UNIVERSITY OF CAPE COAST

RECLASSIFICATION OF GHANA'S AGRO-ECOLOGICAL ZONES

NATHANIEL BIMPONG

2023

UNIVERSITY OF CAPE COAST

RECLASSIFICATION OF GHANA'S AGRO-ECOLOGICAL ZONES

BY

BIMPONG NATHANIEL

Thesis Submitted to the Department of Geography and Regional Planning of the Faculty of Social Sciences, University of Cape Coast, in partial fulfilment of the requirements for the award of Doctor of Philosophy Degree in Geography

OCTOBER, 2023

DECLARATION

Candidate's Declaration

I hereby declare that this thesis is the result of my own original research and that no part of it has been presented for another degree or certification in this University or elsewhere.

Candidate's Signature: ………………………… Date: ……….................

Name: Bimpong Nathaniel

Supervisor's Declaration

I hereby declare that the preparation and presentation of the thesis were supervised in accordance with the guidelines on dissertation laid down by the University of Cape Coast.

Supervisor's Signature: ……………….. Date: ……….....................

Name: Professor Benjamin Kofi Nyarko

Co-Supervisor's Signature: ……………….. Date: ……….................

Name: Professor Nana Ama Browne Klutse

ABSTRACT

Agro-ecological zones (AEZs) are essential for guiding agricultural planning and economic investments. In Ghana, climate change and evolving land use patterns have significantly altered key agro-climatic parameters such as mean annual rainfall (MAR), length of growing period (LGP), and land use and land cover (LULC) characteristics. This study analyzed long-term agro-climatic datasets (1991–2020) and LULC maps (2001, 2010, 2019, and 2021) using standardization, trend analysis, correlation, ANOVA, and Geographic Information System (GIS) tools. Key findings revealed significant reductions in LGP thresholds ($P < 0.05$) across most zones except the Sudan Savanna AEZ. MAR trends varied, with notable decreases in the Tropical Humid, Deciduous Forest, and Transitional AEZs, while the Coastal Savanna AEZ experienced a slight increase. Intra-zonal variations deviated from old FAO AEZs, as shown by anomalies at stations like Saltpond, Yendi, and Sewhi Bekwai. LULC analysis showed substantial forest (-22%) and agricultural land (-27%) losses, alongside increases in built-up areas (+31%), barren land (+27%), and rangeland (+7%). A GIS-based Multi-Criteria Analytical Hierarchy Process (AHP) reclassified AEZs into six zones (A–F), revealing significant spatial shifts. Notable changes included the southward expansion of the SSAEZ into the Guinea Savanna AEZ, a southwest shift in THAEZ and DFAEZ, and cross-migrations in CSAEZ and GSAEZ boundaries. These findings highlight the challenges posed by AEZ changes to crop suitability, land productivity, and agro-economic investments in Ghana's agrarian economy. Regular decadal AEZ revisions using GIS and remote sensing are recommended to support sustainable agricultural planning and resource management.

KEY WORDS

Agro-climatic parameters

Agro-climatic zones

Agro-ecological zones

Agro-edaphic parameters

Analytical Hierarchy Process

Climate change and variability

Intra-zonal heterogeneity

Inter-zonal shifts

Geographical information system

Land use and land cover

Multi-criteria analysis

Reclassification

Remote sensing

ACKNOWLEDGEMENT

I thank my father God in heaven for this great achievement. My warmest appreciation goes my supervisors, Prof. Nana Ama Browne Klutse and Prof, Benjamin Kofi Nyarko for their paternalistic supervisory roles throughout this PhD thesis preparation. Their training, guidance and constructive criticisms are invaluable in this journey. I also express my deepest gratitude to my wife, Diana Dwoumfour and my children for their sacrifices. Again, my sincere appreciation goes to Dr Regina Amoako-Sekyi, Mr. David Adukpo, Prof. P. K Acheampong, Prof. Samuel N. Dadzie, Dr. Gerald Atampugre and Prof. Collins Adjei-Mensah

Additionally, I am proud of my PhD-mentors, Dr. Francis Nkrumah, Dr. Patrick Essien, Dr. Paa Kwesi Quagraine; I cannot forget the tuition of Mr. Juati, Mr. Augustine Arthur of the Department of Meteorology and Atmospheric Science, UCC. The technical supports by Dr. Richard Adade, Barnabas Nfankabi and Martin Paku were very helpful.

Similarly, I extend my gratitude to Dr. Tanu (immediate past Director General), Mrs. Francisca Amartey (Director, Agro-climate and Research Unit), Mrs Elikem (Director, Data Processing Unit), and Master Stephen Amanskwa of GMET. The data supply and training they gave me have yielded good results.

I will always acknowledge the living contributions of my parents Eld. & Mrs. I. K. Marfo, and my father-guardian, Eld. Kyei Baffour Akomeah (all of blessed memory). I am deeply grateful for their love, counsels and sacrifices that laid a firm academic foundation for my PhD endeavours. My siblings, Yaw Boakye, Akua Serwaa, Afia Asantewaa, Akua Marfowa, Akua Koramah, Adu Tutu, Kwabena Marfo and Yaa Boakyewaa acknowledged deeply. Finally, I salute my friends, Kofi Sammy, Yaw Okra, Kwame Essel and Kwadwo Amoah.

DEDICATION

To my wonderful wife, Ohemaa Ama Dwoumfour and adorable children: Kofi Appiah Bimpong, Afia Nhyira Bimpong, Akosua Nimo Bimpong, Akosua Marfowaa Bimpong and Ama Aniwaa Bimpong

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS

Acronyms	**Descriptions**
ACZs	Agro-climatic zones
AEZs	Agro-ecological zones
ASTER	Advanced space-borne thermal emission and reflection Radiometer
CLT-Zmean	Current long-term zonal mean
CMIP-6	Coupled modelled inter-comparison project (phase-6)
CSAEZ	Coastal savanna agro-ecological zone
DEM	Digital elevation model
DFAEZ	Deciduous forest agro-ecological zone
EOS	End of growing season
EPA	Environmental protection agency
ET_0/ PET	Reference evapotranspiration/ potential evapotranspiration
FAO	Food and agriculture organization
FAO-Zmean	Food and agriculture organization zonal means for old AEZs
GAEZ	Global agro-ecological zoning methodology
GAEZ-LGP	Global agro-ecological zoning - length of growing period
GIS	Geographic information system
GSAEZ	Guinea savanna agro-ecological zone
IIASA	International institute for applied systems analysis
IPCC	Intergovernmental panel on climate change
LT-Zmean	Long-term zonal mean differences
LULC	Land use and land cover
MAJ-LGP	Major season length of growing period

MAR	Mean annual rainfall
MIN-LGP	Minor season length of growing period
MC-AHP	Multi-criteria analytical hierarchical process
MODIS	Moderate resolution imaging spectro-radiometer
RDAYS	Rain days
RS	Remote sensing
SOS	Start of the growing season
SSAEZ	Sudan savanna agro-ecological zone
ST-USDA	United state department of agriculture soil taxonomy
THAEZ	Tropical humid forest agro-ecological zone
TMEAN	Mean temperature
WRB-RSGs	World reference base soil resources
Zone A	Aligning old Tropical humid agro-ecological zone
Zone B	Aligning old Deciduous Forest agro-ecological zone
Zone C	Aligning old Transitional agro-ecological zone
Zone D	Aligning old Guinea savanna agro-ecological zone
Zone E	Aligning old Sudan savannah agro-ecological zone
Zone F	Aligning old Coastal Sudan agro-ecological zone

CHAPTER ONE

INTRODUCTION

Climate change and land use changes have significant impacts on agro-ecological zones (AEZs) worldwide. These changes affect relevant agro-climatic and agro-edaphic parameters such as length of growing season, mean temperature, rainfall patterns, and land cover characteristics. As a result, many existing national AEZs may no longer accurately reflect current agro-ecological conditions. To ensure alignment between national agricultural production and economic investments with the current agro-ecological conditions, regular revisions of outdated AEZs are necessary. In a climate-sensitive agrarian economy like Ghana, reclassifying the existing old Food and Agriculture Organization (FAO) AEZs is crucial for sustainable agriculture development, food security, and enhancing the adaptive capacity of farming communities. Reclassified AEZs play a crucial role in evidence-based agriculture and economic investment planning, proactive climate adaptations design, and in sustainable land use management. The rest of Chapter One present the background to the study, problem statement, research objectives, research questions, significance of the study, delimitations and limitations, and the organization of the study.

1.1 Background to the Study

Agro-ecological zones are land resource mapping units defined in terms of homogenous climate, topography, soil and land cover, and having a specific range of potentials and constraints for land use (Food and Agriculture Organisation, FAO, 1996; Fischer, Shah, Tubiello, & van Velhuizen, 2005). Since their inception, AEZs have been central in planning agriculture and economic investments (FAO, 1978; Fischer *et al*; International Institute for Applied Systems Analysis [IIASA] & FAO, 2012). By categorizing land areas based on their homogenous agro-climatic and agro-edaphic characteristics, stakeholders are empowered to make informed decisions regarding choices on suitable cultivars, farming systems or techniques, and on sustainable land management practices (Barber & Shaxson, 1996; Fischer *et al*.; IIASA & FAO; Mudzengi, Simba, Murwendo & Mdlongwa, 2013; Waugh, 1995).

According to Chikodzi, Zinhiva, Simba, and Murwendo (2013), Corbett (1996), FAO (1996), and Fischer, Shah, van Velthuizen, and Nachtergaele (2006), AEZs have been recognized valuable tools not only in assisting for the effective identification of suitable land uses for agriculture purposes; but also, serve as a guide to monitoring and management of scarce land resources, as well as in preserving essential ecosystem services (Anand & Sen, 2000; Corbett,1996; IIASA & FAO, 2012). By providing insights into land characteristics, their constraints and potentials, the adoption of and the reliance on robust AEZs for decision-making in land use ensures environmental sustainability and economically viable agricultural production (Chikodzi *et al*.; FAO; Fischer *et al*., 2005; Mudzengi *et al*., 2013).

Defined by climate-sensitive parameters, over the past two decades, studies by Adnan *et al.* (2017), Fischer *et al*. (2005), IIASA & FAO (2012), Intergovernmental Panel on Climate Change [IPCC], (2019), Kurukulasuriya and Mendelsohn (2008), Lin, Liu, Ma, and Zhang (2013), and Mugandani, Wuta, Makarau, and Chipindu (2012), have emphasized the vulnerability of global, sub-regional, and the national AEZs to climate change and variability.

The impacts of Climate change such as erratic rainfall patterns, rising temperatures, increased evapotranspiration, and rising sea levels, have altered agro-edaphic characteristics of existing AEZs, including the soil conditions, land cover, and vegetation patterns (Chikodzi *et al*, 2013; FAO, 2010; IPCC, 2014; Mugandani *et al*.). Additionally, extremes climatic events such as heavy storms, floods, and droughts have led to the disruption and LGPs of forest lands leading to land users abandoning arable lands (Adnan et al., 2017; FAO; IPCC, Westerling, 2016; United Nations Environmental Programme, UNEP, 2006).

The disruptions observed in agro-climatic and agro-edaphic conditions of AEZs have had direct impacts on agricultural productivity and series of economic activity, food security and achievement of sustainable development goals (FAO, 2020; Godfray, Beddington, & Crute, 2010; IPCC, 2019; Rosegrant & Cline, 2003). Reports of the FAO (2010), Fischer *et al*, (2006), IPCC (2013) and Chikodzi *et al.* (2013) indicate that the changes in AEZs have destabilized agricultural production, and contributed to changing the economic investments structure of many agrarian economies. The changes in AEZs have manifested through the shifting suitability and productivity patterns in known AEZs to supporting specific crop types or land uses; disruptions in crop calendars, failure in agricultural planning, reduction in agricultural production, and significant LGPs of investments (Bierbaum, Fay & Ross-Larson, 2010; Boko *et al*., 2007; Fischer *et al*., 2006; Jayathilaka, Soni, Perret, Jayasuriya & Salokhe 2012; Lane & Jarvis, 2007; Mugandani *et al*., 2012).

Consequently, agrarian economies that rely on existing, but outdated national AEZs are faced with significant challenges in achieving socio-economic development due to possible failures in agricultural production and economic investments, and disruption of livelihoods (FAO, 2009; Godfray *et* *al*., 2010; World Bank, WB, 2010). By relying on obsolete AEZs, existing extension services may prove to be a disservice to farmers in planning agricultural production sustainably. Similarly, governments and economic investors may be misguided by misrepresentative research findings that have been based on these obsolete AEZs. Thus, studies by Chikodzi *et al*. (2013), Jayathilaka *et al*. (2012) and Mugandani *et al*. (2012), recommend that governments and research institutions in developing agrarian economies should prioritize current research; focusing more on revising existing national and district AEZs in the wake of climate change and land use/ land cover changes.

The vulnerability and need for revision of national AEZs go beyond the impacts of climate change and variability. In many developing economies, existing AEZs suffer from significant methodological limitations, including inadequate use of agro-climatic and agro-edaphic parameters (Fischer *et al*., 2006; IIASA & FAO, 2012; Lin *et al*., 2013; Paladini, 2017; Patel, Endang, Kumar & Pande, 2005; Quiroz *et al*., 2001; Steven, 1993; Venkateswaralu *et al*., 1996). Moreover, insufficient utilization of geospatial datasets and limited application of remote sensing and GIS technologies have further hindered the accuracy and dynamism of AEZ assessments (Paladini, Patel *et al*; van Wart *et al*, 2013). Consequently, many AEZs lack the robustness to inform agricultural production and investment decisions due to their reliance on few parameters and subjective approaches (Patel, 2003; Quiroz *et al*., Steven).

