of the total producible area of Liberia is favorable for rice production, including potential land of about 42.41% that can be harnessed using agricultural technologies. Most suitable areas are found in the northern, central and southeastern

regions, with emphases to the following counties: Bong, Lofa, Nimba, Grand Gedeh, and parts of Sinoe and Maryland.

Liberia is overall a climate-resilient country. Current climate conditions are optimal for rice cultivation in the entire country. Precipitation exerted the most substantial influence on the overall suitability, followed by air temperature. Suitability was limited by the combination of the other factors. In particular, unsuitable areas were mostly influenced by slope, pH and soil texture.

By integrating spatial data with various criteria, the study offers key insights to the government and stakeholders to make evidence-based decisions on land management for rice production. Rice production in Liberia can be improved through the expansion of land within the indicated favorable areas. Government and stakeholders should prioritize mechanized agriculture and provide extension services in the counties listed above, including infrastructure development, such as storage facilities and roads, connecting regions with high rice production suitability to gross markets, and to those locations with limited conditions, enhancing production value chain. Semi-suitable areas should be improved by encouraging sustainable use of fertilizers and other agricultural inputs, including soil conservation practices to boost rice productivity in the country. This strategy could improve domestic rice production and reduce Liberia's dependence on importation, thus, impacting directly on farmer's socio-economic stability, such as food security and household income.

The research also highlights the potential of GIS in fostering sustainable development initiatives. A comprehensive approach, combining GIS, MCDM and empirical data, may serve as a valuable asset in advancing sustainable agriculture and tackling food security issues.

As limitations of the study, it was not feasible to use field-based validation of suitability results, though, for example, a field surveys or observed yield data, due to large geographic extent of the study area (national scale) and the lack of systematic records of rice production data. Thus, rather than empirical field observations, validation relied on existing literature, general knowledge on the land use/cover, and consistency check from the AHP model. Another limitation is related to the study reliance on global datasets, what may somehow not adequately capture local-scale variability in soils, topography, microclimate, and land cover, which are critical for rice production, potentially affecting suitability classification accuracy.

Despite field data limitations, the study offers an essential first step to countrywide assessment to identify suitable areas for rice cultivation. More importantly, it provides valuable

baselines to Liberia on suitability mapping, serving as a tool for agricultural planning, policy and decision-making, as well as it establishes a foundational framework for future studies, which should incorporate other relevant factors and a field validation (ground surveys and crop yield data) to refine the suitability results.

## 6. References

1. Su, Q.; Rohila, J.S.; Ranganathan, S.; Karthikeyan, R. Rice Yield and Quality in Response to Daytime and Nighttime Temperature Increase – A Meta-Analysis Perspective. *Sci. Total Environ.* **2023**, 898, 165256, doi:10.1016/j.scitotenv.2023.165256.
2. Adjah, K.L.; Asante, M.D.; Toure, A.; Aziadekey, M.; Amoako-Andoh, F.O.; Frei, M.; Diallo, Y.; Agboka, K. Improvement of Rice Production under Drought Conditions in West Africa: Application of QTLs in Breeding for Drought Resistance. *Rice Sci.* **2022**, 29, 512–521, doi:10.1016/j.rsci.2022.06.002.
3. Pope *et al.* Assessment of Upland Rice Production Constraints and Farmers' Preferred Varieties in Liberia. *Int. J. Res. Innov. Soc. Sci.* **2023**, VII, 1175–1189, doi:10.47772/IJRISS.
4. Daszkiewicz, T. Food Production in the Context of Global Developmental Challenges. *Agric.* **2022**, 12, doi:10.3390/agriculture12060832.
5. Saito, K.; Senthilkumar, K.; Ali, I.; Johnson, J.; Rodenburg, J.; Senthilkumar, K.; Ali, I.; Johnson, J. Status Quo and Challenges of Rice Production in Sub-Saharan Africa. *Plant Prod. Sci.* **2023**, 26, 320–333, doi:10.1080/1343943X.2023.2241712.
6. Ibrahim, A.; Saito, K.; Kokou, A.; Johnson, J.M.; Diagne, M.; Fagnombo, D.J.; Felix, F.; Sylvia, B.O.; Martial, H. Seizing Opportunity towards Sustainable Rice Cultivation in Sub-Saharan Africa. *Environ. Sustain. Indic.* **2022**, 15, 100189, doi:10.1016/j.indic.2022.100189.
7. MOA Liberia National Rice Development Agriculture Republic of Liberia; 2018; [https://riceforafrica.net/wp-content/uploads/2021/09/liberia\\_nrds1.pdf](https://riceforafrica.net/wp-content/uploads/2021/09/liberia_nrds1.pdf) (accessed on 12 Jan 2025).
8. MOA Liberia National Rice Development Strategy - LNRDS. **2012**, 52. [https://riceforafrica.net/wp-content/uploads/2023/01/liberia\\_nrds2.pdf](https://riceforafrica.net/wp-content/uploads/2023/01/liberia_nrds2.pdf) (accessed on 12 Jan 2025).

9. Pluato *et al.* Impact of Post-Harvest Losses on the Profitability of Rice Production Amongst Smallholder Farmers in Liberia. *Agric. Res. Technol. Open Access J.* **2024**, 28, doi:10.19080/artoaj.2024.28.556414.
10. Saysay, J.L.; Gabagambi, D.M.; Mlay, G.I.; Mined, I.J. Technical Efficiency in Rice Production Among Smallholder Farmers in Central Liberia: A Stochastic Production Frontier Analysis. *J. Econ. Sustain. Dev.* **2018**, 9, 47–53.
11. Sumo *et al.* Determinants of Smallholder Rice Farmers' Willingness-to-Pay for Private Extension Services in Liberia: The Case of Gibi District. *Sustain.* **2023**, 15, doi:10.3390/su151914300.
12. Hashim, N.; Ali, M.M.; Mahadi, M.R.; Abdullah, A.F.; Wayayok, A.; Mohd Kassim, M.S.; Jamaluddin, A. Smart Farming for Sustainable Rice Production: An Insight into Application, Challenge, and Future Prospect. *Rice Sci.* **2024**, 31, 47–61, doi:10.1016/j.rsci.2023.08.004.
13. World Bank Ending Poverty and Hunger by 2030 An Agenda for the Global Food System. Second Edition with Foreword.; 2015; Vol. May; <https://documents1.worldbank.org/curated/en/700061468334490682/pdf/95768-REVISED-WP-PUBLIC-Box391467B-Ending-Poverty-and-Hunger-by-2030-FINAL.pdf> (accessed on 10 Feb 2025).
14. Ayehu and Besufekad Land Suitability Analysis for Rice Production: A GIS Based Multi-Criteria Decision Approach. *Am. J. Geogr. Inf. Syst.* **2015**, 4, 95–104, doi:10.5923/j.ajgis.20150403.02.
15. Victor and Samson An Application of GIS-Based Multi-Criteria Decision Making Approach for Land Evaluation and Suitability Mapping for Rice Cultivation in Oye-Ekiti, Nigeria. *J. Agric. Environ. Sci.* **2019**, 8, 25–33, doi:10.15640/jaes.v8n1a3.
16. Hossen, B.; Yabar, H.; Mizunoya, T. Land Suitability Assessment for Pulse ( Green Gram ) Production through Remote Sensing , GIS and Multicriteria Analysis in the Coastal Region of Bangladesh. *Sustainability* **2021**, 2–24.
17. Joseph Kihoro, N.J.B. and H.M. Suitability Analysis for Rice Growing Sites Using a Multicriteria Evaluation and GIS Approach in Great Mwea Region, Kenya. *Springerplus* **2013**, 2, 1–9, doi:10.1186/2193-1801-2-265.
18. December, V.I.; Shhu, P.; Rshq, U.; Mrxuqdo, D.; Salifu, E.; Agyare, W.A.; Abdul-ganiyu,

- A.; Dihi, U.X. Evaluation of Land Suitability for Crop Production in Northern Ghana Using GIS and AHP Based Techniques Evaluation of Land Suitability for Crop Production in Northern Ghana Using GIS and AHP Based Techniques. *Int. J. Environment Geoinformatics* **2022**, 45–56, doi:doi. 10.30897/ijgeo.1022275.
19. Islam *et al* Land Suitability and Insurance Premiums: A GIS-Based Multicriteria Analysis Approach for Sustainable Rice Production. *Sustain.* **2018**, 10, doi:10.3390/su10061759.
  20. Adeboboye, A.J.; Agada, A.S.; Joel, P.C.; Dike, C.E.; Augustina, J.; Adeboboye, A.J.; Agada, A.S.; Joel, P.C.; Dike, C.E.; Rice, J.A.; *et al.* Rice Farming Suitability Assessment in Anambra State Using Multi-Criteria Decision-Making Process To Cite This Version : HAL Id : Hal-04575685 Rice Farming Suitability Assessment in Anambra State Using Multi-Criteria. **2024**.
  21. LISGIS Evaluation of the 2022 Liberia Population and Housing Census; 2023; <https://lisgis.gov.lr/document/LiberiaCensus2022EvaluationReport.pdf> (accessed on 21 Feb 2025).
  22. EPA Republic of Liberia Liberia ' s First Adaptation Communication to the United Nations Framework Convention on Climate Change (UNFCCC); 2021; [https://epa.gov.lr/wp-content/uploads/2024/10/Liberias-Updated-NDC\\_RL\\_FINAL-002.pdf](https://epa.gov.lr/wp-content/uploads/2024/10/Liberias-Updated-NDC_RL_FINAL-002.pdf) (accessed 23 Feb 2025).
  23. CBL Central Bank of Liberia Annual Report 2022; 2023; [https://www.cbl.org.lr/sites/default/files/documents/CBL\\_2022\\_ANNUAL\\_REPORT.pdf](https://www.cbl.org.lr/sites/default/files/documents/CBL_2022_ANNUAL_REPORT.pdf) (accessed on 21 Feb 2025).
  24. CARD Data Collection Survey on Rice Related Programs / Projects in the CARD Member Countries ( with Competitiveness Analysis of Local Rice to Imported Rice; 2021;[https://riceforafrica.net/wpcontent/uploads/2023/12/Mozambique\\_competitiveness-analysis\\_20210808.pdf](https://riceforafrica.net/wpcontent/uploads/2023/12/Mozambique_competitiveness-analysis_20210808.pdf) (accessed on 22 December 2024).
  25. EPA National Policy and Response Strategy on Climate Change Final Document-Min\_0; 2018; <https://www.undp.org/liberia/publications/national-policy-and-response-strategy-climate-change> (accessed on 23 Feb 2025).
  26. Climate Risk Profile: Liberia Liberia Climate Risk Country Profile; 2021; [https://climateknowledgeportal.worldbank.org/sites/default/files/202107/15917-WB\\_Liberia%20Country%20Profile-WEB.pdf](https://climateknowledgeportal.worldbank.org/sites/default/files/202107/15917-WB_Liberia%20Country%20Profile-WEB.pdf) (accessed on 30 Mar 2025).