Reclassifying existing AEZs to align with current climatic and ecological conditions, and incorporating technological advancements in AEZ is crucial (Chikodzi *et al*., 2013; Fischer *et al*., 2009; Patel *et al*., 2005; Steven, 1993). It has the potential to address existing challenges, and ensure accurate and up-to-date AEZ methodology for planning agriculture and economic investments sustainably (IIASA & FAO, 2012; Fischer *et al;* Chikodzi *et al*.)

1.2 Statement of the Problem

Ghana's national AEZs were primarily defined by climate to reflect the country's natural vegetation and soil characteristics (Environmental Protection Agency, EPA, 2008; FAO, 2005). The FAO agro-ecological classification delineated Ghana into six categorical AEZs, namely the Sudan Savanna (SSAEZ), Guinea Savanna (GSAEZ), Transitional (TRAEZ), Deciduous Forest (DFAEZ), Tropical Humid Forest (THAEZ), and the Coastal Savanna (CSAEZ). The FAO relied mainly on key agro-climatic parameters, specifically mean annual rainfall (MAR) and the length of growing period (LGP), which are significant environmental variables influencing agricultural production and agro-investments (Aquastat-Ghana; FAO; MoFA, 2016; Yamba et al., 2023).

Recent studies (Amekudzi *et al*., 2015; Asare-Nuamaha & Botchway, 2019; CIAT, 2014; Baah, 2018; Baidu, *et al*., 2017; Gbangou *et al*., 2020; Codjoe & Owusu, 2009; Bessah et al., 2022; Stanturf *et al*., 2011; Yamba *et al.*, 2023), indicate that climate change and variability, as well as changes in land use patterns have impacted the agro-climatic and agro-edaphic conditions of Ghana's AEZs. The results from Yamba *et al*., reveal that there have been significant changes in the number, sizes, and orientations of the existing agro-climatic zones delineated by the GMet in the 1960s. This suggests potential shifts in the unique MAR and LGP thresholds of the existing FAO classification, and the known land use and land cover characteristics of the six national AEZs.

Numerous studies highlight the vulnerability of existing AEZs, and emphasize the need for reclassification or regular revisions of national AEZs in various regions. In China, Lin *et al*. (2013) observed substantial decadal shifts in the geographical boundaries of AEZs under future climate change, indicating the necessity for regular decadal revisions. Across Africa, Kurukulasuriya and Mendelsohn (2008) found the continent's warming to be shifting AEZs and crop land sizes, with agricultural productivity, food security, cropland net revenue, and livelihood sustainability. Likewise, Mugandani *et al*. (2012) conducted a study in Zimbabwe and, based on observed changes in rainfall patterns, and incorporating additional edaphic datasets, they reclassified the national AEZs to keep them with tandem with the current climate change and variability.

In Ghana, the existing studies on climate change have not directly and sufficiently analyzed how historical climate change and rapid land use and land cover changes impact, or has impacted the prevailing national AEZs. Specifically, there has been no direct analysis of changes in the old established FAO thresholds set for the MAR and LGP parameters used to define the six current AEZs. Despite the growing interest in, and capacity of modern GIS, remote sensing and advanced statistical tools for regular acquisition, processing and analysis of complex geo-spatial, agro-edaphic and agro-climatic datasets in AEZ, Ghana's national AEZs, like many others in developing agrarian economies, still remain unrevised (Fischer *et al*., 2006; Patel *et al*., 2005)

Currently, there is no study shedding direct and adequate information on the potential shifting patterns in Ghana's old FAO AEZs. This gap is concerning as it neglects the potential vulnerability, spatial distribution and possible boundary shifts in existing AEZs despite the potential impacts of climate and land use changes. The lack of comprehensive revision of AEZs is unacceptable, as this suggests an unwarranted assumption of stability in these dynamic zones.

The present study addresses these gaps by reviewing the existing FAO-zonal thresholds for MAR and LGP (major and minor seasons) defined for the six AEZs, and also analyze LULC changes across Ghana in the wake of changes in climate and land use patterns. By utilizing geospatial techniques, this study aims to comprehensively integrate essential agro-climatic and agro-edaphic parameters (including PET, RDAYS, RH, elevation, slope, aspect, soil, and LULC), to create a new, up-dated, and robust national AEZs; for sustainable planning of agricultural production, economic investments, and ensure reliable scientific research in Ghana.

1.3 Purpose of the Study

The main objective is to reclassify Ghana's AEZs to align with current changes in climate and LULC patterns using a dynamic AEZ model (methodology).

1.3.1 Specific objectives

Specifically, the present study seeks to:

1. Analyze the spatio-temporal changes in the key agro-climatic variables of Ghana's AEZs from 1991 to 2020.
2. Analyze the spatio-temporal changes in LULC of Ghana for 2001, 2010, and 2019.
3. Develop a new map showing current spatial distribution of Ghana's AEZs.

1.4 Research Questions

To achieve the specific objectives of the study, the following questions were asked:

1. What are the spatio-temporal changes in the key agro-climatic variables

of Ghana's AEZs from 1991 to 2020?

2. How has the pattern of LULC changed in Ghana for 2001, 2010, and 2019?
3. How have the current changes in climate and LULC pattern affected the spatial patterns in the existing FAO AEZs classification in Ghana?

1.5 Research Hypotheses

In this study, six hypotheses were tested to establish or otherwise any significant differences and/ or changes in the unique thresholds for key agro-climatic parameters across all six old FAO AEZs, in relation to achieving the specific objective one (1), at an alpha value of 0.05. These are as follows:

1. Hypothesis:

   H_0: The CLT-Zmeans for MAR have not significantly changed from the existing FAO-Zmeans.

   Ha: The CLT-Zmeans for MAR have significantly changed from the existing FAO-Zmeans

2. Hypothesis:

   H_0: The CLT-Zmeans for LGP have not significantly changed from the existing FAO-Zmeans.

   Ha: The CLT-Zmeans for LGP have significantly changed from the existing FAO-Zmeans

3. Hypothesis:

   H_0: There is no significant intra-zonal difference in the stations from the standardized FAO-Zmeans for MAR across the AEZs.

   Ha: There is significant intra-zonal difference in the stations from the standardized FAO-Zmeans for MAR across the AEZs

4. Hypothesis:

H_0: There is no significant intra-zonal difference in the stations from the standardized FAO-Zmeans for LGP across the AEZs.

Ha: There is significant intra-zonal difference in the stations from the standardized FAO-Zmeans for LGP across the AEZs

5. Hypothesis:

H_0: There is no significant inter-decadal and long-term variability and shifts in the standardized FAO-Zmeans for MAR across the AEZs

Ha: There is significant inter-decadal and long-term variability and shifts in the standardized FAO-Zmeans for MAR across the AEZs

6. Hypothesis:

H_0: There is no significant inter-decadal and long-term variability and shifts in the standardized FAO-Zmeans for LGP across the AEZs

Ha: There is significant inter-decadal and long-term variability and shifts in the standardized FAO-Zmeans for LGP across the AEZs

1.6 Significance of the Study

This study is highly important for stakeholders in Ghana, including the government, researchers, investors, and farmers. First of all, the study will produce a new national AEZs map of Ghana that aligns with current climatic and LULC patterns. This will also provide government agencies, NGOs, researchers, and other stakeholders with accurate information for decision-making on agricultural production and sustainable resource utilization. Again, the study will contribute to national and global discussions on climate change and its impact on AEZs, agriculture, and land uses. It will enhance understanding of the dynamics of climate change and its implications for agricultural production, economic development planning, and land use suitability assessment. Furthermore, the development of a dynamic climate change-induced AEZ model will serve as an adaptation strategy to climate change. It will enhance the resilience of Ghana's agriculture and protect agro-economic investments from the impacts of climate change. Similarly, the study will provide valuable insights into the historical changes in agro-climatic conditions and LULC patterns. This understanding will shed light on the direct impacts and interactions of climate change on AEZs, agriculture, and economic investments. Moreover, by highlighting methodological challenges affecting existing AEZs in Ghana, the study will guide future researchers in the field. It will provide insights into essential parameters, geospatial techniques (such as GIS and RS), and statistical tools required for delineating micro-scale and robust AEZs. The results of micro-scale AEZs will support site-specific land use planning for suitable crop cultivation. This will facilitate the exchange of research findings, promote technology transfer, and enhance extension services among farmers and stakeholders within similar local areas, regions, or AEZs. The study will explicitly reveal the spatial variability within different local areas or regions of Ghana, considering climatic, topographic, soil, and land use characteristics. This understanding is crucial for effective AEZ delineation and management.

1.7 Delimitations

In this study, the focus is on reclassifying Ghana's existing FAO agro-ecological zones to reflect current climate change and land use; land cover (LULC) impacts. The study uses quantitative datasets, including agro-climatic variables like temperature, rainfall, and sunshine hours, as well as spatial data such as digital elevation models (DEM) and soil maps. The climatic data covers the period from 1991 to 2020, allowing for an analysis of long-term trends. Data from the 22 synoptic stations of the Ghana Meteorological Agency are used to ensure reliable and representative information. The study also examines LULC changes in 2001, 2010, and 2019 to understand the relationship with agro-ecological zones. Remote sensing techniques are employed, DEM data from Advanced Spaceborne Thermal Emission Radiometer (ASTER), a-30 m historical LULC imagery from Moderate Resolution Imaging Spectroradiometer (MODIS), and a baseline current LULC image of Ghana from Sentinel-2 satellites. The goal is to develop an updated and improved AEZ classification system that informs agricultural planning and contributes to sustainable development in Ghana's agricultural sector.

1.8 Limitations

Due to time and financial constraints, this current study focused on reclassifying Ghana's AEZs primarily using quantitative data. The ground climate data is obtained from 22 synoptic stations, which provide reliable and representative data despite their uneven distribution. However, there are limitations in accessing historical remotely sensed geospatial dataset for LULC analysis from sources like MODIS-16 and Sentinel-2 satellites, affecting data availability for certain periods and variables. This influenced the temporal scope of data collection, but significantly falling in the new climatological widow. To overcome these limitations, various approaches were implemented. The study utilizes a GIS process-based spline interpolation model to enhance the spatial representation of the climate data points from the synoptic stations. Statistical interpolation (spline technique) was also applied to correct and validate the station climate datasets with the CMIP-6 ensemble climate datasets for further analysis. Similarly, the last-observation-carried-forward (LOCF) approach was used to correct data gaps and to ensure a more complete dataset.

By leveraging available data and employing appropriate techniques, the study aims to build robust datasets that could support efficient AEZ methodology to ensure effective agro-ecological reclassification of Ghana. This will provide valuable insights for stakeholders' decision-making.

1.8 Organization of the Study

The study is organized into nine chapters. Chapter One serves as the introduction, providing the study's background, problem statement, research objectives, questions, hypotheses significance, delimitations, limitations, definition of terms, and an overview of the study's organization. Chapter Two is a theoretical and conceptual review, discussing the theory of classification, existing classification theories/systems/models related to AEZs, spatial characteristics of AEZs, differences between AEZs and ACZs, AEZ procedural elements, and a summary. Similarly, Chapter Three focuses on the empirical review, covering the historical evolution of AEZs and AEZ methodology, applications, challenges with current methods, the role of GIS and RS, factors influencing AEZs, impacts of climate change on AEZs and agriculture, the need for revisions, and the reclassification of Ghana's AEZs. Chapter Four provides a profile of the study area, Ghana, including its geographical location, climate, vegetation, soils, existing AEZs, and the nature of agriculture. In Chapter Five, we present the research methodology, highlighting the research philosophy, design, approach, data sources, data collection procedures, data processing and analysis, a flow chart outlining the methodology for reclassifying Ghana's

AEZs, ethical considerations, limitations, and a summary of the chapter. Chapter Six focuses on the presentation of results, detailing spatio-temporal changes in agro-climatic parameters within Ghana's AEZs. Chapter Seven presents evidence of changes in the national AEZs by analyzing spatio-temporal changes in land use and land cover (LULC) in Ghana. Similarly, Chapter Eight provides a description of the newly reclassified AEZs in Ghana, comparing them to the existing FAO AEZs. It discusses spatial distribution, intra-zonal variability, and inter-zonal shifts as direct impacts of climate change and LULC changes. Finally, Chapter Nine summarizes the study, emphasizing major findings, conclusions, recommendations, and suggestions for further research.

CHAPTER TWO

THEORETICAL AND CONCEPTUAL REVIEW ON AEZ AND AEZS

2.1 Introduction

In this chapter, there is a review of relevant classification theories and key concepts related to AEZ and AEZs. It begins with the theory of classification and then delves into popular classification theories, systems, and models that underpin the science and practice of AEZ, as well as development of AEZs methodology. These include Linnaean taxonomy, soil taxonomy, topography classification, land use and land cover classifications, and climatic classifications such as Koeppen's, Thornthwaite and Mather's, and Papadakis methods. The Global Agro-ecological Zoning Length of Growing Period (GAEZ-LGP) model by FAO and IIASA is also explored. Similarly, key concepts such as AEZs, AEZ, spatial characteristics of AEZs (or AEZ), and the distinctions between AEZs and agro-climatic zones (ACZs) are explained. Additionally, there is a review of procedural elements of AEZ, followed by a chapter summary. This review aims to provide a firm context for the reclassification of Ghana's AEZs by expounding the underlying theories, concepts, essential parameters, data sources, tools and techniques relevant for developing a robust AEZ methodology to achieve the main purpose of this study.