27. EPA Liberia's First Biennial Update Report to UNFCCC; 2020; <https://unfccc.int/sites/default/files/resource/BUR1.pdf> (accessed on 23 Feb 2025).
28. EPA Liberia's Revised Nationally Determined Contribution (NDC). Minerva. Int. Verzeichnis Wissenschaftlicher Institutionen **2021**, 307–307. Republic of Liberia, July 2021. <https://faolex.fao.org/docs/pdf/lbr206208.pdf> (accessed 23 Feb 2025).
29. EPA Liberia Initial National Communication 2013; 2013; <https://unfccc.int/sites/default/files/resource/lbrnc1.pdf> (accessed on 23 Feb 2025).
30. NAP Liberia National Adaptation Plan 2020-2030; 2022; [https://unfccc.int/sites/default/files/resource/LIBERIA\\_%20NAP\\_%20FINAL\\_%20DOCUMENT.pdf](https://unfccc.int/sites/default/files/resource/LIBERIA_%20NAP_%20FINAL_%20DOCUMENT.pdf). (accessed on 20 February 2025).
31. Singh, R.P.; Bisht, H.; Jain, R.; Suna, T.; Bana, R.S.; Godara, S.; Shivay, Y.S.; Singh, N.; Bedi, J.; Begam, S.; *et al.* Crop-Suitability Analysis Using the Analytic Hierarchy Process and Geospatial Techniques for Cereal Production in North India. Sustainability **2022**, 1–21, doi:<https://doi.org/10.3390/su14095246>.
32. Soil Surve Staf Keys to Soil Taxonomy Thirteenth Edition, 2022; 2022; Vol. 12. <https://www.nrcs.usda.gov/sites/default/files/2022-09/Keys-to-Soil-Taxonomy.pdf>. (accessed on 20 February 2026).
33. ESA 2010 and UCLouvain. Global land cover map. [http://due.esrin.esa.int/page\\_globcover.php](http://due.esrin.esa.int/page_globcover.php) (accessed on 05 Aug 2025).
34. Du, R.; Yang, J. Application of Ordinary Kriging Method in Data Processing of Magnetic Survey. ICCSE 2012 - Proc. 2012 7th Int. Conf. Comput. Sci. Educ. **2012**, 771–774, doi:10.1109/ICCSE.2012.6295186.
35. Samanta, S.; Pal, B.; Pal, D.K. Land Suitability Analysis for Rice Cultivation Based on Multi-Criteria Decision Approach through GIS. **2011**.
36. Bazkiaee, P.A.; Kamkar, B.; Amiri, E.; Kazemi, H.; Rezaei, M.; Araji, H.A. Multi-Criteria GIS-Based Land Suitability Analysis for Rice Cultivation: A Case Study in Guilan Province, Iran. Environ. Monit. Assess. **2024**, 196, doi:10.1007/s10661-024-12811-y.
37. Ozsahin *et al.* Determination of Suitable Lands for Rice Cultivation in Edirne Plain: GIS Supported FAO Limitation Method. Paddy Water Environ. **2022**, 20, 325–338, doi:10.1007/s10333-022-00895-6.
38. Robertson, N.; Oinam, B. Rice Suitability Mapping Using the Analytic Hierarchy Process

- Approach in a River Catchment. **2023**, 9, 141–156, doi:10.22034/gjesm.2023.01.11.
39. Wind and Saaty Marketing Applications of the Analytic. Manage. Sci. 1980, 26, 18. <http://dx.doi.org/10.1287/mnsc.26.7.641>.
  40. Pant, S.; Kumar, A.; Ram, M.; Klochkov, Y.; Sharma, H.K. Consistency Indices in Analytic Hierarchy Process: A Review. Mathematics **2022**, 10, 1–15, doi:10.3390/math10081206.
  41. Hagos, Y.G.; Mengie, M.A.; Andualem, T.G.; Yibeltal, M.; Linh, N.T.T.; Tenagashaw, D.Y.; Hewa, G. Land Suitability Assessment for Surface Irrigation Development at Ethiopian Highlands Using Geospatial Technology. Appl. Water Sci. **2022**, 12, 1–11, doi:10.1007/s13201-022-01618-2.
  42. Mohidem, N.A.; Hashim, N.; Shamsudin, R.; Man, H.C. Rice for Food Security: Revisiting Its Production, Diversity, Rice Milling Process and Nutrient Content. Agric. **2022**, 12, doi:10.3390/agriculture12060741.
  43. Maiti, A.; Hasan, M.K.; Sannigrahi, S.; Bar, S.; Chakraborti, S.; Mahto, S.S.; Chatterjee, S.; Pramanik, S.; Pilla, F.; Auerbach, J.; *et al.* Optimal Rainfall Threshold for Monsoon Rice Production in India Varies across Space and Time. Commun. Earth Environ. **2024**, 5, 1–8, doi:10.1038/s43247-024-01414-7.
  44. Habte, A.; Worku, W.; Mamo, G.; Ayalew, D.; Gayler, S. Rainfall Variability and Its Seasonal Events with Associated Risks for Rainfed Crop Production in Southwest Ethiopia. Cogent Food Agric. **2023**, 9, doi:10.1080/23311932.2023.2231693.
  45. Nguyen, P.T.M.; Ho, P.T.; Pham, H.X. Impacts of Seasonal Climate Variation on Rice Yield: Evidence from the Central Coast of Vietnam. Cogent Econ. Financ. **2024**, 12, doi:10.1080/23322039.2024.2421894.
  46. IPCC, **2023**: Summary for Policymakers. In: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 1-34, doi: 10.59327/IPCC/AR6-9789291691647.001. (accessed on 10 June 2024).
  47. Oort, P.A.J. Van; Zwart, S.J. Impacts of Climate Change on Rice Production in Africa and Causes of Simulated Yield Changes. WILEY Glob. Chang. Biol. **2018**, 1029–1045, doi:10.1111/gcb.13967.
  48. Hussain, W.; Sohaib, O.; Ahmed, A.; Khan, M.Q. Geographical Information System Based

- Model of Land Suitability for Good Yield of Rice in Prachuap Khiri Khan Province , Thailand. *Sci,Tech. Dev.* **2012**, 31, 1–9.
49. Oktaviano, O.; Yuwana, Y.; Barchia, F.; Reflis, R. Evaluation of the Suitability of Irrigated Paddy Fields (*Oryza Sativa L.*) in the Kelingi Irrigation Area, Tugumulyo District, Musi Rawas Regency. *J. Tek. Pertan. Lampung (Journal Agric. Eng.* **2025**, 14, 1758–1766.
  50. Bozdağ *et al.* AHP and GIS Based Land Suitability Analysis for Cihanbeyli (Turkey) County. *Environ. Earth Sci.* **2016**, 75, doi:10.1007/s12665-016-5558-9.
  51. Jr, A.D.A.; Diallo, K. Agricultural Dynamics in Liberia : Current Issues and Solutions. *Int. J. Res. Innov. Soc. Sci.* **2025**, IX, 7430–7437, doi:<https://dx.doi.org/10.47772/IJRISS.2025.910000604> Received:
  52. World Bank Liberia Smallholder Agriculture Transformation and Agribusiness Revitalization Project; 2013. <https://documents1.worldbank.org/curated/en/539361545925964964/pdf/project-appraisal-document-pad-smallholder-agriculture-transformation-and-agribusiness-revitalization-project-star-p-p160945-12192018-63681026525344785.pdf>. (accessed on 10 July 2024).
  53. WFP Resilient Food Systems in Western Africa: WFP Contribution to Food Systems Transformation in Western Africa; 2023; WFP Contribution to Food Systems Transformation in Western Africa. [https://docs.wfp.org/api/documents/WFP0000153294/download/?\\_ga=2.19230013.400229510.1701695545-296211395.1697009928](https://docs.wfp.org/api/documents/WFP0000153294/download/?_ga=2.19230013.400229510.1701695545-296211395.1697009928). (accessed on 20 August 2024).
  54. Toure, A.; Assi, K.J.; Silué, P.D.; Assi-kaudjhis, J.P. GIS Approach and Evaluation of Lowland Rice Production Potential in Cote d ’ Ivoire : Case of the Poro Region. *Int. J. Humanit. Soc. Sci. Res.* **2022**, 8, 3–7.
  55. Konan-waidhet, A.B.; Dibi, B.; Kouadio, Z.A. Modeling of Suitable Areas for Rainfed Rice Growing Using Multicriteria Approach in Geographic Information System : Case of Denguele ( North West of Côte d ’ Ivoire ). *Br. J. Appl. Sci. Technol.* **2015**, 6, 95–104, doi:10.9734/BJAST/2015/14486.
  56. Allen Jr. *et al.* Assessing the Impact of Climate Change on Liberia’s Agricultural Sector and Strategic Adaptation Approaches. *Int. J. Res. Innov. Soc. Sci.* **2025**, IX, 9545–9559, doi:<https://dx.doi.org/10.47772/IJRISS.2025.910000781>.

57. Calvin, K.; Dasgupta, D.; Krinner, G.; Mukherji, A.; Thorne, P.W.; Trisos, C.; Romero, J.; Aldunce, P.; Barrett, K.; Blanco, G.; *et al.* IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (Eds.)]. IPCC, Geneva, Switzerland.; Arias, P., Bustamante, M., Elgizouli, I., Flato, G., Howden, M., Méndez-Vallejo, C., Pereira, J.J., Pichs-Madruga, R., Rose, S.K., Saheb, Y., Sánchez Rodríguez, R., Ürge-Vorsatz, D., Xiao, C., Yassaa, N., Romero, J., Kim, J., Haites, E.F., Jung, Y., Stavins, R., Birt, A., Ha, M., Orendain, D.J.A., Ignon, L., Park, S., Park, Y., Reisinger, A., Cammaramo, D., Fischlin, A., Fuglestvedt, J.S., Hansen, G., Ludden, C., Masson-Delmotte, V., Matthews, J.B.R., Mintenbeck, K., Pirani, A., Poloczanska, E., Leprince-Ringuet, N., Péan, C., Eds.; 2023.
58. Mulungu, K.; Kangogo, D. Striving to Be Resilient: The Role of Crop-Poultry Integrated System as a Climate Change Adaptation Strategy in Semiarid Eastern Kenya. *Heliyon* **2022**, *8*, e11579, doi:10.1016/j.heliyon.2022.e11579.
59. Reyes, F.; Gosme, M.; Wolz, K.J.; Lecomte, I.; Dupraz, C. Alley Cropping Mitigates the Impacts of Climate Change on a Wheat Crop in a Mediterranean Environment: A Biophysical Model-Based Assessment. *Agric.* **2021**, *11*, doi:10.3390/agriculture11040356.
60. Yuan, X.; Li, S.; Chen, J.; Yu, H.; Yang, T.; Wang, C.; Huang, S.; Chen, H.; Ao, X. Impacts of Global Climate Change on Agricultural Production: A Comprehensive Review. *Agronomy* **2024**, *14*, doi:10.3390/agronomy14071360.
61. Jagadish, S.V.K.; Murty, M.V.R.; Quick, W.P. Rice Responses to Rising Temperatures - Challenges, Perspectives and Future Directions. *Plant Cell Environ.* **2015**, *38*, 1686–1698, doi:10.1111/pce.12430.
62. Song, Y.; Wang, C.; Linderholm, H.W.; Fu, Y.; Cai, W.; Xu, J.; Zhuang, L.; Wu, M.; Shi, Y.; Wang, G.; *et al.* The Negative Impact of Increasing Temperatures on Rice Yields in Southern China. *Sci. Total Environ.* **2022**, *820*, 153262, doi:10.1016/j.scitotenv.2022.153262.
63. Wassmann and Dobermann Climate Change Adaptation through Rice Production in Regions with High Poverty Levels Reiner. An open access J. Publ. by SESSO Period. **2012**, *1*, 2–24.
64. Roudier, P.; Sultan, B.; Quirion, P.; Berg, A. The Impact of Future Climate Change on West

- African Crop Yields: What Does the Recent Literature Say? *Glob. Environ. Chang.* **2011**, 21, 1073–1083, doi:10.1016/j.gloenvcha.2011.04.007.
65. Oluwatimilehin; Ayanlade Climate Change Impacts on Staple CropAs: Assessment of Smallholder Farmers’ Adaptation Methods and Barriers. *Clim. Risk Manag.* **2023**, 41, 100542, doi:10.1016/j.crm.2023.100542.
  66. Sultan, B.; Gaetani, M. Agriculture in West Africa in the Twenty-First Century: Climate Change and Impacts Scenarios, and Potential for Adaptation. *Front. Plant Sci.* **2016**, 7, 1–20, doi:10.3389/fpls.2016.01262.
  67. Hat, J.L.; Prueger, J.H. Temperature Extremes : Effect on Plant Growth and Development. *Weather Clim. Extrem. J.* **2015**, 10, 4–10, doi:10.1016/j.wace.2015.08.001.
  68. Li, N.; Zhao, Y.; Han, J.; Yang, Q.; Liang, J.; Liu, X.; Wang, Y.; Huang, Z. Impacts of Future Climate Change on Rice Yield Based on Crop Model Simulation—A Meta-Analysis. *Sci. Total Environ.* **2024**, 949, doi:10.1016/j.scitotenv.2024.175038.
  69. Togbah, C.F. An Analysis of Liberia ’ s Vulnerability to Climate Change in the Context of Least Developed Countries (LDCs): A Review. **2024**, 230–250, doi:10.4236/ajcc.2024.132013.
  70. Birkmann *et al.* Poverty, Livelihoods and Sustainable Development; 2023; <https://doi.org/10.1017/9781009325844.010>
  71. Zhao, C.; Liu, B.; Piao, S.; Wang, X.; Lobell, D.B.; Huang, Y.; Huang, M. Temperature Increase Reduces Global Yields of Major Crops in Four Independent Estimates. *PNAS* **2017**, 1–6, doi:10.1073/pnas.1701762114.
  72. Baruah, U.; Das, S.; Kalita, P.; Saikia, M.; Bhougal, S.; Pal, S.; Das, R. High-Night Temperature-Induced Changes in Chlorophyll Fluorescence, Gas Exchange, and Leaf Anatomy Determine Grain Yield in Rice Varieties. *J. Plant Growth Regul.* **2023**, 42, 5538–5557, doi:10.1007/s00344-023-10934-z.

## Statements and Declarations

**Funding:** This research was funded by the Centre of Excellence in Agri-Food Systems and Nutrition (CE-AFSN), Eduardo Mondlane University, Mozambique.

**Ethics declaration:** not applicable

**Author Contributions:** B.T.S. and J.L.M.U. proposed the study objectives, methodology, performed the data analysis, wrote original draft and reviewed the manuscript. C.M.M. and A.N. supervised, critically revised the manuscript. All authors approved the last version of manuscript to be published.

**Conflicts of Interest:** The authors declare no conflicts of interest.

**Consent to Publish declaration:** not applicable

**Consent to Participate declaration:** not applicable

**Data Availability:** Data supporting reported results can be made available upon request, through the following contacts: Bondo T. Simpson: [bondosimpson@gmail.com](mailto:bondosimpson@gmail.com) and Jone L. Medja Ussalu: [jonemedja@gmail.com](mailto:jonemedja@gmail.com).

**Acknowledgments:** The authors would like to fully acknowledge the financial support received from the Centre of Excellence in Agri-Food Systems and Nutrition (CE-AFSN), Eduardo Mondlane University, Mozambique, for the accomplishment of this research. The following databases were also crucial for this study: C3S-AgERA5, CHIRPS, LIBSIS, FAO, SRTM and SEA.

## CHAPTER VI: INTEGRATIVE DISCUSSION

### 6.1. Integrative Discussion of Thesis

This study examines the effect of climate variability on rice production and identifies areas that are suitable for rice production in Liberia. Findings indicate that rice production in Liberia had a significant upward trend from 1990 to 2023; nevertheless, this growth was not accompanied by corresponding increases in yield, indicating that production gains maybe primarily driven by expansion of cultivated area rather than productivity improvements. This pattern is consistent with global reports (FAO, 2018) and broader Sub-Saharan African trends (Ibrahim *et al.*, 2022; Saito *et al.*, 2023), where extensification dominates agricultural growth. Despite the overall increase, production remains considerably fluctuating across years due to the interaction of climatic shocks, policy interventions, and socio-economic constraints (FAO, 2015; EPA, 2018). The persistent stagnation in yield ( $1.2 \text{ t ha}^{-1}$ ), significantly below regional averages, echoes structural limitations, including low adoption of improved seed varieties, minimal fertilizer use, limited irrigation, and weak extension services and credit systems (Sumo *et al.*, 2022; World Bank, 2022). These findings with corresponding literature, underscore that productivity constraints in Liberia are largely institutional and technological rather than principally climatic.

Climatic variability assessment reveals non-significant trends in precipitation but substantial intra-seasonal variability, alongside a significant increase in temperature, consistent with regional and global evidence (Sultan & Gaetani, 2016, IPCC, 2023). While no significant long-term relationship was found between climate variables and rice production, time-specific analyses indicate that extreme rainfall and rising temperatures, particularly minimum (nighttime) temperatures—negatively affect productivity, mainly through physiological stress during critical growth stages (Hatfield & Prueger, 2015; Jagadish *et al.*, 2015a). Results of the regression analysis further highlight the dominant role of minimum temperature in reducing production, while precipitation positively influences yield, signifying the dependence of Liberia's rice systems on rainfall. Nevertheless, the low explanatory power of climate variables suggests that non-climatic factors (limited access to improved seed varieties, poor irrigation infrastructure, inadequate use of fertilizers, limited credit, and low extension services) maybe the primary drivers of yield variability in Liberia. Land suitability analysis supports this conclusion, showing that over 50% of Liberia is

suitable for rice cultivation, yet actual utilization remains low due to structural constraints (Allen Jr. *et al.*, 2025; Jr & Diallo, 2025). Collectively, these findings highlight a critical paradox: high agroecological potential coexisting with low productivity, emphasizing the need for integrated strategies that combine sustainable intensification, institutional strengthening, and climate adaptation to enhance resilience and food security.

## **6.2. Research Limitation**

The current study provides a comprehensive assessment of rice production trends, climatic impacts on rice production, and land suitability for rice cultivation in Liberia; however, it faces several constraints. First, the absence of field-based data, including yield records and surveys, limits the analysis to correlations rather than causal inference. Secondly, the suitability map validation relied on literature, general land-use knowledge, and AHP consistency checks rather than empirical observations. The use of global datasets may not capture local variability in soils, microclimate, topography, and land cover, while the national-level focus limits capture of regional heterogeneity and socio-demographic differences. Additionally, extreme climate events, such as floods and prolonged droughts, were not explicitly considered despite their significant influence on yields. Nonetheless, the study establishes a baseline for national rice production and suitability assessment. Future research should integrate field data, high-resolution climate extremes, and local socio-geographic factors to provide more precise, context-specific insights for climate-resilient rice production and policy planning in Liberia.

## **6.3. Recommendations for future research**

The study recommends that an integrated pathway for strengthening rice production in Liberia should prioritize the transition from correlation-based assessments to more robust, evidence-driven approaches by incorporating field-based and experimental data to establish causal linkages between climate variables and rice productivity, particularly focusing on crop physiological and morphological responses to temperature and precipitation. Future research should also incorporate high-resolution climate datasets that capture extreme events, such as floods and droughts to better quantify their direct and localized impacts on yield variability. Likewise, it is also important for

the inclusion of socio-demographic dimensions and sub-national geographical heterogeneity to enable more targeted, context-specific, and equitable interventions.

From a strategic development standpoint, expanding rice cultivation within identified highly suitable areas should be a national priority, supported by the promotion of mechanized agriculture and strengthened agricultural extension systems. Targeted investments in rural infrastructure especially road networks and storage facilities, are essential to enhance connectivity between high-potential production areas and markets, thereby improving efficiency across the rice value chain. In moderately suitable areas, productivity gains can be achieved through the sustainable application of fertilizers, soil amendments, and conservation practices aimed at improving soil quality and resilience.

Furthermore, the integration of geospatial technologies, particularly GIS and multi-criteria decision-making frameworks, should be strengthened and systematically combined with empirical data to support evidence-based land-use planning and climate-resilient agricultural strategies. Overall, a holistic framework that aligns technological innovation, climate analysis, field validation, and socio-economic considerations is critical for enhancing domestic rice production, strengthening food security, and reducing reliance on imports while improving farmers' livelihoods.

## CHAPTER VII: GENERAL CONCLUSION

This study provides a robust and cohesive understanding of how climate variability, environmental suitability, and socioeconomic conditions interact to shape rice production and farmers' resilience in Liberia between 1990 and 2023. The results indicate a consistent rise in mean, minimum, and maximum temperatures, coupled with pronounced rainfall variability characterized by delayed onset and irregular distribution, as perceived by farmers. These climatic variations exert complex, seasonally dependent influences on rice production and yield, causing both positive and negative effects depending on the timing and magnitude of temperature and precipitation changes. Although climate variability contributes to fluctuations in rice output, its overall explanatory power remains limited, indicating that additional non-climatic factors play a substantial role in determining production outcomes.

Empirical evidence shows that minimum temperature negatively affects rice production, whereas precipitation is the only climate variable that exerts a significant positive influence on yield. Spatial analysis further highlights considerable heterogeneity in the distribution of temperature and rainfall across counties, emphasising the localized nature of climate impacts on crop productivity. Future projections under high-emission scenarios revealed continued temperature increases and persistent precipitation variability, suggesting heightened uncertainty and potential risks for rice production systems in the coming decades.

Even though there exhibited a general increase in total rice production, yield stagnation exists, signifying the critical impact of structural constraints, such as limited access to improved inputs, inadequate irrigation, weak extension services, and financial barriers. This suggests that climate variability alone does not fully explain the country's low productivity; rather, a combination of climatic factors and agronomic and socioeconomic limitations perpetuates the existing productivity gap and reliance on rice imports. Farmers' adaptation strategies are largely based on indigenous knowledge and pragmatic learning, which include adjustments in planting dates, crop diversification, and basic soil and water management practices. However, these responses remain relatively rudimentary and inadequate to fully safeguard against increasing climate variability, leaving farming systems highly vulnerable.

The land suitability analysis further demonstrates that a substantial proportion of Liberia's producible land is favorable for rice cultivation, particularly in the northern, central, and southeastern regions, with precipitation and temperature as dominant factors of suitability. However, factors such as slope, soil pH, and texture impose significant limitations in less suitable areas. Generally, while Liberia shows considerable natural potential and generally optimal climatic conditions for rice cultivation, the study underscores that sustainable improvements in productivity and resilience depend on addressing the interconnected effects of climate variability, spatial environmental constraints, and persistent socioeconomic challenges.