2.2 Theory of Classification

Classification underpins scientific theory and practice, enabling our understanding of the complex social and physical world. The term, classification, means both the act of classifying and the outcome, known as taxonomy. Classifying involves sorting objects or phenomena based on shared characteristics, properties, or criteria. It also involves creating, modifying, and organizing categories within a system over time (FAO, 2016; Simon, 2014; Waugh, 1995).The theory of classification refers to the study of the fundamental principles, philosophies, methods, and criteria that govern how things are categorized and organized. It is a foundational cognitive process, methodological framework, and organizational tool that supports research across various fields, including biology, library science, data science, earth sciences, agriculture, and agro-ecology (FAO, 2016; IIASA & FAO, 2012; Simon, 2014; Waugh, 1995). They assist scientists, researchers, and professionals in making sense of complex phenomena and information by systematically categorizing both social and physical entities into clear and distinct groups, facilitating communication, comparisons, and analysis (FAO; Simon, 2014; Waugh).

Studies (FAO, 2016; Simon, 2014; Waugh, 1995); van Wart *et al*., 2013) have described classification theories as purpose-specific, independent of scale and data, hierarchically structured, subjective, flexible, and subject to significant changes over time with the emergence of new knowledge, data, and technology. Therefore, in this study, it is reasonable to update Ghana's outdated AEZs (taxonomy) to align with changes in climate, alterations in land use patterns, and the availability of improved geospatial datasets using modern RS and GIS techniques, as well as other advanced statistical tools and testing methods.

2.3 Existing Classification Theories/ Systems/ Schemes relevant to AEZ

Agro-ecological zoning is based on the theory of classification (FAO, 1996; Fischer *et al*., 2005; Paladini, 2017; Waugh, 1995). The popular classification theories, systems and models that underpin AEZ and development of AEZ methodology include biological taxonomy, soil taxonomy, topography classification, land-use and land-cover classification, and climatic classifications (including Koeppen's, Thornthwaite and Mather's, and Papadakis'). Moreover, the FAO and IIASA's GAEZ-LGP model plays a significant role (Chikodzi *et al*, 2013; FAO, 2016; Fischer *et al*.; IIASA & FAO, 2012; Patel *et al*., 2005; van Wart *et al.*, 2013).

2.3.1 Linnaean taxonomy

Linnaeus' taxonomy, developed in 1735, has played a crucial role in scientific classifications (Simon, 2014). This biological taxonomy was built on Aristotle's scientific taxonomy and Ranganathan's faceted classification, grouping organisms based on shared physical traits, and into distinct facets. This system categorized life from great kingdoms down to specific species. Later, with Darwin's ideas and fossil discoveries, Linnaeus' static system was modified to reflect the evolution of life in the evolutionary taxonomy. Modern cladistics taxonomy also shifted the focus towards common ancestry and speciation events. In the context of AEZ, these biological theories provide frameworks for categorizing biophysical resources into homogeneous land resource units, called AEZs. Significantly, the continuous modifications observed in the traditional taxonomy set a good context for reclassification and regular revisions of AEZs, including Ghana's AEZs.

2.3.2 Soil classification

Soil classification is key to Agro-Ecological Zoning (AEZ), providing a framework to categorize soils based on physical, chemical, and biological properties. This process helps create soil maps essential for identifying suitable areas for crop production and land management (Lee, Kim, Son, & Kim, 2022; IIASA & FAO, 2012). Recent advances in land evaluation, land suitability mapping, and in AEZ, emphasize two widely adopted soil schemes: the United State Department of Agriculture Soil Taxonomy (USDA, ST) and the FAO World Reference Base (WRB) (Adjei-Gyapong & Asiamah, 2002; IIASA & FAO, 2012; Lee et al., 2022). The study reviewed and correlated these modern systems with the local Interim Ghana Soil Classification System, Ghana's Great Soil Groups (Brammer, 1962), to ensure consistency and universal relevance.

In many developing agrarian economies, local soil classification systems face issues, including limited data, outdated technology, reliance on expert judgment, and inconsistencies with international standards (Lee et al., 2022). Ghana's Great Soil Groups share these challenges, highlighting the need for a universal soil classification system. Such a system would improve communication among soil scientists, support the transfer of soil-based technologies, and enhance AEZ frameworks. These advancements are crucial for increasing agricultural productivity, sustaining food production, and conserving the environment (Adjei-Gyapong & Asiamah, 2002; ISSS/ISRIC/FAO, 1998). Aligning local Great Soil Groups with global systems can enhance scientific communication, support technology transfer, and strengthen AEZ frameworks, boosting productivity and conserving the environment (ISSS/ISRIC/FAO, 1998; Adjei-Gyapong & Asiamah, 2002).

Soil taxonomy (ST)

The ST scheme classifies soils into 12 hierarchical orders, using diagnostic horizons and specific soil characteristics as its foundation. This system is highly precise and globally recognized, making it ideal for scientific research and international comparisons. However, its reliance on diagnostic horizons can limit its adaptability to regional variations, particularly in developing countries. Table 2.1 presents a description of ST 12 soil orders.

Table 2.1. USDA Soil Taxonomy 12 Orders and their descriptions

Soil Orders	Descriptions
Entisols	Recent soils with minimal development
Inceptisols	Slightly developed soils with some horizons
Andisols	Soils formed from volcanic materials
Aridisols	Dry soils with limited moisture
Mollisols	Grassland soils with deep, fertile horizons
Spodosols	Acidic soils with organic horizons
Ultisols	Highly weathered soils with clay-rich horizons
Oxisols	Highly weathered, tropical soils with oxides
Gelisols	Soils with permafrost near the surface
Histosols	Organic soils like peat and muck
Vertisols	Soils with significant shrink-swell properties
Alfisols	Soils with clay-enriched horizons

Source: Soil Survey Staff (2022)

World reference base (WRB) soil groups system

The FAO WRB model classifies soils into 32 Reference Soil Groups (RSGs) based on diagnostic horizons, soil environments, and formation processes. It is more Flexible than the ST system and accommodates diverse agro-ecological contexts, making it valuable for global applications. However, its complexity may pose challenges for less experienced users. (Bationo *et al.*, 2006; IIASA & FAO; IUSS Working Group WRB, 2022). Table 2.2, is a description of the 32 RSGs.

Table 2.2: FAO WRB 32 Reference Soil Groups

RSGs	Descriptions
Albeluvisols	Soils with clay illuviation and a clay-rich horizon, found in various climates.
Alisols	Soils with clay illuviation in subsurface horizons, typically found in forested regions.
Anthrosols	Soils influenced or modified by human activities, such as agriculture or urban development.
Arenosols	Sandy soils found in arid or semi-arid regions, often with low natural fertility.
Calcisols	Soils with calcium carbonate accumulation, typically found in arid or semi-arid regions.
Cambisols	Soils with horizon differentiation and moderate weathering, found in various climates.
Chernozems	Soils with dark, fertile horizons, often found in grassland regions with rich organic matter.
Cryosols	Soils influenced by permafrost and cold temperatures, often found in polar regions.
Durisols	Soils with a hardened horizon, typically found in arid or semi-arid regions.
Ferralsols	Soils with a high content of iron and aluminum oxides, commonly found in tropical regions.
Fluvisols	Soils formed from alluvial deposits, often found in floodplains and riverbanks.
Gleysols	Soils with waterlogging and gleying processes, found in wetland and poorly drained areas.
Gypsisols	Soils with gypsum accumulation, typically found in arid or semi-arid regions.
Histosols	Organic soils like peat and muck, often found in wetland and swampy areas.
Kastanozems	Soils with chestnut-colored horizons, typically found in temperate regions.
Kryosols	Soils influenced by cold temperatures and permafrost, often found in polar regions.
Leptosols	Shallow soils with limited development in various climates.
Lixisols	Soils with clay enrichment in subsurface horizons, often found in tropical and subtropical regions.
Luvisols	Soils with horizon differentiation and good fertility, typically found in temperate regions.
Nitisols	Soils with a high content of clay and good fertility, often found in tropical regions.
Phaeozems	Soils with dark, humus-rich horizons, typically found in temperate regions.
Planosols	Soils with a hard, compacted horizon and poor drainage, found in various climates.
Plinthosols	Soils with ironstone nodules or crusts, often found in seasonally waterlogged areas.
Podzols	Soils with an acidic, leached horizon, often found in forested regions with coniferous trees.
Regosols	Soils with limited horizon development and often rocky, found in various climates.
Solonchaks	Soils with salt accumulation, often found in arid regions with saline conditions.
Solonetz	Soils with sodium accumulation, typically found in arid regions with alkaline conditions.
Stagnosols	Soils with stagnic properties and poor drainage, found in wetland and waterlogged areas.
Umbrisols	Soils with a dark-colored horizon enriched in organic matter, found in various climates.
Vertisols	Soils with significant shrink-swell properties due to clay content, found in various climates.

Source: IUSS Working Group WRB (2022)

Interim Ghana soil classification system

he Great Soil Groups by Brammer (1962)) relied mainly on local soil formation factors, overemphasized few individual soil properties, and is tailored to Ghana's agricultural and environmental contexts. While straightforward and practical for national use, it lacks the precision and international compatibility of the ST and WRB systems. Table 2.3 show a description of the 10 Great soils.

Table 2.3. Ghana's Great Soil Groups (Brammer, 1962)

Great soils	Nature	Distribution	Suitability
Forest Ochrosols	Weathered, less acidic, moderately fertile soils	Deciduous and forest-savanna transition zone	Cocoa, coffee, cassava, yams, and plantains
Forest Oxysols	Deeply weathered, highly leached, acidic, slightly fertile	South-west high rainfall forest	Oil palm, coconut, para-rubber, coffee, and cassava
Savannah Ochrosols	Well-drained soils with moderate fertility	Semiarid Guinea and Sudan areas	Yams, maize, sorghum, millet, cowpea, cassava and groundnuts
Tropical Black Clays	High clay content, prone to swelling and cracking	Coastal savanna zone (Accra-Ho-Keta plains)	Rice, sugar cane, vegetables, and cotton
Groundwater Laterites	High iron and aluminum content, hardpan formation in subsurface, poor internal drainage	Interior savanna of Ghana	Maize, sorghum, millet, cowpea groundnuts, and bambara nuts, rice
Tropical Grey Earths	Develop over acidic gneiss and schist, has a thick sodium saturated clay pan show cracking.	Accra-Ho-Keta plains (coastal savanna)	Grazing fields
Lithosols	Shallow or brashy soils on steep slopes, or on hard rock and ironpan	Forest and savanna vegetation	Grazing fields
Alluviosols	Fertile soils formed by river deposits, rich in organic matter	River valleys (Volta, Pra, and Ankobra)	Rice, sugarcane, vegetables, and fruits.
Gleisols	Waterlogged soils with high clay content	Wetland areas and Coastal lagoons	Rice, taro, sugar cane, vegetables, grazing
Regosols	Deep sands, highly acid, and poor in nutrients	Along the coast of Ghana	Coconut plantations

Correlation of Ghana's Great Soil Groups with WRB and UT systems

The effort to address inherent inconsistencies in Great Soil Groups, aligns local soils with global standards, enhances the applicability of the local soil scheme, and thus makes them more useful for AEZs, Ghana's Great Soil Groups was correlated with the ST and WRB systems. This standardization enhances soil mapping, improves communication, and supports better agricultural planning and sustainability. Table 2.4 shows the summary of Soil

System Correlation.

Table 2.4: Soil correlation of the Ghana Great Soil Groups with WRB and UT Systems

Great Soil Groups (Brammer, 1962)	WRB Reference Soils (ISSS/ISRIC/FAO, 1998)	USDA Taxonomy (1992)
Forest Oxysols	Ferralsols/Acrisols	Oxisols
Forest Ochrosols	Acrisols/Alisols/Lixisols/ Nitisols /Ferralsols/ Plinthosols	Ultisols/Alfisols
Savanna Ochrosols	Lixisols/Luvisols/Plinthosols	Alfisols
Groundwater Laterites	Plinthosols/Planosols	Plinthic Alfisols/ Planosols
Tropical Black Clays	Vertisols (Gleysols)	Vertisols
Tropical Grey Earths	Solonetz/Planosols	Natrustalfs/Planosols
Lithosols	Leptosols/Plinthosols	Entisols
Rubrisols	Lixisols/Luvisols/Plinthosols	Alfisols
Alluviosols	Fluvisols	Entisols
Gleisols	Gleysols/Cambisols	Aquic Entisols/ Histosols
Sodium Vleisols	Solonchaks	Salorthids
Regosols	Regosols/Arenosols	Entisols

Sources: Senayah et al., 1998; Soil Survey Staff, 2022; WRB, 1998)

In the current reclassification of Ghana's AEZs, the standardized and correlated Ghana's Interim Great Soils with the WRB system ensured alignment with global standards. Given WRB system's flexibility and use of modern data, its correlation was ideal for creating a strong AEZ framework, supporting better land management and agricultural planning. The correlated-WRB soil units were reclassified into four classes based on FAO's management categories.

2.3.3 Land use and land cover classifications

In AEZ, classifying LULC is crucial (IIASA & FAO, 2012; Patel *et al.*, 2005). It involves categorizing areas based on of human activities (land use) and what naturally or artificially covers the land (land cover). LULC classification helps to explore, map, and monitor landscapes and understand over time how environmental hazards or human actions alter AEZs (Anderson *et al.*, 1976; FAO, 2016).

Two widely adopted LULC classification system are the Anderson 1976 classification and FAO land cover classification system (LCCS). FAO LCCS is a global framework for monitoring LULC changes related to agriculture and forestry. It has been used in various LULC database, projects, and classifications such as FAOSTAT, AFRICOVER, System of Environmental Economic Accounting Central Framework (SEEA-CF) LULC classification, World Census of Agriculture Land Use Classification (WCALUC), and the Good Practice Guidance for Land Use, Land-Use Change and Forestry (GPG-LULUCF) (FAO, 2010b; IPCC, 2003; UN *et al*., 2014).