## REFERENCES

- Adjah, K. L., Asante, M. D., Toure, A., Aziadekey, M., Amoako-Andoh, F. O., Frei, M., Diallo, Y., & Agboka, K. (2022). Improvement of Rice Production under Drought Conditions in West Africa: Application of QTLs in Breeding for Drought Resistance. *Rice Science*, 29(6), 512–521. <https://doi.org/10.1016/j.rsci.2022.06.002>
- African Development Bank Group. (2020). African Economic Outlook 2020 : Developing Africa's Workforce for the Future. In African Development Bank. [https://www.afdb.org/fileadmin/uploads/afdb/Documents/Publications/African\\_Economic\\_Outlook\\_2018\\_-\\_EN.pdf](https://www.afdb.org/fileadmin/uploads/afdb/Documents/Publications/African_Economic_Outlook_2018_-_EN.pdf)
- Akıncı, H., Özalp, A. Y., Turgut, B. (2013). Agricultural land use suitability analysis using GIS and AHP technique. *Computers and Electronics in Agriculture*, 97, 71–82. <https://doi.org/10.1016/j.compag.2013.07.006>
- Jr, A.D.A.; Diallo, K. (2025). Assessing the Impact of Climate Change on Liberia's Agricultural Sector and Strategic Adaptation Approaches. *International Journal of Research and Innovation in Social Science (IJRISS)*, IX(X), 9545–9559. <https://doi.org/https://dx.doi.org/10.47772/IJRISS.2025.910000781>
- Ampaire, E. L., Acosta, M., Huyer, S., Kigonya, R., Muchunguzi, P., Muna, R., & Jassogne, L. (2020). Gender in climate change, agriculture, and natural resource policies: insights from East Africa. *Climatic Change*, 158(1), 43–60. <https://doi.org/10.1007/s10584-019-02447-0>
- Asfaw, A., Simane, B., Bantider, A., & Hassen, A. (2019). Determinants in the adoption of climate change adaptation strategies: evidence from rainfed-dependent smallholder farmers in north-central Ethiopia (Woleka sub-basin). *Environment, Development and Sustainability*, 21(5), 2535–2565. <https://doi.org/10.1007/s10668-018-0150-y>
- Asfaw, A., Simane, B., Hassen, A., & Bantider, A. (2018). Variability and time series trend analysis of rainfall and temperature in northcentral Ethiopia: A case study in Woleka sub-basin. *Weather and Climate Extremes*, 19(June 2017), 29–41. <https://doi.org/10.1016/j.wace.2017.12.002>
- Ayanlade, A., Oluwatimilehin, I. A., & Ayanlade, O. S. (2023). Climate Change Impacts on Agriculture and Barriers To Adaptation Technologies Among Rural Farmers in Southwestern Nigeria. *Routledge Handbook of Climate Change Impacts on Indigenous Peoples and Local Communities*, 259–272. <https://doi.org/10.4324/9781003356837-20>

- Ayanlade, A., Radeny, M., Morton, J. F., & Muchaba, T. (2018). Rainfall variability and drought characteristics in two agro-climatic zones: An assessment of climate change challenges in Africa. *Science of the Total Environment*, 630, 728–737. <https://doi.org/10.1016/j.scitotenv.2018.02.196>
- Ayehu and Besufekad. (2015). Land Suitability Analysis for Rice Production: A GIS Based Multi-Criteria Decision Approach. *American Journal of Geographic Information System*, 4(3), 95–104. <https://doi.org/10.5923/j.ajgis.20150403.02>
- Bamba, A., Dieppois, B., Konaré, A., Pellarin, T., Balogun, A., Dessay, N., Kamagaté, B., Savané, I., & Diédhiou, A. (2015). Changes in Vegetation and Rainfall over West Africa during the Last Three Decades (1981-2010). *Atmospheric and Climate Sciences*, 05(04), 367–379. <https://doi.org/10.4236/acs.2015.54028>
- Bationo, a, Hartemink, A., Lungu, O., Naimi, M., Okoth, P., Smaling, E., & Thiombiano, L. (2006). African soils: Their productivity and profitability of fertilizer use. Background Paper for the Africa Fertilizer Summit, 9–13. <chrome-extension://efaidnbmnnnibpcajpcgclefindmkaj/https://edepot.wur.nl/26759>
- Beck, H. E., McVicar, T. R., Vergopolan, N., Berg, A., Lutsko, N. J., Dufour, A., Zeng, Z., Jiang, X., van Dijk, A. I. J. M., & Miralles, D. G. (2023). High-resolution (1 km) Köppen-Geiger maps for 1901–2099 based on constrained CMIP6 projections. *Scientific Data*, 10(1), 1–16. <https://doi.org/10.1038/s41597-023-02549-6>
- Bedair, H., Alghariani, M. S., Omar, E., Agbolade, Q., & Michael, A. (2023). Global Warming Status in the African Continent: Sources, Challenges, Policies, and Future Direction. *International Journal of Environmental Research*. <https://doi.org/10.1007/s41742-023-00534-w>
- Benjamin, J., Idowu, O., Babalola, O. K., Oziegbe, E. V., Oyedokun, D. O., Akinyemi, A. M., & Adebayo, A. (2024). Cereal production in Africa: the threat of certain pests and weeds in a changing climate—a review. *Agriculture and Food Security*, 13(1), 1–16. <https://doi.org/10.1186/s40066-024-00470-8>
- Berhane, A. (2018). Climate Change and Variability Impacts on Agricultural Productivity and Food Security. *Journal of Climatology & Weather Forecasting*, 06(03). <https://doi.org/10.4172/2332-2594.1000240>
- Birkmann *et al.* (2023). Poverty, Livelihoods and Sustainable Development. In *Climate Change*

- 2022 – Impacts, Adaptation and Vulnerability. <https://doi.org/10.1017/9781009325844.010>
- Bouteska, A., Sharif, T., Bhuiyan, F., & Abedin, M. Z. (2024). Impacts of the changing climate on agricultural productivity and food security: Evidence from Ethiopia. *Journal of Cleaner Production*, 449(March), 141793. <https://doi.org/10.1016/j.jclepro.2024.141793>
- Bozdag, A., Yavuz, F., Gu'nay, A. S. (2016). AHP and GIS based land suitability analysis for Cihanbeyli (Turkey) County. *Environmental Earth Sciences*, 75(9). <https://doi.org/10.1007/s12665-016-5558-9>
- Brandolini and Tigani. (2006). Liberia environmental profile. *Governance An International Journal Of Policy And Administration*, (December), 1–110. [https://ekmsliberia.info/wp-content/uploads/2021/09/cep\\_liberia\\_2006\\_.pdf](https://ekmsliberia.info/wp-content/uploads/2021/09/cep_liberia_2006_.pdf)
- Calvin, K., Dasgupta, D., Krinner, G., Mukherji, A., Thorne, P. W., Trisos, C., Romero, J., Aldunce, P., Barrett, K., Blanco, G., Cheung, W. W. L., Connors, S., Denton, F., Diongue-Niang, A., Dodman, D., Garschagen, M., Geden, O., Hayward, B., Jones, C., ... Ha, M. (2023). IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland. (P. Arias, M. Bustamante, I. Elgizouli, G. Flato, M. Howden, C. Méndez-Vallejo, J. J. Pereira, R. Pichs-Madruga, S. K. Rose, Y. Saheb, R. Sánchez Rodríguez, D. Ürge-Vorsatz, C. Xiao, N. Yassaa, J. Romero, J. Kim, E. F. Haites, Y. Jung, R. Stavins, ... C. Péan, Eds.). <https://doi.org/10.59327/IPCC/AR6-9789291691647>
- CARD. (2021). Data collection survey on rice related programs / projects in the CARD member countries ( with Competitiveness Analysis of Local Rice to Imported Rice. [https://riceforafrica.net/wp-content/uploads/2023/12/Liberia-Competitiveness-analysis\\_20210808.pdf](https://riceforafrica.net/wp-content/uploads/2023/12/Liberia-Competitiveness-analysis_20210808.pdf)
- CBL. (2023). Central Bank of Liberia Annual Report 2022. [https://www.cbl.org.lr/sites/default/files/documents/CBL\\_2022\\_ANNUAL\\_REPORT.pdf](https://www.cbl.org.lr/sites/default/files/documents/CBL_2022_ANNUAL_REPORT.pdf)
- CCKP Liberia Country Profile-WEB; 2021; Vol. 3. Available online: [https://climateknowledgeportal.worldbank.org/sites/default/files/2021-07/15917-WB\\_Liberia%20Country%20Profile-WEB.pdf](https://climateknowledgeportal.worldbank.org/sites/default/files/2021-07/15917-WB_Liberia%20Country%20Profile-WEB.pdf)
- Ceci, P., Monforte, L., Perelli, C., Cicatiello, C., Branca, G., Franco, S., Diallo, F. B. S., Blasi, E., & Scarascia Mugnozza, G. (2021). Smallholder farmers' perception of climate change and

- drivers of adaptation in agriculture: A case study in Guinea. *Review of Development Economics*, 25(4), 1991–2012. <https://doi.org/10.1111/rode.12815>
- Chala, D., Belay, S., & Bamlaku, A. (2020). Analysis of farmers perceived and observed climate variability and change in Didessa sub-basin, Blue Nile River, Ethiopia. *African Journal of Agricultural Research*, 15(2), 149–164. <https://doi.org/10.5897/ajar2019.14054>
- Copernicus Climate Change Service. (2020). Agrometeorological indicators from 1979 to present derived from reanalysis. Copernicus Climate Change Service (C3S), Climate Data Store (CDS). <http://dx.doi.org/10.24381/cds.6c68c9bb>
- da Silva, R. M., Santos, C. A. G., Moreira, M., Corte-Real, J., Silva, V. C. L., & Medeiros, I. C. (2015). Rainfall and river flow trends using Mann–Kendall and Sen’s slope estimator statistical tests in the Cobres River basin. *Natural Hazards*, 77(2), 1205–1221. <https://doi.org/10.1007/s11069-015-1644-7>
- Daszkiewicz, T. (2022). Food Production in the Context of Global Developmental Challenges. *Agriculture (Switzerland)*, 12(6). <https://doi.org/10.3390/agriculture12060832>
- December, V. I., Shhu, P., Rshq, U., Mrxuqdo, D., Salifu, E., Agyare, W. A., Abdul-ganlyu, A., & Dihy, U. X. (2022). Evaluation of land suitability for crop production in Northern Ghana using GIS and AHP based techniques Evaluation of land suitability for crop production in Northern Ghana using GIS and AHP based techniques. *International Journal of Environment and Geoinformatics (IJECEO)*, 45–56. <https://doi.org/doi.10.30897/ijegeo.1022275>
- Dorbor-soko, L. M. (2024). Assessment of the Impacts of Climate Variability and Change on Rice Production in Bong County, Liberia (Number June).
- Dorbor Wuokolo, J. (2023). Perception of Climate Change and Barriers to Strategic Adaptation for Smallholder Farming in Todee District, Liberia [Chulalongkorn University]. <https://www.researchgate.net/publication/367392196>
- Dubey, A. N., Verma, S., Goswami, S. P., & Devedee, A. K. (2018). Effect of Temperature on Different Growth Stages and Physiological Process of Rice crop-A Review. *Bulletin of Environment, Pharmacology and Life Sciences*, (September), 162–169.
- EPA. (2013). Liberia Initial national communication 2013. <https://unfccc.int/sites/default/files/resource/lbrnc1.pdf>
- EPA. (2018). National Policy and Response Strategy on Climate Change Final Document-min\_0. <https://www.undp.org/liberia/publications/national-policy-and-response-strategy-climate->

change

- EPA. (2020). Liberia's First Biennial Update Report to UNFCCC. <https://unfccc.int/sites/default/files/resource/BUR1.pdf>
- EPA. (2021a). Liberia's Revised Nationally Determined Contribution (NDC). *Minerva Internationales Verzeichnis Wissenschaftlicher Institutionen*, (July), 307–307. <https://faolex.fao.org/docs/pdf/lbr206208.pdf>
- EPA. (2021b). Liberia's Second National Communication to the United Nations Framework Convention on Climate Change. <https://unfccc.int/sites/default/files/resource/SNC.pdf>
- EPA. (2021c). Republic of Liberia Liberia ' s First Adaptation Communication to the United Nations Framework Convention on Climate Change (UNFCCC) (Number November). [https://unfccc.int/sites/default/files/resource/First\\_Adaptation\\_Communication\\_AdCom\\_LI BERIA.pdf?glarity\\_translate=1](https://unfccc.int/sites/default/files/resource/First_Adaptation_Communication_AdCom_LI BERIA.pdf?glarity_translate=1)
- EPA. (2024). Liberia's National Adaptation Plan Communication Strategy (Number March). <https://napglobalnetwork.org/resource/liberias-national-adaptation-plan-communication-strategy/>
- ESA. (2010). Global land cover map. [http://due.esrin.esa.int/page\\_globcover.php](http://due.esrin.esa.int/page_globcover.php)
- FAO. (2015). Climate change and food security: risks and responses. Rome, Italy: FAO. (September), 122. <https://www.fao.org/3/i5188e/i5188e.pdf>
- FAO. (2018). Rice Production Report: XXI (Number 1). <https://openknowledge.fao.org/server/api/core/bitstreams/07b6c7b4-065b-47ac-88d5-bbdafcb2baae/content>
- Fosu-Mensah, B. Y., Vlek, P. L. G., & MacCarthy, D. S. (2012). Farmers' perception and adaptation to climate change: A case study of Sekyedumase district in Ghana. *Environment, Development and Sustainability*, 14(4), 495–505. <https://doi.org/10.1007/s10668-012-9339-7>
- Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A., & Michaelsen, J. (2015). The climate hazards infrared precipitation with stations - A new environmental record for monitoring extremes. *Scientific Data*, 2, 1–21. <https://doi.org/10.1038/sdata.2015.66>
- Grigorieva, E., Livenets, A., & Stelmakh, E. (2023). Adaptation of Agriculture to Climate Change: A Scoping Review. *Climate*, 11(10), 1–37. <https://doi.org/10.3390/cli11100202>

- Gumel, D.Y.; Abdullah, A.M.; Sood, A.M.; Elhadia, R.E.; Jamalani, M.A.; Youssefa, K.A.A.B. Assessing Paddy Rice Yield Sensitivity to Temperature and Rainfall Variability in Peninsular Malaysia Using DSSAT Model. *Int. J. Appl. Environ. Sci.* **2017**, *12*, 1521–1545 .
- Gwambene, B., Liwenga, E., Mung’ong’o, C. Climate Change and Variability Impacts on Agricultural Production and Food Security for the Smallholder Farmers in Rungwe, Tanzania. *Environ. Manage.* **2023**, *71*, 3–14, <https://doi.org/10.1007/s00267-022-01628-5>.
- Hansen J, Sato M, Ruedy R. Perception of climate change. *Proc Natl Acad Sci U S A.* 2012 Sep 11;109(37):E2415-23. doi: 10.1073/pnas.1205276109. Epub 2012 Aug 6. PMID: 22869707; PMCID: PMC3443154.
- Hasanuzzaman, M., Hakeem, K. R., Nahar, K., & Alharby, H. F. (2019). Plant abiotic stress tolerance: Agronomic, molecular and biotechnological approaches. *Plant Abiotic Stress Tolerance: Agronomic, Molecular and Biotechnological Approaches*, (October), 1–490. <https://doi.org/10.1007/978-3-030-06118-0>
- Hatfield, J. L., & Prueger, J. H. (2015). Temperature extremes: Effect on plant growth and development. *Weather and Climate Extremes*, *10*, 4–10. <https://doi.org/10.1016/j.wace.2015.08.001>
- Hossen, B., Yabar, H., & Mizunoya, T. (2021). Land Suitability Assessment for Pulse (Green Gram) Production through Remote Sensing , GIS and Multicriteria Analysis in the Coastal Region of Bangladesh. *Sustainability*, 2–24.
- Hussain, W., Sohaib, O., Ahmed, A., & Khan, M. Q. (2012). Geographical Information System Based Model of Land Suitability for Good Yield of Rice in Prachuap Khiri Khan Province , Thailand. *Sci,Tech. and Dev.*, *31*(1), 1–9.
- Ibrahim, A., Saito, K., Kokou, A., Johnson, J. M., Diagne, M., Fagnombo, D. J., Felix, F., Sylvia, B. O., & Martial, H. (2022). Seizing opportunity towards sustainable rice cultivation in sub-Saharan Africa. *Environmental and Sustainability Indicators*, *15*(January), 100189. <https://doi.org/10.1016/j.indic.2022.100189>
- IPCC Scientific Review of the Impact of Climate Change on Plant Pests—A Global Challenge to Prevent and Mitigate Plant Pest Risks in Agriculture, Forestry and Ecosystems; FAO on Behalf of the IPPC Secretariat: Rome, Italy, 2021. <https://doi.org/10.4060/cb4769en>.
- IPCC. (2023a). IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate

- Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland. <https://doi.org/10.59327/IPCC/AR6-9789291691647>
- IPCC. (2023b). Summary for Policymakers:IPCC. (2023). Summary for Policymakers: Synthesis Report. Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, 1–34. S. In Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. [https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC\\_AR6\\_SYR\\_SPM.pdf](https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_SPM.pdf)
- Islam, Monjurul Md., Ahamed T., & Noguchi R. (2018). Land suitability and insurance premiums: A GIS-based multicriteria analysis approach for sustainable rice production. Sustainability (Switzerland), 10(6). <https://doi.org/10.3390/su10061759>
- Jackson, E. A. (2020). Munich Personal RePEc Archive Deconstructing Sustainable Livelihood Framework for Equitable Living in Crisis of Global Pandemic. Munich Personal RePEc Archive, (101977), 1–14.
- Jagadish, S. V. K., Murty, M. V. R., & Quick, W. P. (2015). Rice responses to rising temperatures - challenges, perspectives and future directions. Plant Cell and Environment, 38(9), 1686–1698. <https://doi.org/10.1111/pce.12430>
- Jalloh, A. A., Edo, G. I., Onyibe, P. N., & Nwosu, L. C. (2023). Farmers' Perception of Climate Change: A Case Study from Subsistence Farming in Lalehun Kovama of Kailahun in Eastern Sierra Leone. Environmental Protection Research, 14–25. <https://doi.org/10.37256/epr.3120231905>
- Jalloh, A.; Nelson, G.C.; Thomas, T.S.; Zougmore, R.B.; Roy-Macauley, H. West African Agriculture and Climate Change: A Comprehensive Analysis; International Food Policy Research Institute: Washington, DC, USA, 2013; ISBN 9780896292048.
- Japhet, A., Francis, M., Fukah, K., Kisetu, E., George, N., & Tryphone, M. (2025). Analysing rice ( *Oryza sativa* L .) production trends — area harvested , quantity and yield stability in Tanzania. Discover Agriculture. <https://doi.org/10.1007/s44279-025-00204-9>
- Jena, B. K. (2023). Rice Production and Global Climate Change. Biomedical Journal of Scientific & Technical Research, 48(1), 39075–39095. <https://doi.org/10.26717/bjstr.2023.48.007592>
- Jie, Huang, J., Ahmad, S., Nanda, S., Anwar, S., Shakoor, A., Zhu, C., Zhu, L., Cao, X., Jin, Q., & Zhang, J. (2020). Rice Production Under Climate Change: Adaptations and Mitigating

- Strategies. *Environment, Climate, Plant and Vegetation Growth*, (June), 659–686.  
[https://doi.org/10.1007/978-3-030-49732-3\\_26](https://doi.org/10.1007/978-3-030-49732-3_26)
- Jiqin, H.; Gelata, F.T.; Chaka Gameda, S. (2023). Application of MK trend and test of Sen’s slope estimator to measure impact of climate change on the adoption of conservation agriculture in Ethiopia. *Journal of Water and Climate Change*, 14(3), 977–988.  
<https://doi.org/10.2166/wcc.2023.508>
- Joseph Kihoro, N. J. B. and H. M. (2013). Suitability analysis for rice growing sites using a multicriteria evaluation and GIS approach in great Mwea region, Kenya. *SpringerPlus*, 2(1), 1–9. <https://doi.org/10.1186/2193-1801-2-265>
- Joseph, M., Moonsammy, S., Davis, H., Warner, D., Adams, A., & Timothy, T. D. (2023). Heliyon Modelling climate variabilities and global rice production : A panel regression and time series analysis. *Heliyon*, 9(4), e15480. <https://doi.org/10.1016/j.heliyon.2023.e15480>
- Jr, A. D. A., & Diallo, K. (2025). Agricultural Dynamics in Liberia : Current Issues and Solutions. *INTERNATIONAL JOURNAL OF RESEARCH AND INNOVATION IN SOCIAL SCIENCE (IJRISS)*, IX(2454), 7430–7437.  
<https://doi.org/https://dx.doi.org/10.47772/IJRISS.2025.910000604> Received:
- Katz, W. A., & Rothenberg, R. (2005). Section I: Introduction. *Journal of Clinical Rheumatology : Practical Reports on Rheumatic & Musculoskeletal Diseases*, 11(2 Suppl).  
<https://doi.org/10.4324/9781315226378-6>
- Kissi, A. E., Abbey, G. A., & Villamor, G. B. (2023). Perceptions of Climate Change Risk on Agriculture Livelihood in Savanna Region, Northern Togo. *Climate*, 11(4).  
<https://doi.org/10.3390/cli11040086>
- Kılıc, O. M., Ersayın, K., Gunal, H., Khalofah, A., & Alsubeie, M. S. (2022). Combination of fuzzy-AHP and GIS techniques in land suitability assessment for wheat (*Triticum aestivum*) cultivation. *Saudi Journal of Biological Sciences*, 29(4), 2634–2644.  
<https://doi.org/10.1016/j.sjbs.2021.12.050>
- Kwak, S. K., & Kim, J. H. (2017). Statistical data preparation: Management of missing values and outliers. *Korean Journal of Anesthesiology*, 70(4), 407–411.  
<https://doi.org/10.4097/kjae.2017.70.4.407>
- Lal, R. (2015). Restoring soil quality to mitigate soil degradation. *Sustainability (Switzerland)*, 7(5), 5875–5895. <https://doi.org/10.3390/su7055875>