Similarly, Anderson's classification offers a detailed system tailored to regional and national needs. It is also used in projects like the USGS LULC project, supporting applications like RS and GIS tools (Anderson et al.). In the context of AEZ, especially in reclassifying Ghana's AEZs, these classification projects and systems' objectives, principles, and methods offer direct insight into analyzing past LULC changes and their impact on national AEZs. With RS and GIS techniques, LULC data can readily be accessed, reclassified, and integrated with other agro-ecological parameters such as soil, topography, and climate to define homogenous AEZs (Musher *et al*., 2016; UN *et al*., 2014).

Table 2.5 present a description of common LULC classes found in the Anderson 1976 and FAO LCCS systems.

Table 2.5. Common LULC classes in Anderson 1976 and FAO LCC Systems

Anderson	**FAO LCCS**	**Descriptions of LULC**
Urban / Built-up	Urban	Areas of human habitation, infrastructure, (cities and towns).
Agriculture	Agriculture	Areas for farming and agricultural activities
Rangeland	Forestry	Areas with vegetation for grazing by livestock or wildlife. In FAO, this class includes forestry land.
Forest	Other wooded land	Areas dominated by trees and woody vegetation.
Water bodies	Water bodies	Natural or artificial rivers, lakes etc.
Wetlands	Wetlands	Areas with waterlogged soils
Barren Land	Barren Land	Areas with limited/ no vegetation
Miscellaneous	Miscellaneous	Built-up areas and unknown LULC

Sources: Adapted from Anderson et al (1976) and FAO (2016)

2.3.4 Topography classification

Topography classification involves categorizing landscapes based on their elevation, slope, and aspect. This helps to understand the physical conditions of land areas and how they affect natural processes in AEZs (FAO, 1991). In the context of AEZ, land use mapping, and landscape monitoring, two commonly used topographic models are the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) DEM and the Shuttle Radar Topographic Mission (SRTM3) DEM (Fischer *et al.*, 2006; Subyani, Qari & Matsah, 2010; Mendas 2010). These models divide land areas into elevation zones like lowland, upland, or mountainous regions, providing insights into how altitude influences climate, vegetation, land use, and AEZs. Slope classification creates groups such as gentle rolling, moderately steep, or steep slopes, which are vital for land use planning, soil erosion assessment, and slope stability analysis. Aspect classification defines the direction a slope faces (North, South, East, West), impacting solar radiation exposure, vegetation distribution, and microclimates FAO, 2005; Fischer *et al*.)

2.3.5 Climatic Classification

Climatic classification, a method of categorizing and describing climate patterns based on factors such as temperature, precipitation, and other variables, is central to AEZ (FAO, 2005; Fischer et al., 2006; Waugh, 1995) It provides the methodological framework to delineate agro-climatic zones, which are crucial in determining the climatic conditions of different geographic regions, and helps to analyze the suitability of places for specific agricultural activities. In this study, the notable climatic classifications reviewed include Koeppen's Climatic Classification (1928), Thornthwaite and Mather's Climatic Classification (1955), Papadakis Climatic Classification (1970), and the Global Agro-Ecological Zoning Length of Growing Period (GAEZ-LGP) (FAO & IIASA, 2012).

Koeppen's climatic classification model (1928)

The Koeppen's classification model is widely used to classify climates for agriculture and land use (FAO, 2005; van Wart *et al*., 2013; Paladini; 2017). It categorizes climates based on temperature and precipitation, revealing a link between climate and vegetation. The model divides the world into five major climatic zones: A (Tropical), B (Dry), C (Warm Temperate), D (Cold Snow Forest), and E (Cold), with further subdivisions by the seasons of dryness using four small letters: f (as no dry season), m (as Monsoon/ short dry), w (as winter dry season), and s (as summer dry) (Fischer *et al*., 1996; Paladini; van Wart *et al*., Waugh, 1995)

The strength of the Koeppen's model is its simplicity and wide applicability. It helps to understand and compare climates globally, aiding in agro-climatic zoning. It also helps assess land suitability for agriculture by considering specific vegetation types associated with different climatic zones. (Fischer *et al*., 1996; IIASA & FAO, 2012; van Wart *et al*., 2013). However, the model has limitations. It focuses mainly on temperature and precipitation, overlooking other important factors like solar radiation, wind patterns, and humidity just to mention but few, which significantly influence agriculture. It also has a coarse spatial resolution, which may not capture fine-scale datasets such as soil characteristics, topography, and land use are necessary for a holistic analysis of agriculture systems. (Fischer *et al*., 1996; Paladini; van Wart *et al*.). Figure 2.1 illustrates Koeppen's climatic classification map (model).

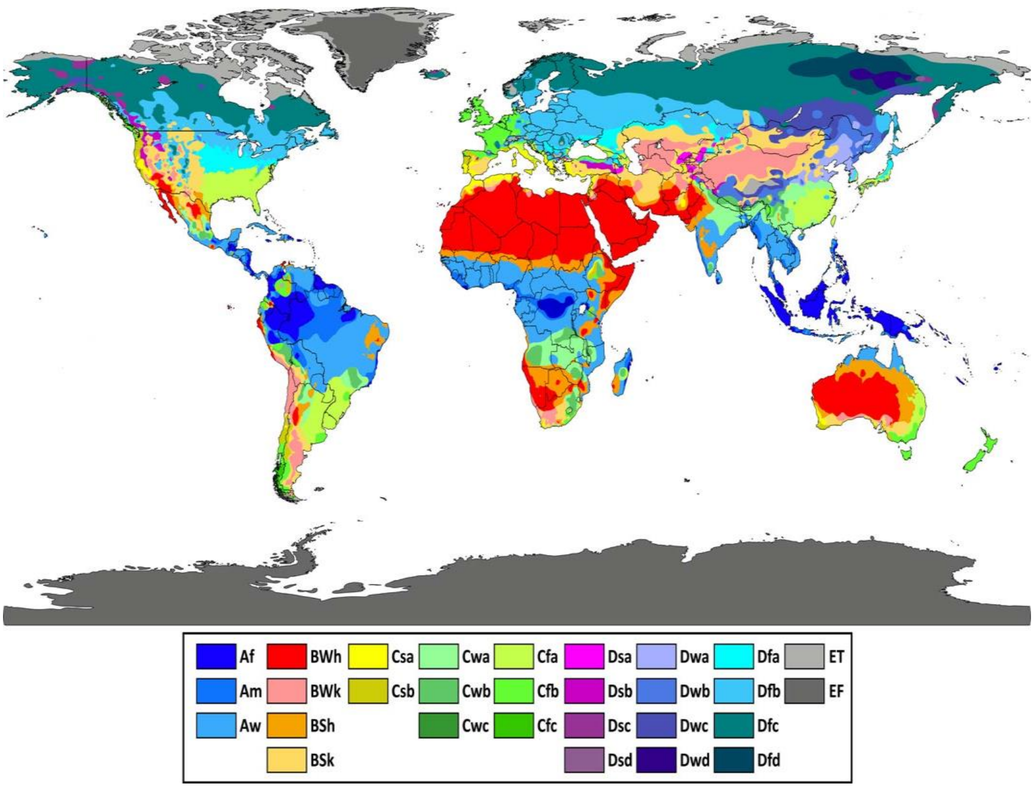

Figure 2.1: Koeppen's Climatic Classification model (1928)

***Thornthwaite climate classification model* (1931/ 48)**

Thornthwaite' s climate classification model (Figure 2.2), developed in 1931 and revised in 1948, categorizes climates into distinct zones based on vegetation characteristics (Carter, 1954). The model utilizes the precipitation effectiveness index (P/E) to delineate five humidity-vegetation zones: rainforest (>127), forest (64–127), grassland (32–63), steppe (16–31), and desert (<16). The five humidity-vegetation zones provide a framework for assessing the potential of rainforests, forests, grasslands, steppes, and deserts in different climatic regions (FAO, 2005).

Again, in 1948, Thornthwaite enhanced his classification system by introducing the soil moisture index and the index of potential evapotranspiration (PE) to improve agro-climatic classification for agriculture land use. These parameters, evapotranspiration and soil moisture, play a crucial role in agricultural planning and land use decisions. These parameters helped in assessing the water availability and demand for plant growth, providing valuable information for AEZ.

However, it is worthy to note in any agro-ecological zoning that, relying solely on climatic parameters, including evapotranspiration and soil moisture, may overlook other significant factors such as solar radiation, wind patterns, length of growing season, and relative humidity that impact agriculture. Thornthwaite’s vegetation-climate associative approach employed can be considered as a simplified method for defining robust AEZs (FAO, 2005; Fischer *et al*., 2005).

Figure 2.2 shows Thornwaite's Climatic (moisture) Classification Map

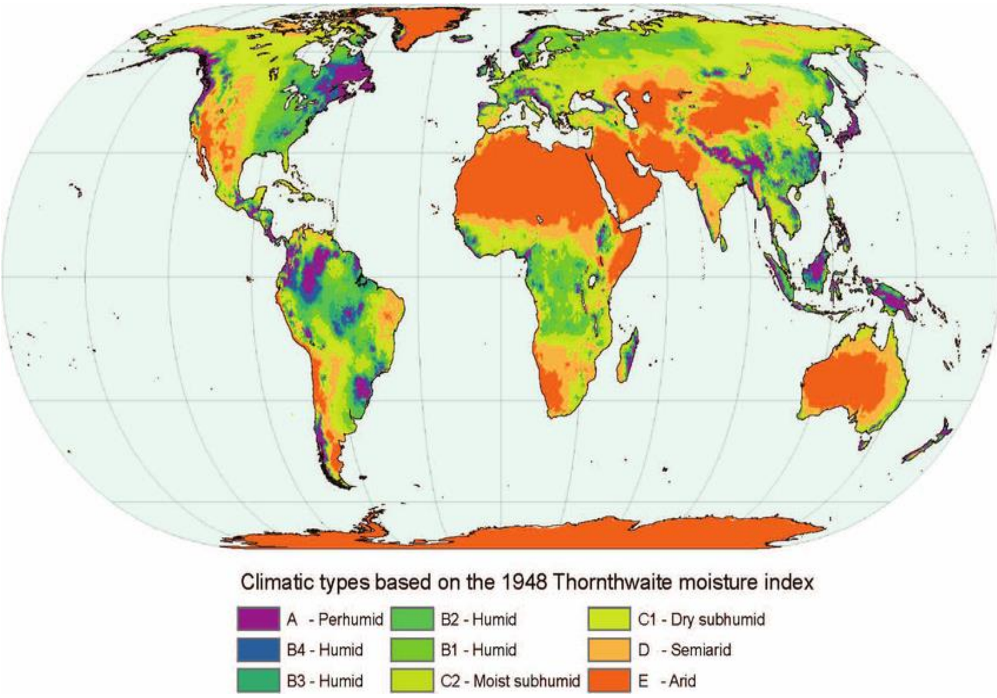

Figure 2.2: Thornwaite's Climatic (Moisture Index) Classification Map

Global agro-ecological zonation-LGP model (IIASA* & FAO, *2012)

The Global Agro-ecological Zoning (GAEZ) methodology, developed by the FAO (1978) and improved upon by the IIASA and FAO (2012) as the GAEZ-LGP model, is widely used for land suitability delineation and agricultural development planning. The model utilizes the Length of Growing Period (LGP), soil features, elevation, land use, and land cover to classify the world into distinct Agro-ecological Zones (AEZs). The AEZs are categorized into four zones based on LGP duration (<60 days, 60-179 days, 180-270 days, and >270 days) for agricultural purposes and land use evaluations. The model integrates Geographic Information System (GIS), and Remote Sensing (RS) techniques, allowing for broad data analysis in AEZ.

While LGP provides valuable information about the duration of favorable conditions for plant growth, it does not capture other important climatic and environmental factors that influence agricultural productivity.

Relying solely on LGP may overlook variations in temperature, precipitation patterns, solar radiation, wind patterns, and humidity, which can significantly impact crop suitability and agricultural practices (Mugandani *et al*., 2012; Lin *et al*., 2013).

A comprehensive understanding of agro-ecological systems requires considering a broader range of factors such as soil characteristics, topography, water availability, and other agro-climatic variables. These additional parameters can provide crucial insights into the suitability of specific crops, irrigation needs, and management practices. Neglecting these factors by relying solely on LGP may lead to inadequate assessments of land suitability and suboptimal agricultural planning. The GAEZ-LGP map of the world is shown in Figure 2.3.

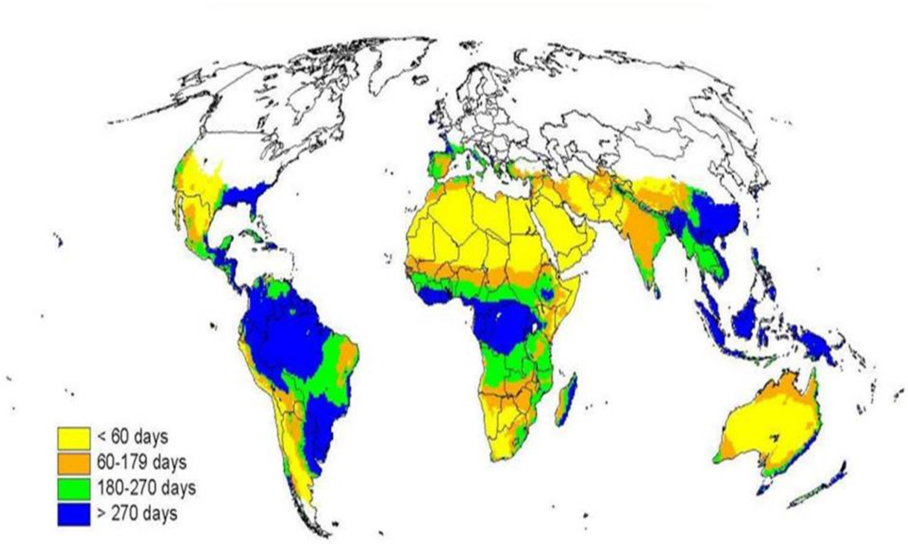

Figure 2.3: The GAEZ-LGP Model (FAO & IIASA, 2012)

Papadakis' Climatic Classification (1970)

The Papadakis' climatic classification model, developed in 1970 offers an innovative approach to agro-ecological zoning by considering the ecological classification of crops and their agricultural potentialities (Paladini, 2017). The model focuses on specific minimum, maximum, or extreme values of climatic elements to accurately define winter severity, summer heat, and moisture regime, which directly impact crop development. Papadakis' model classifies the world into 10 main climate groups: Tropical, Tierra Fria, Desert, Subtropical, Pampean, Mediterranean, Marine, Humid Continental, Steppe, and Polar Alpine (Paladini).

Though a climatic classification, it highlights the ecological requirements of different crops, and provides insights into the agricultural potential and limitations of a region. In AEZ, it is useful to interpreting the possible LUTs of an area. It has demonstrated satisfactory results in agro-climatic and agro-ecological zoning of the world, as noted by Papadakis (1970), FAO (1996), Cariño *et al*. (2021). However, it is important to acknowledge that while Papadakis' model offers valuable insights, it still faces challenges capturing the complexity and variability of agro-ecological conditions at finer scales and comprehensively.

2.4 Agro-ecological Zones and Agro-ecological Zoning

Etymologically, AEZs can be understood by examining sub-concepts such as agro, ecology, agro-ecology, and agro-ecosystem (FAO, 1996; Fischer *et al*., 2006; Martin & Sauerborn, 2013). The term "agro" refers to fields, farms, soil, or crop production, highlighting its connection to agriculture, the primary human activity (FAO, 2005; Martin & Sauerborn). "Ecology" describes the interrelationships among animals and plants within a specific social and environmental context, forming an integrated system (Agroecosystem Health Project, 1996; Martin & Sauerborn).

"Agro-ecology" is the study of how organisms interact in environments transformed through agriculture for crop or livestock production (Dalgaard, Hutchings & Porter 2003; Wezel, 2009). The fundamental unit of analysis is the "agro-ecosystem", which encompasses the living and non-living components of an agricultural system and their interactions (Agroecosystem Health Project, 1996; Martin & Sauerborn). To this end, the development of AEZ methodology was conceived to rightly delineate homogenous areas (AEZs) based on their agro-climatic and ecological factors to understand the interactions of organisms within unique agricultural environments, to provide insights into the sustainability and productivity of farming systems, and to enable sustainable planning in agriculture.

According to the report of FAO (1978) and IIASA and FAO (2012), agro-ecological zones are land mapping units defined in terms of homogenous climate, soil, landform, and land cover characteristics, and having a specific range of potentials and constraints determining their potential and limitations for land use. Agro-ecological zoning is the methodology involving systematic division of an area of land into smaller units, which have similar characteristics related to land suitability, potential production, and environmental impact (FAO, 1996; Williams, 2008). Over the past 3 decades, AEZs have been widely used as a unit of analysis in studies on crop suitability, agro-economic development, and land-use planning worldwide (Atehnkeng, *et al*., 2008; FAO, 1978/96; FAO & IIASA; Fischer *et al*., 2006). In this study, AEZs are construed as geographical regions that show considerable homogeneity in agro-climatic and agro-edaphic characteristics, having the potential to guide agriculture and economic investments, and a dynamic decision system subject to changes.

2.5 Distinction between Agro-ecological Zones and Agro-climatic Zones

Many studies on crop suitability assessment and in land-use planning for agricultural production have often adopted either AEZs or ACZ as units of analysis (Fischer *et al*., 2006; FAO & IIASA, 2012; Van Wart *et al*., 2013). However related they could be perceived, the AEZs and ACZs are fundamentally different in terms of their spatial characteristics and; or scope of essential parameters usage (FAO, 1984; FAO & IIASA). One challenge with AEZs classification is the potential confusion and interchangeability of the two concepts, which can lead to misguidance in the design and application of the distinct methodologies of the AEZs and ACZs.

In data scarce regions of the world, and in the remote past when there were low applications of geospatial techniques, the AEZs and ACZs were misconceived as same AEZs (Steven, 1993; Paladini, 2017; Patel *et al.,* 2005; van Wart *et al*, 2013). Though, seemingly subtle, the occurrence of this set wrong premises, and have contributed severally to the existing methodological limitations in many global and national agro-ecological classification. The poor contextualization has led to research misguidances and citation inconsistencies, where different researchers cite wrongly climatic classification for agro-climatic, ecological for agro-ecological and ACZs for AEZs, or interchangeably (Amekudzi, 2015; Aryee et al., 2018; Bessa et al., 2022; EPA, 2008; FAO & IIASA, 2012; Mugandani *et al*., 2012).

Studies such as FAO (1996), IIASA and FAO (2012), and Patel *et al*. (2005) indicate that the AEZs and ACZs can be distinguished by properly setting reasonable boundaries for their definitions, essential parameters, and their zoning methodology. From the FAO report (1983), the agro-climatic zones

(ACZs) are units of land defined mainly in terms of a combination of climatic variables, which are suitable for a specific range of crops or agricultural productions. The ACZ methodology thus involves using meteorological variables to delineate an area into distinct climatic units to influence agricultural production (FAO, 1996; IIASA & FAO). The meteorological variables include direct daily temperature (minimum and maximum temperature) and rainfall, or some derived parameters such as the length of growing season or period (LGP/LGP), aridity index, growing degree days (GDD), and the reference evapotranspiration (ET_0) (Chikodzi *et al*; IIASA & FAO, 2012; Koeppen, 1928; Papadakis, 1970; Thornthwaite, 1931,1948).

According to the FAO (1996), IIASA and FAO (2012), and van Wart *et al*. (2013), the spatial characteristics of agro-climatic zones are limited to climatic variables, or significantly in their combination with either soils or vegetation characteristics. From the reports of Chikodzi *et al*. (2013), FAO (1996), Fischer *et al*. (2005), and Fischer, Makowski, and Granat (1999), many existing ACZs used relatively few and simple climatic variables; and thus, applied manual or simple statistical methods to delineate the ACZs for planning agricultural productions and land-use (Fischer *et al*.; van Wart *et al*; Yamba *et al*, 2023).

In contrast, the AEZs can be construed as any land resource mapping units defined in terms of homogenous climate, soil, landform/ topography, and land cover, and having a specific range of potentials and constraints for land use (FAO, 1996; Fischer *et al*., 2005). Similarly, the methodology of dividing an area of land into smaller units, which have similar characteristics related to land suitability, potential production, and environmental impact is known as agro-ecological zoning or zonation (AEZ) (FAO, 1996; Williams, 2008). From a theoretical, conceptual and practical perspectives or analysis, the AEZs and ACZs are fundamentally different in the following ways:

First, the AEZs are geographical land resource mapping units having homogeneous climate, soil, landform, vegetation, land use and land cover; while the ACZs are climatic land units defined mainly by temperature, rainfall or their combination with or without soil or vegetation (FAO, 1996; IIASA & FAO, 2012; Williams, 2008). In this way, the scope of essential parameters of the AEZs can be wide-ranging, consisting of both agro-climatic and agro-edaphic parameters such as land use and land cover, soil, and topography. ACZs are comparatively limited to only the meteorological or climatic variables (FAO; Mücher *et al*., 2016; Steven, 1993; Williams).

Again, the classification of AEZs requires complex and remote geospatial agro-edaphic datasets such as DEM, LULC, and soil imageries are usually accessed from remote satellite sensors (Fischer *et al*, 2006; IIASA & FAO, 2012; Paladini, 2017; Patel *et al.*, 2005). Given their nature and sources, AEZs and AEZ methodology require the applications of satellite remote sensing and geographic information systems techniques (Fischer *et al*., 2005; IIASA & FAO; Quiroz *et al*., 2001; Steven, 1993). However, the delineation of agro-climatic zones can be done by a simple manual overlay of isolines representing either rainfall, temperature, potential evapotranspiration or their combination, and superimposed on an existing soil map or vegetation map of an area, region or country (Williams, 2008; Steven).

It is evident from the comparative analysis of the two phenomena that, relative to the wider scope of parameters used in AEZ, a well delineated AEZs are more robust in guiding agricultural developmental planning, in evaluation of potential suitability of crops and land uses, and in assessing climate change impacts on agriculture and on series of economic activities more comprehensively (FAO, 1996; FAO & IIASA, 2012; Martin & Sauerborn, 2013). Thus, in this study, the distinctions drawn between AEZs and ACZs have the potential to correctly guide the right choice agro-climatic and agro-edaphic. Similarly, the selection of appropriate sources for data, and the data processing and analysis techniques would also be adequately informed. Ultimately, the contrast drawn will ensure the design and application of a robust and dynamic AEZ methodology for reclassifying the existing AEZs of Ghana under the impacts of current climate change and changes in the country's land use and land cover patterns.

2.6 Spatial Characteristics/ Essential Elements of AEZs

According to the FAO (2005), Paladini (2017), and Mücher *et al*. (2016), the spatial characteristics of AEZs encompass a range of biophysical factors that contribute to the uniqueness of AEZs, or create differences among them. These factors include crucial elements such as climate, topography, soil composition, vegetation, land cover, and geographical location. These characteristics are conspicuously featured in the definitions and descriptions of AEZs and AEZ, revealing the essential parameters and tools for the development of robust AEZ methodology (FAO & IIASA, 2012; Fischer *et al*., 2006; Mudzengi *et al*, 2013).

2.6.1 Key agro-climatic parameters

In AEZ, the essential agro-climatic or hydro-climatic parameters primarily include direct temperature and rainfall (FAO, 1996; Koeppen's 1928;

Thornthwaite and Mather's, 1955), as well as key derived agro-climatic parameters, including like length of growing season (LGP), evapotranspiration (ET_0), and the thermal regime (TR) defined using accumulated mean or degree days (GDD) . These parameters are essential for guiding decisions on what, where, when, and how to sustainably manage agricultural production and land use in different AEZs (FAO, 2005; FAO & IIASA, 2012; Fischer *et al*, 2005; Mugandani, *et al*., 2012).

Length of the growing period/ season (LGP/LGP)

The length of the growing season (LGP) is a vital aspect of agricultural planning and is a key component of the AEZ methodology (FAO, 1995; FAO & IIASA, 2012; Merugu, Shashikala, & Mathyam, 2015). The LGP can be understood as the duration of the rainy season, from the beginning to the end of significant rainfall (Merugu et al., 2015). However, it also encompasses the continuous period when conditions like precipitation, soil moisture, and temperature are suitable for crop growth in a broader sense (FAO & IIASA; Fischer et al., 2005). Estimating LGP involves using a water balance model that compares rainfall (P) with Penman evapotranspiration (PET) and considers factors like soil moisture reserve or available water holding capacity (AWC) (FAO, 2005; FAO & IIASA, 2012).

In reclassifying Ghana's AEZs, LGP helps in assessing drought risks, understand climate changes, and plan agriculture effectively by considering rainfall patterns and moisture availability (FAO, 1996; Fischer *et al*., 2005).

Thermal regime (TR)

The thermal regime (TR) is another relevant factor in determining agro-climatic zones (ACZs) (Chikodzi *et al.*, 2013; FAO, 2005; IIASA &, FAO, 2012). It defines the temperature characteristics of AEZs and represents the amount of heat available for plant growth during the growing period. The thermal regime can be described using mean temperatures or accumulated degree days (GDD) based on specific temperature thresholds for different crops and climatic zones. For national-scale studies in tropical and sub-tropical climates, standard temperature intervals of 2.5 °C, 5 °C, and 10 °C are commonly used to calculate accumulated GDD (FAO, 2005; Fischer *et al*., FAO & IIASA, 2012). In this study, the 5°C threshold was applied to calculate GDD using the equation:

$$GDD_5 = \sum_{i=1}^{365} [\![\left(\frac{Td_{i,min}+Td_{i,max}}{2}]\!] - Td_{base5}\right) \quad \text{Eqn. (2.1)}$$

where, Tdi,min and Tdi,max are the daily maximum and minimum temperatures respectively; Tdbase (5 °C) is the base temperature.

Potential evapotranspiration (PET)

Considering PET (ET_0) is crucial in AEZ. It measures plant water needs under ideal conditions. By comparing PET with actual rainfall and soil moisture, assess of water availability for crops is done, helping with irrigation, crop selection, and efficient water use. The Penman-Monteith equation, widely used since 1948, estimates reference evapotranspiration (ET_0) considering factors like net radiation, soil heat flux, air temperature, and wind speed (Allen, Pereira, Raes, & Smith, 1998; Chikodzi *et al.*, 2013; FAO, 2005; FAO & IIASA, 2012; Fischer *et al*., 1996)

$$ET_O = 0.408 * \Delta * (Rn - G) + \gamma * \left(\frac{900}{I + 273}\right) * u2 * \frac{es - ea}{\Delta + \gamma * (1 + 0.34 * u2)} \quad \text{Eqn}(\mathbf{2.2})$$

where: ET_O is the reference evapotranspiration (mm/day); Δ is the slope of the saturation vapor pressure-temperature curve (kPa/ °C); Rn is the net radiation at the crop surface (MJ/m^2/day); G is the soil heat flux density (MJ/m^2/day); γ is the psychrometric constant (kPa/°C); T is the mean air temperature at 2 meters height (°C); u2 is the wind speed at 2 meters height (m/s); es is the saturation vapor pressure (kPa); ea is the actual vapor pressure (kPa).

2.6.2 Key agro-edaphic parameters

Agro-edaphic parameters constitute a specific range of conditions aside climate in the environment necessary for the growth and development of crops (FAO, 1996). In modern agro-ecological classifications, the agro-edaphic parameters considered essential include soil types, topography, and land cover features. These factors greatly influence agricultural practices, crop suitability, and agricultural land management options (Chikodzi *et al.*, 2013; FAO, 2005; FAO & IIASA, 2012; Fischer *et al*, 2006; Mugandani, *et al*., 2012).