- LISGIS. (2022). Thematic Report on Population Size , Distribution and Structure 2022 Liberia Population and Housing Census. <https://lisgis.gov.lr/censusreport/thematic/ThematicReportonPopulationSizeDistributionandStructure.pdf>
- LISGIS. (2024). Government of the republic of liberia. LIBERIA AGRICULTURE CENSUS 2022/23 (Number August). <https://lisgis.gov.lr/censusreport/LAC202223ProvisionalResults090124Final.pdf>
- Longzhu, G., Jr, A. D. A., & Nuah, I. (2025). Evaluating Agricultural Policy and Performance in Liberia ( 2004-2024 ): Implications for Policy in Post-Civil War Liberia. *International Journal of Environmental & Agriculture Research (IJOEAR)*, Vol-11(11), 43–56.
- Maiti, A., Hasan, M. K., Sannigrahi, S., Bar, S., Chakraborti, S., Mahto, S. S., Chatterjee, S., Pramanik, S., Pilla, F., Auerbach, J., Sonnentag, O., Song, C., & Zhang, Q. (2024). Optimal rainfall threshold for monsoon rice production in India varies across space and time. *Communications Earth and Environment*, 5(1), 1–8. <https://doi.org/10.1038/s43247-024-01414-7>
- Makungwe, M., Chabala, L. M., Van Dijk, M., Chishala, B. H., & Lark, R. M. (2021). Assessing land suitability for rainfed paddy rice production in Zambia. *Geoderma Regional*, 27, e00438. <https://doi.org/10.1016/j.geodrs.2021.e00438>
- Al Mamun MA, Nihad SAI, Sarkar MAR, Sarker MR, Skalicka J and Skalicky M (2023). Spatio-temporal variability of climatic variables and its impacts on rice yield in Bangladesh. *Frontiers in Sustainable Food Systems*, 7(December). <https://doi.org/10.3389/fsufs.2023.1290055>
- Matulla, C., Hollósi, B., Andre, K., Gringinger, J., Chimani, B., Namyslo, J., Fuchs, T., Auerbach, M., Herrmann, C., Sladek, B., Berghold, H., Gschier, R., & Eichinger-Vill, E. (2018). Climate Change driven evolution of hazards to Europe’s transport infrastructure throughout the twenty-first century. *Theoretical and Applied Climatology*, 133(1–2), 227–242. <https://doi.org/10.1007/s00704-017-2127-4>
- Micha *et al.* (2020). Global Nutrition Report. In *Global Nutrition Report*. [https://media.globalnutritionreport.org/documents/2020\\_Global\\_Nutrition\\_Report\\_2hrssKo.pdf](https://media.globalnutritionreport.org/documents/2020_Global_Nutrition_Report_2hrssKo.pdf).
- MOA. (2012). National Rice Development Strategy of Liberia Doubling Rice Production by 2018.

- (May 2012), 1–52. [https://riceforafrica.net/wp-content/uploads/2021/09/liberia\\_nrds1.pdf](https://riceforafrica.net/wp-content/uploads/2021/09/liberia_nrds1.pdf)
- MOA. (2017). Baseline Survey in the Rice Sector Development Hubs of Liberia Final Report Smallholder Agricultural Productivity Enhancement and Commercialization (SAPEC) Project. (July). <https://www.moa.gov.lr/document/smallholder-agricultural-productivity-enhancement-commercialization-sapec/baseline-survey>
- MOA. (2018). Liberia National Rice Development Agriculture Republic of Liberia. [https://riceforafrica.net/wp-content/uploads/2023/01/liberia\\_nrds2.pdf](https://riceforafrica.net/wp-content/uploads/2023/01/liberia_nrds2.pdf)
- MOCI. (2017). Ministry of Commerce and Industry Annual Trade Bukkletin. [https://www.moci.gov.lr/sites/default/files/documents/MoCI.AnnualTradeBulletin.2017\\_final.pdf](https://www.moci.gov.lr/sites/default/files/documents/MoCI.AnnualTradeBulletin.2017_final.pdf)
- Mubarak, T., Jehangir, I. A., Hussain, A., Dar, E. A., Shah, Z. A., Lone, A. H., Mir, M. S., & Elhendawy, S. (2025). Yield and water productivity of rice as influenced by crop establishment and irrigation methods under temperate environment. <https://doi.org/10.1038/s41598-025-09584-w>
- Mulungu, K., & Kangogo, D. (2022). Striving to be resilient: the role of crop-poultry integrated system as a climate change adaptation strategy in semiarid eastern Kenya. *Heliyon*, 8(11), e11579. <https://doi.org/10.1016/j.heliyon.2022.e11579>
- NAP. (2020). Liberia national adaptation plan 2020 – 2030. <https://faolex.fao.org/docs/pdf/lbr214252.pdf>
- NAP. (2022). Liberia National Adaptation Plan 2020-2030. <https://faolex.fao.org/docs/pdf/lbr214252.pdf>
- Nguyen, P. T. M., Ho, P. T., & Pham, H. X. (2024). Impacts of seasonal climate variation on rice yield: Evidence from the Central Coast of Vietnam. *Cogent Economics and Finance*, 12(1). <https://doi.org/10.1080/23322039.2024.2421894>
- Niang, I., O.C. Ruppel, M.A. Abdrabo, A. Essel, C. Lennard, J. Padgham, and P. Urquhart, 2014: Africa. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp.

1199-1265.

- NPRSCC. (2018). UNDP\_Ir\_National-Policy-and-Response--Strategy-on-Climate-Change.pdf. <https://www.undp.org/liberia/publications/national-policy-and-response-strategy-climate-change>
- Oluwatimilehin, & Ayanlade. (2023). Climate change impacts on staple cropAs: Assessment of smallholder farmers' adaptation methods and barriers. *Climate Risk Management*, 41(August), 100542. <https://doi.org/10.1016/j.crm.2023.100542>
- Ondiek, R. A., & Saber, M. (2024). Spatial – Temporal Analysis of Impacts of Climate Variability on Maize Yield in Kenya. *Agriculture (MDPI)*, 1–20. <https://doi.org/https://doi.org/10.3390/agriculture14081415>
- Page, Z., Akintayo, I., Roger, A., Paul, B., & Robert, Z. (2023). Rice ratooning as a sustainable climate smart adaptation for agriculture in Liberia. 19(1), 20–23. <https://doi.org/10.5897/AJAR2022.16120>
- Peng, S., Huang, J., Sheehy, J. E., Laza, R. C., Visperas, R. M., Zhong, X., Centeno, G. S., Khush, G. S., & Cassman, K. G. (2004). Rice yields decline with higher night temperature from global warming. *Proceedings of the National Academy of Sciences of the United States of America*, 101(27), 9971–9975. <https://doi.org/10.1073/pnas.0403720101>
- Pluato, E.E.; Mutondo, J.; Kolleh, J.B. Impact of Post-Harvest Losses on the Profitability of Rice Production Amongst Smallholder Farmers in Liberia. *Agricultural Research & Technology: Open Access Journal*, 28(3). <https://doi.org/10.19080/artoaj.2024.28.556414>
- Pope, E.M.; Opile, W.; Ngode, L.; Emmy, C. Assessment of Upland Rice Production Constraints and Farmers' Preferred Varieties in Liberia. *International Journal of Research and Innovation in Social Science (IJRISS)*, VII(2454), 1175–1189. <https://doi.org/10.47772/IJRISS>
- Rath, S. S., Panda, J., Annadurai, R., & Nanda, S. (2018). A Study on Land Suitability for Rice Cultivation in Khordha District of Odisha (India) Using Remote Sensing and GIS. *Earth Systems and Environment*, 2(1), 119–132. <https://doi.org/10.1007/s41748-018-0037-y>
- Reyes, F., Gosme, M., Wolz, K. J., Lecomte, I., & Dupraz, C. (2021). Alley cropping mitigates the impacts of climate change on a wheat crop in a mediterranean environment: A biophysical model-based assessment. *Agriculture (Switzerland)*, 11(4). <https://doi.org/10.3390/agriculture11040356>
- Robertson, N., & Oinam, B. (2023). Rice suitability mapping using the analytic hierarchy process

- approach in a river catchment. 9(1), 141–156. <https://doi.org/10.22034/gjesm.2023.01.11>
- Roy, I. (2020). Major Climate Variability and Natural Factors in Boreal Winter. *Pure and Applied Geophysics*, 177(10), 4983–5005. <https://doi.org/10.1007/s00024-020-02522-z>
- Saito, K.; Senthilkumar, K.; Ali, I.; Johnson, J.; Rodenburg, J.; Senthilkumar, K.; Ali, I.; Johnson, J. (2023). Status quo and challenges of rice production in sub-Saharan Africa. *Plant Production Science*, 26(3), 320–333. <https://doi.org/10.1080/1343943X.2023.2241712>
- Samanta, S., Pal, B., & Par, D. K. (2011). Land Suitability Analysis for Rice Cultivation Based on Multi-Criteria Decision Approach through GIS. *International Journal of Science & Emerging Technologies*, 2(1), 12–20.
- Sarnoh. (2024). Assessment of Climate Risks in Central and Northern Liberia Yusuff Mohammed Sarnoh [University of Glasgow]. <https://theses.gla.ac.uk/84580/>
- Saysay, J. L., Gabagambi, D. M., Mlay, G. I., & Mined, I. J. (2018). Technical Efficiency in Rice Production Among Smallholder Farmers in Central Liberia : A Stochastic Production Frontier Analysis. *Journal of Economics and Sustainable Development*, 9(20), 47–53. [www.iiste.org](http://www.iiste.org)
- Shah, F., & Wu, W. (2019). Soil and Crop Management Strategies to Ensure Higher Crop Productivity within Sustainable Environments. *Sustainability*, 11(5), 1485. <https://doi.org/10.3390/su11051485>
- Sharifnia, A. M., Kpormegbey, D. E., Thapa, D. K., & Cleary, M. (2026). A Primer of Data Cleaning in Quantitative Research: Handling Missing Values and Outliers. *Journal of Advanced Nursing*, 82(1), 970–975. <https://doi.org/10.1111/jan.16908>
- Shrestha, S., Mahat, J., Shrestha, J., Madhav, K. C., & Paudel, K. (2022). Influence of high-temperature stress on rice growth and development. A review. *Heliyon*, 8(12), e12651. <https://doi.org/10.1016/j.heliyon.2022.e12651>
- Sissoko, M. S., Van Den Hoogen, L. L., Samake, Y., Tapily, A., Diarra, A. Z., Coulibaly, M., Bouare, M., Gaudart, J., Knight, P., Sauerwein, R. W., Takken, W., Bousema, T., & Doumbo, O. K. (2015). Spatial patterns of plasmodium falciparum clinical incidence, asymptomatic parasite carriage and anopheles density in two villages in Mali. *American Journal of Tropical Medicine and Hygiene*, 93(4), 790–797. <https://doi.org/10.4269/ajtmh.14-0765>
- Song, Y., Wang, C., Linderholm, H. W., Fu, Y., Cai, W., Xu, J., Zhuang, L., Wu, M., Shi, Y., Wang, G., & Chen, D. (2022). The negative impact of increasing temperatures on rice yields in southern China. *Science of the Total Environment*, 820, 153262.