Soil mapping unit

In AEZ, soil units represent different types of soil in an area, with characteristics like pH, texture, organic matter, and depth affecting plant growth (Chikodzi *et al.*, FAO, 2005; Fischer *et al*, 2005). These units indicate the main soil type and any minor types, which can be single or multiple without a clear pattern. Soil types are essential for understanding agricultural conditions, requiring specific management practices and crop selection for optimal productivity. In AEZ, "soil unit," "land unit," and "soil mapping unit" have distinct meanings. "Land" refers to the earth's surface, including soil, climate, and other elements, while "soil" specifically focuses on land properties excluding climate. A "soil unit" is a specific soil type with its unique characteristics, whereas a "soil mapping unit" represents a combination of soil features (FAO, 1996; Fischer et al., 2006; IIASA & FAO, 2012).

Topography

Topography is a key parameter in AEZ, describing areas based on their slope, elevation, aspects, and relief zones (FAO, 1996). It helps assess land potential and limitations for agriculture and other land uses, guiding land management decisions (FAO, Fischer et al., 2006). The elevation aspect describes height above sea level, slope indicates steepness, and aspects show direction (FAO). In the current reclassification of Ghana's AEZs, topography has been considered as a relevant factor, influencing where and how of agricultural activities and land use planning in Ghana (FAO, 1991; IIASA & FAO 2012)

Land use and land cover

Another very important variable considered for AEZ is LULC imageries (FAO, 1996; Fischer et al., 2006). Land use refers to human activities on (Anderson, 1976; Mücher *et al*., 2016; Sleeter et al., 2018). LULC classes include forests, woodlands, grasslands, arable land and built-up etc. Studying past LULC helps understand climate change and human impacts on AEZs (FAO, 2016; IPCC. (2003; Paladini, 2017; UNDP, 2015). Changes in LULC monitor agro-ecological resource degradation and guide ecological conservation (FAO, 2010; Fischer et al., 2005; Paladini). In this study, apart from the analysis for changes in agro-climatic parameters, Ghana's historical LULC will be analyzed to assess their spatio-temporal changes and impacts on AEZs in the wake of climate change.

2.7 Key AEZ procedural elements

The process of AEZ and/ or development of efficient AEZ methodology involves 3 key procedural steps (FAO, 2005). These steps include land resource inventory, description of land utilization types and crop adaptability, and classifying land suitability (FAO, 1996; IIASA & FAO, 2012; Fischer *et al.*, 2006). These procedures have been carefully reviewed below to serve as a later guide for developing a robust AEZ methodology for the reclassification of Ghana's AEZs.

2.7.1 Land resource inventory

This step involves collecting, compiling, processing, and storing crucial data on agro-climatic parameters (like rainfall, temperature, PET, RH, and LGP) and key agro-edaphic variables such as topography, soil, and land cover, used for AEZ development (Fischer et al., 2006; FAO & IIASA, 2012; Mugandani et al., 2012). Besides traditional ground-based data collection, modern geospatial technologies like satellite remote sensing offer easy access to diverse remote geospatial datasets, enhancing AEZ analysis (FAO & IIASA; Fischer et al.; Pater et al., 2005; Steve, 1993). In this study, creating a comprehensive land resource inventory using geospatial techniques is vital for developing a dynamic AEZ methodology in Ghana, ensuring easy revisions of AEZs to address ongoing climate and LULC changes.

2.7.2 Land utilization types and crop adaptability

Similarly, in ensuring a robust AEZ, describing different land utilization types (LUTs) suitable for the study areas is crucial step (FAO, 2005; Fischer et al., 2006). According to IIASA and FAO (2012), LUTs encompass how land is used for various purposes, including products, inputs, operations, and socioeconomic aspects of land production. Identifying relevant LUTs is a necessary step before conducting land suitability evaluations (FAO; FAO & IIASA). This information guides the inclusion of relevant parameters in the land resource inventory and helps define classification algorithms and thresholds for agro-ecological characterization (FAO, 1996; Fischer et al.; FAO & IIASA, 2012; Mugandani *et al*., 2012)

2.7.3 Land suitability evaluation/ classification

In AEZ, land suitability evaluation is a crucial process (FAO, 2005). It involves assessing the suitability of land units based on their compatibility with the agro-climatic and soil conditions required for specific crops. To estimate crop productivity potential, the maximum attainable total biomass index is frequently employed (FAO, 1996; Fischer et al., 2006). Factors like the area's radiation and temperature characteristics, crop photosynthetic efficiency, and the proportion of net biomass converted into economically useful yield determine the potential maximum crop yield (FAO & IIASA, 2012; van Wart *et al.*, 2013).

2.8 Chapter Summary

Chapter Two reviewed the theory of classification, focusing on popular theories on soils, LULC, topography, and climate for AEZ. Key concepts, AEZs, ACZ etc., were defined to set proper context for reclassification of Ghana’s AEZs.

CHAPTER THREE

EMPIRICAL REVIEW ON AEZ AND AEZS METHODOLOGY

3.1 Introduction

This chapter reviews previous works on AEZs from different regions, emphasizing national AEZ studies and focusing on Ghana. It explores the evolution, descriptions, applications, and methodological challenges of AEZ and the AEZs methodology. Additionally, it examines existing agro-ecological zoning methods, the use of Geographical Information System and Remote Sensing in AEZ, and the impacts of climate change on global AEZs. The review also addresses the effects of changes in AEZs on agriculture and land uses, the revision of national AEZs, and presents the Flow model for agro-ecological zoning in Ghana.

This review is relevant for identifying gaps in the literature, noting essential parameters, data, tools, methods, and techniques for the new classification of Ghana's AEZs. It contributes to drawing conclusions and recommendations to enhance agricultural sector planning, promote economic development, and address climate change impacts on AEZs and natural land resources supporting agriculture and economic activities in Ghana. There is the presentation of a chapter summary.

3.2 Evolution of AEZ and the AEZs Methodology

Land classification for agricultural purposes has a long history, dating back to ancient times (Waugh, 1995; FAO, 1996). Studies by Paladini, FAO and Van Wart *et al.*, list early bio-climatic classifications (Köppen, 1828, Thornthwaite, 1931/ 48; Seljaninov, 1966/ 72 and Papadakis, 1970) as laying the foundation for agro-climatic zoning methodologies (FAO, 2005; Paladini, 2017; Van Wart *et al*., 2013). The methodology of these classification involved simple overlaying of isolines representing rainfall, temperature, potential evapotranspiration, or their combinations onto soil and vegetation maps to delineate zones for different economic uses (Barber, 1996; Steven, 1993; Vankakewalaru, 1996). Agro-climatic zoning became a widely used approach for categorizing and analyzing farming systems and land productivity (FAO, 2005; Fischer *et al*., 2006; Patel *et al.,* 2005).

The early agro-climatic classification systems recognized climate as a crucial factor in assessing natural land cover and agricultural potential (*Patel et al*, 2005). However, over time, the simple isolines overlay method used in the early agro-climatic zoning had limitations in evaluating complex land uses and farming systems. This included over-generalizations, and the neglect of important factors like physiography, vegetation, land cover, and soils (Fischer *et al*. 1994; Patel, 2003). As a result, there was a growing interest in improving land evaluation systems, particularly interest grew towards the development of AEZ methodology (FAO, 1996; 2005; Fischer *et al*.; Patel, 2003).

Consequently, the FAO published the first guidebook on AEZs in 1978, which introduced concepts, processes, and tools like Geographical Information Systems (GIS) and satellite Remote Sensing (RS) (Barber, 1996; FAO, 1996; Fischer *et al*., 2006). The AEZ methodology aimed to delineate homogeneous land areas based on multiple factors such as climate, topography, soils, land cover, and vegetation, allowing for more precise land use planning and assessment of suitable areas for crop production (FAO, 2009; Fischer *et al*., 2006). This approach contributed to the proliferation of land suitability applications in agriculture during the late 1970s and 1980s (FAO; Fischer *et al*.)

Over the past two decades, the methodology of agro-ecological zoning (AEZ) has evolved, becoming more complex and integrating additional components and techniques (Patel *et al*., 2005; FAO & IIASA, 2012). Initially focused on computing crop growth periods using rainfall and potential evapotranspiration data, AEZ research has advanced with the application of computer-based models (Fischer *et al*., 2005; FAO & IIASA). Incorporating computer models has improved data processing and provided a more cost-effective approach to AEZ (Barber, 1996; de Vries *et al*., 1993; FAO, 2005). This development enabled researchers to create various scenarios and offer decision-makers multiple options to choose from based on their specific needs (FAO; Patel, 2003; Fischer *et al*.).

One notable example of AEZ methodology advancement is the Kenya-AEZ approach, which included models for land suitability, land productivity assessment, and multi-objective land use optimization (FAO, 2005). This was followed by the development of AEZWIN, a Windows-based computer program that facilitated AEZ delineation and allowed the creation of multiple scenarios using additional criteria (Fischer *et al*., 1999). AEZWIN simplified the process and increased its effectiveness compared to the Kenya-AEZ method (Fischer *et al*., 1999).

More recently, decision support systems (DSS) have been introduced in AEZ to aid in policy-making and agricultural sustainability (de la Rosa *et al*., 2009; Boateng, 2005). For instance, the MicroLEIS DSS system was used to evaluate land use in the study by de la Rosa *et al*. (2009) in the Southern province of Spain. In Ghana, Boateng (2005) employed GIS as a DSS to determine suitable lands for rice production; similarly, Netty *et al*. (2016) used a similar approach to model land areas suitable for mango production in four main AEZs of Ghana.

The rapid development in computer and information technologies has catalyzed the integration of GIS and remote sensing (RS) technologies into modern AEZ practices (Fischer *et al*., 2006; Patel *et al.*, 2005; Steve, 1993; IIASA & FAO, 2012). These technologies have introduced new dimensions to AEZ delineation, allowing for improved access, processing, and analysis of large quantitative datasets related to agro-climatic factors, as well as regular acquisition of geospatial information from satellite remote sensing sources (FAO, 2005; Fischer *et al*., 2005; Patel, 2003; Patel *et al.*, 2005, Paladini, 2017). Thus, with the development in modern GIS and RS, Ghana's current methodological challenged AEZs can be better reviewed and reclassified. The application of these tools would ensure readily accessibility to improved and adequate datasets (geospatial) on relevant agro-climatic and agro-edaphic parameters. Through these improved data processing tools, a robust and dynamic AEZ methodology would be developed for Ghana.

3.3 Description of Agro-ecological Zoning Methodology

The agro-ecological zoning methodology (in Figure 3.4), constitutes simply a theoretical methodological framework for guiding the delineation of AEZs, and for building several land evaluation applications (Fischer *et al.*, 2006; IIASA & FAO, 2012; Patel *et al.*, 2005). The AEZ framework is structured mainly into two parts: the core applications and advanced applications. The core applications relate to three main processes: input compilation, data processing and output generation; these fundamentally form the basics of the AEZ methodology (FAO, 1996; 2005).

The process of land resources inventory for Agro-Ecological Zones (AEZ) is described by various authors. The FAO (2005), Fischer *et al*. (2006), IIASA and FAO (2012), Mugandani *et al*. (2012), Paladini (2017), and Patel (2005) provide insights into this process. It involves compiling agro-climatic datasets, including length of the growing period, rainfall, evapotranspiration, humidity, temperature, and soil moisture. Soil and topography characteristics such as pH, texture, depth, slope, and aspect are also compiled, along with information on land use and vegetation types. These resources are transformed into maps, serving as input layers for GIS-based AEZ analysis (FAO; Fischer *et al.*; Patel, 2003; 2005). The data sources for this inventory include observed ground station data and satellite remotely sensed data (FAO & IIASA; Lin *et al*., 2013).

In the AEZ methodology, data processing and analysis play a crucial role. This involves using computer techniques and advanced models to convert the land resources database into meaningful input maps (FAO, 1996; IIASA & FAO, 2012). The input database contains various agro-climatic and geo-spatial data layers (Patel *et al.*, 2005; Fischer *et al*., 2006). The geographic information system and Remote Sensing (RS) tools and models are commonly applied in this process (Fischer *et al*., 2005; Paladini, 2017; van Wart *et al*., 2013). GIS, in particular, is recognized for its effectiveness in integrating large agro-ecological datasets and digitizing spatial information like land use, land cover, and soil (FAO & IIASA; Paladini; Patel, 2003; Steve, 1993; van Wart *et al*.).

The AEZ methodology generates maps and tables that describe the AEZs (FAO, 1996; Fischer *et al*., 2006; IIASA & FAO, 2012). These outputs include land suitability classes and an inventory of land resources (FAO, 1996;

Fischer *et al*., 2005). These outputs are valuable for assessing the impact of climate change on AEZs and monitoring land use changes (Chikodzi *et al.;* FAO, 2010; Fischer *et al*., 2005; IIASA & FAO, Lin et al., 2013; UNEP, 2006). Additionally, they support activities such as evaluating land potential, estimating arable land, planning land use, assessing land degradation risk, and modeling livestock productivity (Bun e*t al*, 2014; FAO, 2005; 2015; Fischer *et al*., 2006; IIASA & FAO, 2012; Netty *et al.*, 2016; van Wart *et al.*, 2013).

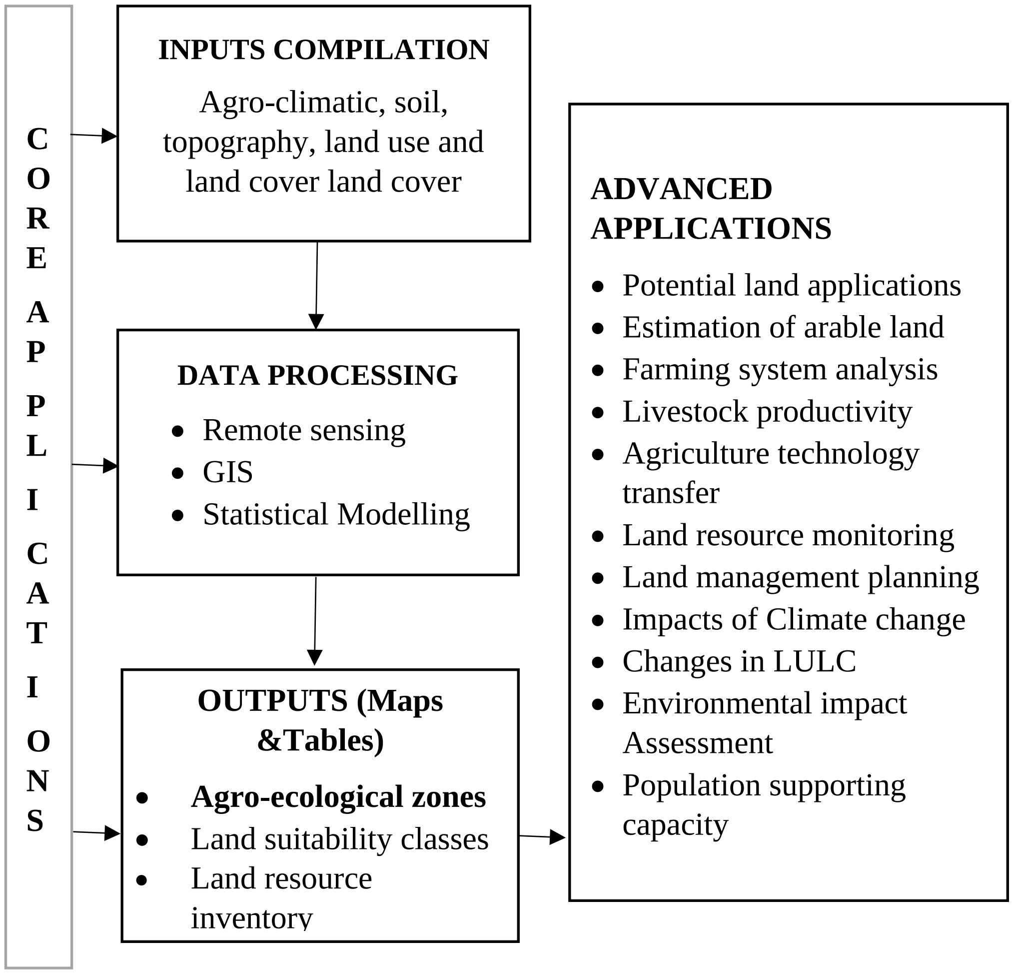

Figure 3.4: The AEZs Methodology Framework) (IIASA & FAO, 2012)

3.4 Applications of AEZs and the AEZ methodology

Agro-ecological zones and the AEZ methodology have wide-ranging applications in the literature, relating to environmental, socio-cultural, political and economic aspects (FAO, 2005; Fischer *et al*., 2005; van Wart *et al*., 2013).

The IIASA and FAO (2012), Fischer *et al.* (2006), and Patel (2003) opine that AEZs and AEZ methodology constitute a multi-purpose decision-making tool, applied in agricultural development planning, land use planning and evaluation, land degradation assessment, population carrying capacity estimation, and in assessing climate change impacts, vulnerability and adaptations studies (FAO; FAO & IIASA; Fischer *et al*., 2002).

The global agro-ecological zones (GAEZs) provided a prediction for crop productivity in a specific environment under limiting factors including climate and soil (FAO, 1996). They were adopted in the Global Trade Analysis Project (GTAP) as the main analysis unit of agricultural production (FAO). The AEZs and AEZ methodology have been used to identify yield variability and the limiting factors for crop growth (Caldiz *et al*., 2002; van Wart *et al*., 2013; Williams *et al*., 2008); to compare yield trends (Gallup & Sachs, 2000); and to determine suitable locations for new crop production technologies (Geerts *et al*., 2006; Araya *et al*., 2010).

Agro-ecological zones have been used to recommend fertilizer use in Bangladesh (FAO, 2005), and to manage the combination of nutrients such as nitrogen, phosphorus and potassium that affect crop production in Kenya (Smaling, 1993). Smaling realized that the exceeding amounts of nutrients in the land were caused by artificial rather than natural causes. Studies on AEZ related to land use include the evaluation of the appropriate use of land in Thailand, and AEZ in Sri Lanka (FAO). The AEZ process was used in assessing the ability of Palawan province in the Philippines to support its populace (Fischer *et al*., 2005).

The application of AEZ in determining the suitability of arable land for farming to promote economic growth has been cited in the literature (Fischer *et al.*, 2006). The AEZs were used to assess the future productivity of cocoa-growing areas in West Africa**,** and the suitability of regions fit for planting Arabica Coffee (Bunn *et al*., 2015). In Ghana, the AEZs were adopted by Boateng (2005) to define suitable economic regions for rice production, and for delineating productive zones for cultivating mango (Netty *et al*., 2016). Aside from food production, a study on suitable land for planting Jatropha for fuel production was done according to agro-ecological provisions (Jingura *et al.*, 2011).

On the socio-economic and vulnerability aspect, a study in Bangladesh showed a connection between AEZs and Poverty (Moral & Rainis, 2011). The results of the vulnerability assessment showed that in regions with less agricultural production potential, the people become poor. However, the connection between poverty and climatic and edaphic conditions still remains inconclusive (Moral & Rainis).

The AEZs and the AEZ methodology have been widely utilized to evaluate the effects of climate change on natural resources, agricultural production, and arable land productivity (Fischer *et al*., 2005; Paladini, 2017; van Wart *et al*., 2013). The GAEZ datasets have been employed in various studies, such as assessing food production shortfalls and water availability in Russia under climate change scenarios (Alcamo *et al*., 2007), estimating potential changes in cereals production (Tatsumi *et al*., 2011), identifying global hot-spots of heat stress on crops (Fischer *et al*., 2009; Teixeira *et al*., 2013), appraising climate change impacts on food consumption (Hasegawa *et al*., 2013; Fischer *et al*., *2005*), and analyzing historical and future impacts of climate change on AEZs (Chikodzi et al., 2013; FAO & IIASA, 2012; Fischer *et al.*, 2005; Kurukulasuriya & Mendelsohn, 2008; Mugandani *et al.*, 2012; Lin *et al.*, 2013).

3.5 Existing Agro-ecological Zoning Methods and Techniques

Different agro-ecological zoning methods and techniques have been adopted for classifying land for agricultural purposes, and for evaluating land uses at global, sub-regional, national, and regional scales (FAO, 1996;2005; Fischer *et al*., 2006; van Wart *et al*., 2013; Patel *et al, 2005*). To start, Koeppen (1928), Thornthwaite (1948), and Papadakis (1970) classification methods adopted climate or weather variables such as temperature, rainfall, or their combination to derive evapotranspiration, moisture and aridity indexes. The climatic variables were developed into isolines, and manually superimposed on soil and vegetation maps to delineate bio-climatic regions or agro-climatic zones (Fischer *et al*., 1996; Patel, 2003). In this simple overlay method, assessments of crop suitability, the productivity of arable land, and other potential land uses were described for the world (Barber, 1996; Patel *et al.*, 2005).

The FAO (1978) developed the global agro-ecological zone/ zoning methodology, which was later improved by the IIASA and FAO (2012) to be the Global Agro-Ecological Zone Length of Growing Period (GAEZ-LGP) method, a matrix construction. This AEZ model relied customarily on the length of the growing period (LGP), and also soil, land cover and vegetation features to divide the world into distinct AEZs (Fischer, *et al*., 2006; IIASA & FAO, 2012). The GAEZ-LGP approach used monthly weather data with a spatial resolution of 10 × 10 km sourced from the Climate Research Unit (New *et al.*, 2002), and from the Global Precipitation Climatology Centre (Rudolf *et al*., 2005).

The essential agro-climatic variables used include: 1) length of the growing period, 2) accumulated temperature sum for mean daily temperature above a base temperature (growing degree days, GDD), 3) annual temperature profiles based on mean annual temperature and seasonal trends, 4) delineation of continuous, discontinuous, sporadic and no permafrost zones, 5) and quantification of soil water balance and actual evapotranspiration for referenced crops. The FAO and IIASA model used the total terrestrial area of the world to spatially analyze crop suitability, land productivity, and evaluate the impact of agricultural policies on the global scale (FAO, 2005; Fischer, 2009; Fischer *et al*., 2005; van Wart *et al*., 2013).

The GAEZs or GAEZ-LGP methodology has been adopted as a conceptual and theoretical framework in many global, sub-regional, and national AEZ or AEZs studies (FAO, 2006; Lin et al., 2013). The Center for Sustainability and the Global Environment (SAGE) at the University of Wisconsin adopted the IIASA and FAOGAEZ data, aggregated it, and derived six categories of global LGPs of approximately 60 days per LGP as: (1) LGP1: 0– 59 days, (2) LGP2: 60–119 days, (3) LGP3: 120–179 days, (4) LGP4: 180–239 days, (5) LGP5: 240–299 days, and (6) LGP6: more than 300 days (Ramankutty, Hertel, Lee, & Rose, 2005). According to (FAO, 1995), the six LGPs roughly divided the world along humidity gradients, which are in tandem with other studies in global agro-ecological zoning. Chen (2001) classified China into twelve AEZs based on the mode of agricultural production, the productivity of farmland, heat, water, and landform. He *et al*. (2002) divided the Chinese wheat-producing area into three major regions and ten AEZs depending on the produced grain traits, ecological factors, soil properties, and cropping system.

Lin *et al*. (2013) used observed historical and future projected climate datasets including mean daily temperature, rainfall, absolute minimum temperature, daily maximum and minimum temperatures from China Meteorological Administration; soil moisture from soil categories and soil composite datasets at the scale of 1:1000,000; and evapotranspiration from MODIS (Moderate Resolution Imaging Spectroradiometer) Global Evapotranspiration Project (MODIS 16). They developed a data processing and analysis model, which involved 3-stage mathematical equations to analyze climate data, and combined with other relevant parameters to delineate the future pattern of AEZs for China induced by climate change (Lin *et al*.).

Bunn *et al*. (2015) used bio-climatic variables and employed the random forest classification technique (RF Classifier) to model the spatial distribution of agro-ecological zones suitable for Arabica Coffee in the wake of climate change. This method allowed for the identification of spatially explicit climate impact scenarios, and to choose locations for long-term evaluation of adaptation measures to address climate changes (Bunn *et al*.). Chikodzi, *et al*. (2013) and Mugandani *et al*. (2012) used soil data from a soil map of Zimbabwe; mean annual rainfall using rainfall data from selected meteorological stations in Zimbabwe; and the length of growing season data from the FAO New Local Climate database. A simple limitation approach was used to delineate a suitability zone map using all the parameters with the same weighting (Chikodzi, *et al*.; Mugandani *et al*.).

Patel *et al.* (2005) used monthly rainfall data, USGS DEM, temperature from meteorological stations, computed potential evapotranspiration and moisture indicator computed based on the method developed by Thornwaite and Mather in 1955, NDVI extracted from NOAA AVHRRR (Advanced Very High-Resolution Radiometer), ground validated land use generated from IRS WiFS satellite data as well as soil data from National Bureau of Soil Survey and Land Use Planning of ICAR in India. Through overlaying these mapped datasets, cells containing agro-ecological data could be extracted (Patel, 2003).

Fischer *et al*. (1999) described the datasets on land and atmosphere inventoried in AEZWIN. These datasets are rasterized. Cross-tabulation was used to derive class combinations. The mean harvest and the predicted harvest exposed to various climate specifications are computed. Rules based on the factors affecting crop growth is formulated. Land productivity is computed based on these rules. This will result in the productivity of various crops planted in different agro-ecological zones. After this, the land use layer could be incorporated into AEZWIN for the generation of various scenarios (FAO, 2005; Fischer *et al*., 1999).

3.6 Challenges with existing AEZ Methods

The selection of appropriate data sources, methods, techniques, and tools for data collection, processing, and analysis is a critical decision in AEZ (IIASA & FAO, 2012; Mücher *et al*., 2016; Paladini, 2017; Patel, 2003; Van Wart *et al*., 2013). Various studies on global, sub-regional, and national AEZs have revealed methodological challenges (Fischer *et al*., 2006; Paladini; Patel *et al.*, 2005; Steven, 1993). But, using technologies like GIS and RS helps overcome limitations (FAO & IIASA; Fischer *et al*., 1996; Patel 2003; Steven, 1993;

Venkateswaralu *et al*., 1996).

Several studies, including those by Fischer *et al*. (2006), Paladini (2017), Patel (2003), and Steven (1993), recognize inherent challenges with past global, sub-regional, and many existing national AEZs methodologies. These include limited use of relevant agro-climatic and edaphic parameters, issues of inaccessible and unreliable data. According to Patel *et al.* (2005) and Quiroz *et al*. (2001), the lack of accessibility to geospatial data, especially in mountainous areas, contributed a significant limitation to AEZ studies. Similarly, Fischer *et al*. (2006) and Paladini highlight scarcity of geospatial dataset in the application of AEZs in many poor and data-scarce developing countries.

The shortage of data in AEZ studies is attributed to various factors, such as uneven distribution of meteorological stations, limited data collection instruments, high survey costs, and low utilization of satellite remote sensing technology (Fischer *et al*., 2006; Paladini, 2017; Patel *et al.*, 2005; Quiroz *et al*., 2001). This limited data availability often results in the over-reliance on a few agro-climatic variables, leading to less robust AEZ delineations that may be better described as agro-climatic zones (Mugandani *et al*., 2012; Steven, 1993). As a result, the delineated AEZs are criticized for being less robust, lacking sufficient information on defined zones, and resembling fitted agro-climatic zones (Patel 2003; Steven).