<https://doi.org/10.1016/j.scitotenv.2022.153262>

- Soullier, G., Demont, M., Arouna, A., Lançon, F., & Mendez del Villar, P. (2020). The state of rice value chain upgrading in West Africa. *Global Food Security*, 25(March), 100365. <https://doi.org/10.1016/j.gfs.2020.100365>
- Su, Q., Rohila, J. S., Ranganathan, S., & Karthikeyan, R. (2023). Rice yield and quality in response to daytime and nighttime temperature increase – A meta-analysis perspective. *Science of the Total Environment*, 898(March), 165256. <https://doi.org/10.1016/j.scitotenv.2023.165256>
- Sultan, B., & Gaetani, M. (2016). Agriculture in West Africa in the twenty-first century: Climate change and impacts scenarios, and potential for adaptation. *Frontiers in Plant Science*, 7(AUG2016), 1–20. <https://doi.org/10.3389/fpls.2016.01262>
- Sultan, B., Roudier, P., Quirion, P., Alhassane, A., Muller, B., Dingkuhn, M., Ciais, P., Guimberteau, M., Traore, S., & Baron, C. (2013). Assessing climate change impacts on sorghum and millet yields in the Sudanian and Sahelian savannas of West Africa. *Environmental Research Letters*, 8(1). <https://doi.org/10.1088/1748-9326/8/1/014040>
- Sumo, T.V.; Ritho, C.; Irungu, P. (2023). Determinants of Smallholder Rice Farmers' Willingness-to-Pay for Private Extension Services in Liberia: The Case of Gibi District. *Sustainability (Switzerland)*, 15(19). <https://doi.org/10.3390/su151914300>
- Sumo, T. V., Ritho, C., & Irungu, P. (2022). Effect of farmer socio-economic characteristics on extension services demand and its intensity of use in post-conflict Liberia. *Heliyon*, 8(12), e12268. <https://doi.org/10.1016/j.heliyon.2022.e12268>
- Tambo, J. A., & Abdoulaye, T. (2013). Smallholder farmers' perceptions of and adaptations to climate change in the Nigerian savanna. *Regional Environmental Change*, 13(2), 375–388. <https://doi.org/10.1007/s10113-012-0351-0>
- Tarway-twalla, A. K. (2013). Agricultural Productivity , Climate Change and Smallholder Farmer ' s Entrepreneurship : A Case Study of the Central and Western Regions of Liberia By Monrovia , Liberia. (February). [www.trustafrica.org/icbe](http://www.trustafrica.org/icbe)
- TNA. (2020). Republic of Liberia Barrier Analysis & Enabling Framework Report for the Adaptation Sector – Agriculture. <https://tech-action.unepccc.org/wp-content/uploads/sites/2/2020/08/tna-agriculture-baef-report-liberia.pdf>
- Tran, B. L., Tseng, W. C., & Chen, C. C. (2025). Climate change impacts on crop yields across temperature rise thresholds and climate zones. In *Scientific Reports (Vol. 15, Number 1)*.

- <https://doi.org/10.1038/s41598-025-07405-8>
- UNFCCC. (2021). United Nations Climate Change Report 2021. [https://unfccc.int/sites/default/files/resource/UNFCCC\\_Annual\\_Report\\_2021.pdf](https://unfccc.int/sites/default/files/resource/UNFCCC_Annual_Report_2021.pdf)
- USAID-BEST. (2014). Liberia-Environmental Threats & Opportunities. [https://pdf.usaid.gov/pdf\\_docs/PA00KDJM.pdf](https://pdf.usaid.gov/pdf_docs/PA00KDJM.pdf)
- USAID. (2013). Liberia Climate Change Assessment (Number MARCH). [https://epa.gov.lr/wp-content/uploads/2024/06/Liberia-CC-Assessment-March-2013-v4.pdf?utm\\_source=openai](https://epa.gov.lr/wp-content/uploads/2024/06/Liberia-CC-Assessment-March-2013-v4.pdf?utm_source=openai)
- Victor and Samson. (2019). An Application of GIS-Based Multi-Criteria Decision Making Approach for Land Evaluation and Suitability Mapping for Rice Cultivation in Oye-Ekiti, Nigeria. *Journal of Agriculture and Environmental Sciences*, 8(1), 25–33. <https://doi.org/10.15640/jaes.v8n1a3>
- Wang, Q., Sun, L., & Yang, X. (2024). Identifying Spatial Determinants of Rice Yields in Main Producing Areas of China Using Geospatial Machine Learning. *International Journal of GEO-Information*.
- Wassmann and Dobermann. (2012). Climate Change Adaptation through Rice Production in Regions with High Poverty Levels Reiner. *An Open Access Journal Published by SESSO Periodicals*, 1(4), 2–24. [https://d1wqtxts1xzle7.cloudfront.net/115127006/sp8-libre.pdf?1716350771=&response-content-disposition=inline%3B+filename%3DClimate\\_Change\\_Adaptation\\_through\\_Rice\\_P.pdf&Expires=1735601597&Signature=fJDuxmH5jy1k7Se43xFYlmTGakf6tJDVuiKzBn3Mej-ZqK11enQp9iQeT](https://d1wqtxts1xzle7.cloudfront.net/115127006/sp8-libre.pdf?1716350771=&response-content-disposition=inline%3B+filename%3DClimate_Change_Adaptation_through_Rice_P.pdf&Expires=1735601597&Signature=fJDuxmH5jy1k7Se43xFYlmTGakf6tJDVuiKzBn3Mej-ZqK11enQp9iQeT)
- WMO. (2021). State of the Global Climate 2020 (Number 1264). [https://library.wmo.int/index.php?lvl=notice\\_display&id=21880#.YHg0ABMzZR0](https://library.wmo.int/index.php?lvl=notice_display&id=21880#.YHg0ABMzZR0)
- WMO. (2024). State of the Climate in Africa 2023. WMO-No. 1360 (Number 1360). <https://library.wmo.int/records/item/69000-state-of-the-climate-in-africa-2023>
- World Bank. (2022). Improving Service Delivery in Liberia’s Agriculture Sector. <https://documents1.worldbank.org/curated/en/099755001262239106/pdf/P1752640ae486b0a089630a7454908775f.pdf>
- World Bank. (2023). Republic of Liberia Economic Update Getting Rice Right for Productivity and Poverty Alleviation Macroeconomic, Trade, and Investment Global Practice West and Central Africa Region (Number June). [www.worldbank.org](http://www.worldbank.org)

- World Bank Liberia Country Climate Development Report; 2024.  
<https://documents1.worldbank.org/curated/en/099032024143525952/pdf/P1798481a4fb560431a86a1bb83f1117b00.pdf>.
- Wuokolo. (2023). Perception of Climate Change and Barriers to Strategic Adaptation for Smallholder Farming in Todee District, Liberia [Chulalongkorn University].  
<https://www.researchgate.net/publication/367392196>
- Yeleliere, E., Antwi-Agyei, P., & Baffour-Ata, F. (2023). Impacts of climate change on the yields of leguminous crops in the Guinea Savanna agroecological zone of Ghana. *Regional Sustainability*, 4(2), 139–149. <https://doi.org/10.1016/j.regsus.2023.04.002>
- Yila, K. M., Gboku, M. L. S., Lebbie, M. S., & Kamara, L. I. (2023). Changes in Rainfall and Temperature and Its Impact on Crop Production in Moyamba District, Southern Sierra Leone. *Atmospheric and Climate Sciences*, 13(01), 19–43. <https://doi.org/10.4236/acs.2023.131003>
- Yohannes, H., & Soromessa, T. (2018). Land suitability assessment for major crops by using GIS-based multi-criteria approach in Andit Tid watershed, Ethiopia. *Cogent Food and Agriculture*, 4(1). <https://doi.org/10.1080/23311932.2018.1470481>
- Yu, J., Du, T., Zhang, P., Ma, Z., Chen, X., Cao, J., & Li, H. (2024). Impacts of High Temperatures on the Growth and Development of Rice and Measures for Heat Tolerance Regulation : A Review. 1–24.
- Yuan, X., Li, S., Chen, J., Yu, H., Yang, T., Wang, C., Huang, S., Chen, H., & Ao, X. (2024). Impacts of Global Climate Change on Agricultural Production: A Comprehensive Review. *Agronomy*, 14(7). <https://doi.org/10.3390/agronomy14071360>

## **APPENDICES**

### **Appendix 1. Ethical Clearance**

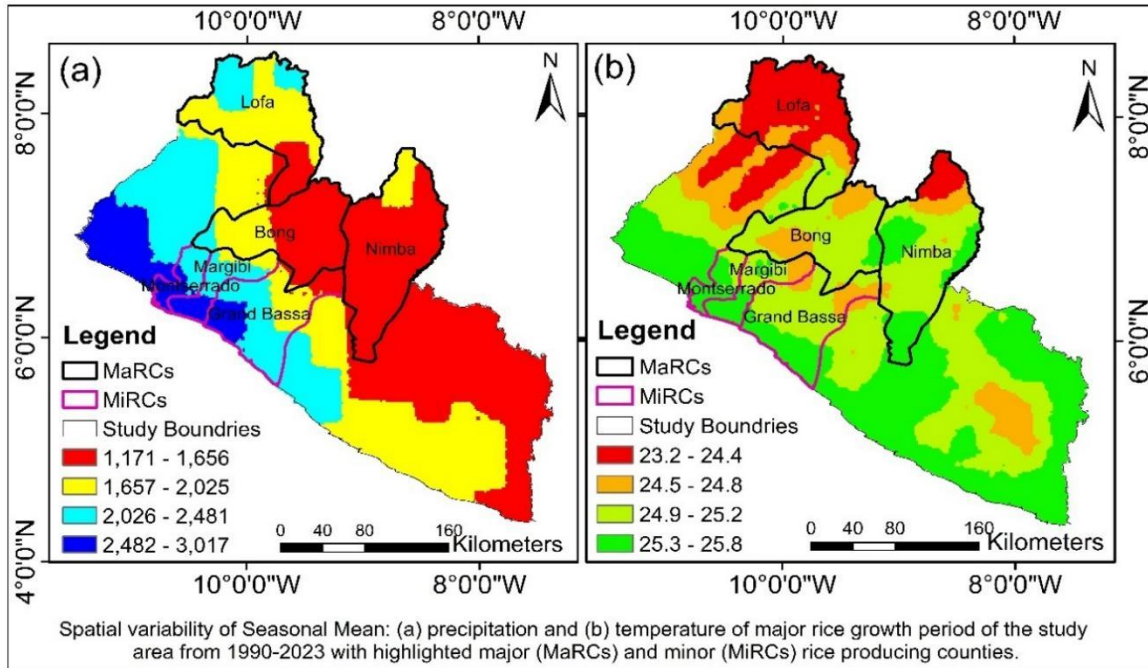
This is not applicable to our study. The study solely based on secondary data that are fully accessible online and did not used field survey.

### **Appendix 2. Data Collection Tool**

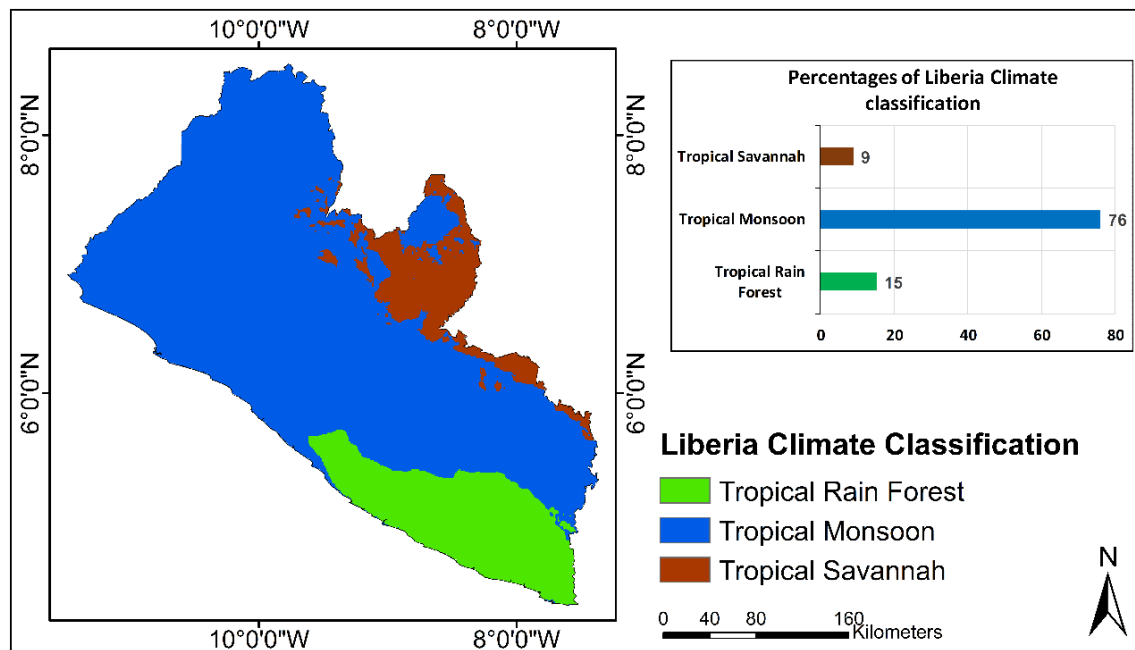
Secondary data was used in this study and were collected from publicly available online sources, including FAOSTAT (<https://www.fao.org/faostat/en/#data/QCL>), the ERA5 Agrometeorological Indicators, available online at: <https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels>, the CHIRPS (the Climate Hazards Precipitation with station), available at: (<https://data.chc.ucsb.edu/products/CHIRPS-2.0/>), and the CORDEX (Coordinated Regional Climate Downscaling Experiment), available online: <https://cds.climate.copernicus.eu/datasets/projections-cordex-domains-single-levels?tab=download>, as well as government reports, journal articles, and online statistical databases. The data were systematically reviewed and analyzed to answer the research objectives.

### Appendix 3. Supplementary Materials

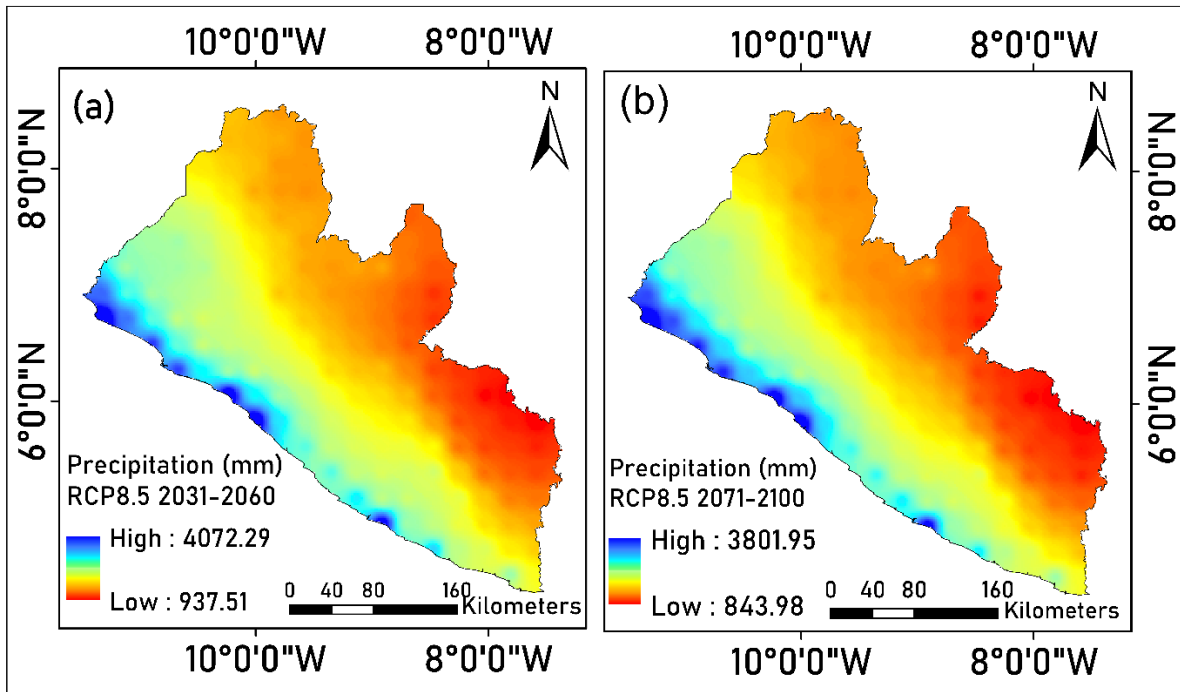
#### Appendix 3.1. Supplementary Materials (Figure S1. Spatial variability of precipitation and temperature with major and minor rice production areas).



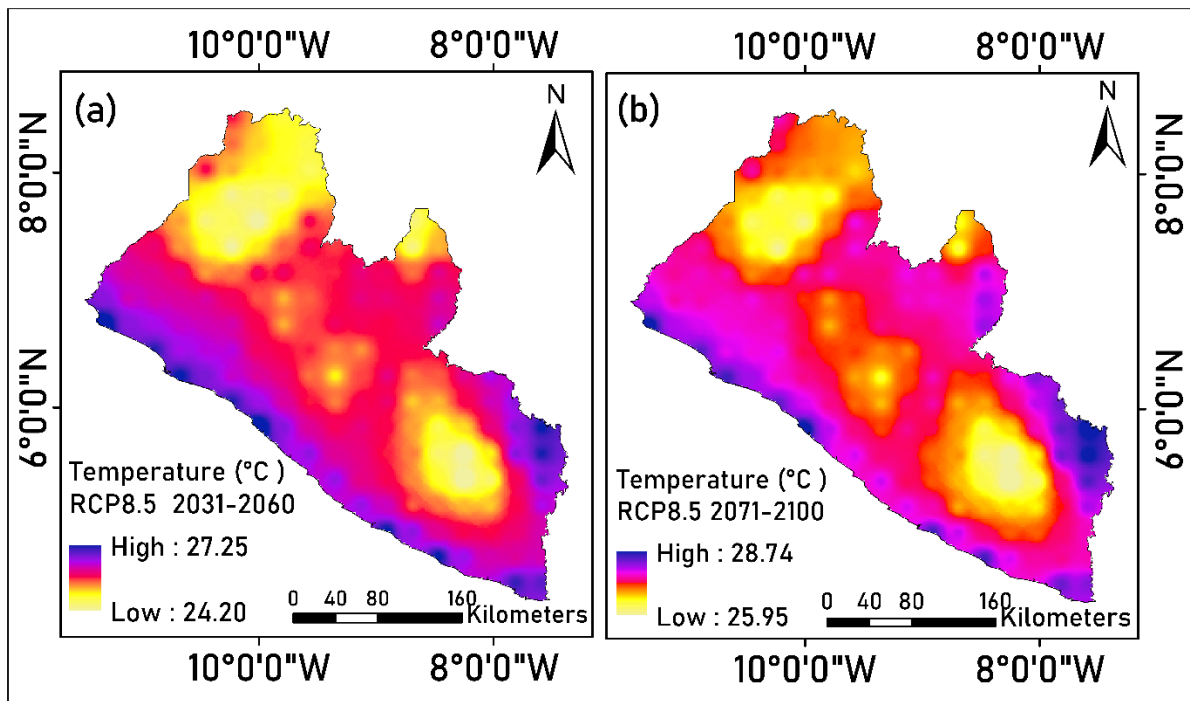
#### Appendix 3.2. Supplementary Materials (Figure S2. Liberia climate classes based on Köppen classification).



Appendix 3.3. Supplementary Materials (Figure S3. Climate Projection of Precipitation).



Appendix 3.4. Supplementary Materials (Figure S4. Climate projection of temperature).



## Appendix 4. Proof of Acceptance/Publication

### Appendix 4.1. Certificate of publication of the article titled: Effect of Climate Variability on Rice Production in Liberia.



## Appendix 4.2. Letter of acceptance of the manuscript titled: Geospatial Multi-Criteria Decision-Making for Land Suitability Analysis for Rice Cultivation in Liberia.



Jone Lucas Medja Ussalu <jonemedja@gmail.com>

### Discover Sustainability: Decision on your manuscript

Discover Sustainability <discoverSustainability@springernature.com>

Mon, Apr 6, 2026  
at 8:02 AM

To: jonemedja@gmail.com

Ref: Submission ID 1accfb43-b809-42fe-9a7c-d7e2fae2fd13

Dear Dr Ussalu,

Re: "Geospatial Multi-Criteria Decision-Making for Land Suitability Analysis for Rice Cultivation in Liberia"

We're delighted to let you know your manuscript has now been accepted for publication in Discover Sustainability.

#### Licence to Publish and Article Processing Charge

As the corresponding author of an accepted manuscript, your next steps will be to complete an Open Access Licence to publish on behalf of all authors, confirm your institutional affiliation, and arrange payment of your article-processing charge (APC). You will receive an email with more information in the coming days.

#### Checking the proofs

Prior to publication, our production team will also check the format of your manuscript to ensure that it conforms to the standards of the journal. They will be in touch shortly to request any necessary changes, or to confirm that none are needed.

Once we've prepared your paper for publication, you will receive a PDF proof. At this stage, for the main text, only errors that have been introduced during the production process, or those that directly compromise the scientific integrity of the paper, may be corrected.

Please make sure that only one author communicates with us and that only one set of corrections is returned. As the corresponding (or nominated) author, you are responsible for the accuracy of all content, including spelling of names and current affiliations.

To ensure prompt publication, your proofs should be returned within two working days.

#### Publication policies

Acceptance of your manuscript is conditional on all authors agreeing to our publication policies at: <https://link.springer.com/brands/discover/policies>

Once again, thank you for choosing Discover Sustainability, and we look forward to publishing your article.

Kind regards,

Preshit Priolkar  
Editorial Board Member

<https://mail.google.com/mail/u/0/?ik=9705994f93&view=pt&search=all&permmsgid=msg-f:1861699899366995760&simpl=msg-f:1861699899366995760> 1/2