Past studies by Venkateswaralu *et al*. (1996), Paladini (2017), and Patel (2003) have shown that many agro-ecological zoning methods involved artificially combining agro-climatic variables and other natural resources data to define the AEZs. According to de Vries *et al*. (1993), some previous methods simply intersected mapped data sets and used statistical analysis to determine AEZs. Pater and Steven (1993) criticized the manual overlay of isolines representing rainfall, temperature, evapotranspiration, or their combination onto existing soil and vegetation maps to delineate AEZs.

In the past, too, there were instances of over-generalization in AEZ, where areas with different physiography, climate, and soil characteristics were grouped together (Patel, 2005). This premature aggregation of data and disregard for geographical differences resulted in the LGPs of relevant information on spatial variability, which is a key aspect of AEZ (Mugandani *et al*., 2012; Venkateswaralu *et al*., 1996). Moreover, crude approaches driven by subjective expert opinions were applied in data processing and analysis, leading to methodological challenges and data LGPs, thereby affecting the robustness and reliability of the delineated AEZs (Patel, 2003; Steve, 1993).

3.7 Application of Geospatial technology in AEZ and AEZs Methodology

The incorporation of advanced tools such as RS and GIS has greatly improved the AEZ methodology and delineation of modern AEZs (Paladini, 2017; Patel, 2003; Steven, 1993; van Wart *et al*., 2013). Studies by the Bisht *et al.* (2019), FAO (1996); IIASA & FAO (2012) Fischer *et al*. (2006), Paladini, Patel (2005), and van Wart *et al*. have demonstrated the successful use of GIS and RS techniques in capturing, storing, and processing various spatial and geographical data required for AEZ delineation. These modern tools enable sophisticated analysis of large datasets, allowing for evaluation of spatial and dynamic aspects of agriculture, land use, and other phenomena (Corbett, 1996; Fischer *et al*., 2002; Paladini; Patel).

Similarly, GIS enables the use of spatial data in a digital environment, ensure automated integration of bio-climatic, topography, land use and land cover, and soil of different scales, and store data to inform agricultural and land evaluation researches (Corbett, 1996; Patel, 2003). Sivakumar, Roy, Harmsen, & Saha (2003) opine that the excellent solution to the delineation of AEZs, and to monitoring and modelling of crops at a different range of spatial scales has been through the application of satellite digital elevation models. GIS process-based interpolations tools and by crop simulation models (Bisht, 2019; Quiroz *et al*., 2001; van Wart *et al.*, 2013).

Climate change has been identified as the main driver of agro-ecological zoning changes, along with rapid land use and land cover changes (Chikodzi *et al*., 2013; Fischer *et al*., 2005; Lin *et al.*, 2013; IIASA & FAO, 2012; IPCC, 2019; Mugandani *et al*., 2012; Olesen & Bindi, 2002; UNFCCC, 2010). Regular monitoring and revision of AEZs are crucial (Fischer *et al*.; Mugandani *et al*.; Lin *et al.*). However, conducting field campaigns to collect agro-climatic, soil, and land use data is costly and challenging (Olesen & Bindi, 2002; Paladini, 2017). Remote sensing has made it feasible to monitor land use dynamics and provide information on climatic variables (Mücher *et al*., 2016; Paladini; Sivakumar, 1997). Satellite remote sensing offers up-to-date information on land resource inventory with broader spatial and temporal coverage (Paladini; Patel, 2003; Steven, 1993).

Satellite earth observation technology, including missions like LANDSAT, SPOT, MODIS, ASTER, SENTINELS, and NOAA satellites, has significantly improved AEZ (Chikodzi *et al*., 2013; Fischer *et al*., 2006; Paladini, 2017; Patel, 2003). These satellites provide historical data and help validate ground-based information, enhancing the reliability of AEZ data (Paladini; Quiroz *et al*., 2001). The challenge of poor spatial resolution in satellite images has been addressed with the launch of high-resolution sensors on modern satellite missions like ASTER, MODIS, and Sentinel 2 (Fischer *et al*.; Paladini; Van Wart *et al*., 2013). These satellites offer detailed images of soil, vegetation, land cover, and land use at spatial resolutions ranging from 10 m to 30 m (Bisht *et al*., 2019; FAO & IIASA, 2012; Fischer *et al*.; Paladini; Patel et al., 2005).

Studies by FAO (2005), Chikodzi *et al*., 2013 ; Fischer *et al*. (2002 ; 2006), Mücher *et al*. (2016) Paladini (2017), Patel *et al*. (2005), and Van Wart *et al*. (2013) have highlighted the successful contributions of GIS and RS to the regular assessment, revision, and improvement of global and national AEZs and AEZ methodology. The advancements in GIS and RS technology have enabled the continuous assessment of global AEZs and the GAEZ methodology since the year 2000 (Fischer *et al*.; Mugandani *et al*., 2012; Lin *et al.,* 2013). Continuous updates of GAEZ datasets and revisions outdated national AEZs have become possible due to the dynamic capabilities of GIS and RS techniques (FAO, 1996; 2005; Fischer *et al*.; IIASA & FAO, 2012; Mücher *et al*., 2016; Paladini; van Wart *et al*.). In connection with the main objective of this study, Remote sending technique is crucial to assisting in remotely accessing data on agro-climatic and geospatial datasets on the agro-edaphic parameters, while GIS has the potential to effectively combine all the different parameters to delineate new and robust AEZs for agricultural purpose and other applications.

3.8 Factors responsible for changes in AEZs

Defined by climate-sensitive parameters, studies by Fischer *et al.* (2006), Mugandani *et al*. (2012), IPCC (2019), Kurukulasuriya and Mendelsohn (2008) and Lin *et al.*, (2013) show the global, sub-regional and national AEZs to be profoundly susceptible to the impacts of climate change; even within a relatively short time-lapse such as decades or over the long-term (Chikodzi *et al*., 2013; Lin *et al.,* Kurukulasuriya & Mendelsohn; Westerling, 2016). Similarly, changes in anthropogenic factors couple with climate change to disrupt the conditions, spatial extents, suitability and productivity of AEZs (Mücher *et al*., 2016; Mudzengi *et al*, 2013; Sleeter *et al.*, 2018). The vulnerability of AEZs to the impacts of climate changes, which is the primary driver of change in AEZs, requires constant monitoring and revisions (Chikodzi *et al*.; Fischer *et al*., 2021; Kurukulasuriya & Mendelsohn; Lin *et al*.; Mücher *et al*.; Mudzengi *et al*; Quiroz *et al*., 2001).

3.8.1 Impacts of anthropogenic factors on AEZs

Human activities, including agricultural practices, population pressure, land tenure, and markets have a significant impact on AEZs (Sleeter *et al*., 2018; UNEP, 2006; UNDP, 2015; United Nations Framework Convention on Climate Change [UNFCCC], 2010). Slash and burn, shifting cultivation, continuous farming, and overgrazing have resulted in reduced vegetation, soil fertility LGPs, decreased groundwater, deforestation, and land degradation (Fischer *et al*., 2006). The growing population has led to the conversion of forest and arable land into woodland, grassland, and residential areas (CIAT, 2014; FAO; 2015; Ramankutty *et al*., 2002). These anthropogenic factors contribute to changes in AEZs and land use patterns (FAO, 2016; Fischer & Heilig, 1997; UNDP; World Bank, 2010).

Global markets have played a significant role in shaping land use, land cover, and climatic variables in AEZs (Dale, 1997; Lambin & Meyfroidt, 2011). The local, state, and national policies have also impacted global AEZs including measures to address land degradation and sea level rise, timber harvest regulations, and initiatives promoting cultivated lands for energy production. Technological innovation and rapid industrialization have further influenced land use and land cover changes (Drummond, 2007; Drummond *et al*., 2012).

The changes in land use, land cover, and vegetation indirectly result in localized changes in climate and weather patterns such as precipitation and temperature (Hale, Gallo, Owen & Loveland, 2006; Pielke *et al*., 2007). The aggregation of these changes over large areas has affected the earth's climate system, changing the regional and global circulation patterns (Mahmood *et al*., 2013; Zhao, Pitman & Chase, 2001); changing the albedo of Earth's surface (Betts *et al*., 2016; Barnes & Roy, 2008); and changing the amount of carbon dioxide (CO2) in the atmosphere (Houghton *et al*, 2012).

In relation to the present study, changes in land use and land cover have been analyzed as having the potential to influence the local climate and weather patterns, and over the long-term alter the agro-climatic parameters and conditions of Ghana's AEZs. These LULC-induced changes in AEZs can affect the flow and availability of water resources, the length of growing seasons; and also have significant implications on the suitability and productivity of the national AEZs.

3.8.2 Impacts of global climate change on AEZs

According to the World Meteorological Organization (WMO, 2010) and IPCC (1995), climate change encompasses all forms of climatic inconsistency (any deviations or shifts from the long-term statistics of the meteorological elements, calculated for different periods regardless of their statistical nature or physical causes. The IPCC (2007), defined it as a change or a shift in the average state of the climate of the earth or part of it that persists for an extended period, usually decades or longer whether due to natural causes or as a result of human action. Similarly, the Article (1) of the UNFCCC (1995), defined climate change as the change in climate, directly or indirectly due to human activities, which alters the composition of the global atmosphere, observed over comparable periods. Climate change is now recognized as 'human-induced' or 'anthropogenic-orchestrated' (FAO, 2020; FAO & UNEP, 2020; IPCC, 2018; UNDP, 2015; UNEP, 2006; UNFCCC, 2019).

According to Kurukulasuriya and Mendelsohn (2008), Mugandani *et al*. (2012), and Mücher *et al*. (2016), climate change and variability exert a major influence on the climatic variables (temperature and rainfall), which in turn impact the other bio-physical variables such as soil, land use, land cover and vegetation characteristics of the AEZs (FAO & UNEP, 2020; Fischer *et al*., 2006; IPCC, 2014; Lin *et al.*, 2013; Mücher *et al*.). Changes in these parameters have led to shifts in the spatial boundaries, changes in the economic suitability, and a significant reduction in the productivity of existing global, sub-regional and national AEZs (Chikodzi *et al*., 2013; CIAT, 2014; FAO; 2020; IPCC, 2013; Lin *et al*.; Mugandani *et al.;* Zhao *et al*., 2017)

Climate change and variability, as highlighted in reports by the IPCC (2018), UNEP (2006), UNDP (2015) and UNFCCC (2010), have significantly impacted rainfall patterns, increasing their unpredictability. Global warming has led to rising temperatures resulting in more frequent occurrence of extreme climatic events like floods, droughts, hurricanes, and storms (Fischer *et al*., 2005; IPCC, 2019; UNDP, 2008; World Bank, 2010). The timing and duration of rainfall seasons, as well as the length of growing periods, have undergone changes worldwide. These shifts have affected the condition, suitability, and productivity of global, sub-regional, and national agro-ecological zones (FAO, 2020; Fischer *et al*., 2012; IPCC, 2014; Kurukulasuriya & Mendelsohn, 2008; Lane & Jarvis, 2007).

Land cover, including vegetation, plays a crucial role in agro-ecological zoning (Fischer *et al*., 2006; Mücher *et al*., 2016; Olesen & Bindi, 2002; Paladini 2017). It is an essential parameter for studying nutrient dynamics and environmental pollution related to agriculture (Mücher *et al*., 2016). Climate change has resulted in rapid changes in land cover within global, sub-regional, and national agro-ecological zones (Fischer *et al*, 2006; IPCC; Mücher *et al*.). The effects of global warming, such as erratic rainfall patterns, increased drought, and forest fires, have led to significant forest LGPs and the expansion of woody vegetation into grasslands (Flannigan, Stocks, Turetsky & Wotton, 2009; Westerling, 2016).

Climate change has influenced the land use types within global and national agro-ecological zones. Arable land and forest areas have been impacted by climate change and variability (Mücher *et al*., 2016; Sleeter *et al*; UNEP, 2006). Droughts and rising temperatures have led to the abandonment of arable land and desertification in many regions (IPCC, 2019; Melton *et al*., 2015). Excessive precipitation and flooding have transformed agricultural lands into open water (Taylor, Acevedo, Auch, & Drummond, 2015). However, in some northern latitudes, climate change has extended growing seasons and positively affected arable land use (Friedl *et al*., 2014; Park *et al*., 2016; IPCC). Historical drought events caused by global warming have also had significant consequences.

3.9 Impacts of changes in AEZs on Agricultural production and Land Use

Climate change has resulted in noticeable changes in the global, sub-regional, and national agro-ecological zones (FAO, 2005; FAO & IIASA, 2012; Fischer *et al*, 2006; Mugandani, *et al*., 2012; Sivakumar & Valentin, 1997). These changes have had significant direct and indirect impacts on agricultural production, economic investment planning, and land use (FAO & UNEP, 2020; FAO, 2020; IPCC, 2018; Kurukulasuriya & Mendelsohn; World Bank, 2010; UNDP, 2006). Specifically, the alteration in AEZs have disrupted investment patterns in agriculture, particularly in developing agrarian economies (FAO, 2009; Fischer *et al*., 2006). Studies by Jayathilaka *et al*. (2012), Fischer *et al*., Lane and Jarvis (2007) have revealed alterations in the suitability of arable areas previously suitable for specific crops. Arable lands once suitable for staple food crops (e.g., maize, rice, wheat, potato) and cash crops (e.g., apple, banana, and coffee) have changed (IPCC, 2014; Lane & Jarvis; Läderach *et al*., 2012; Ramankutty *et* al., 2002)

Research by Lin *et al*. (2013), Fischer *et al*. (2006), and Mugandani *et al*. (2012) has shown a notable decline in the spatial extent of arable lands within AEZs for agriculture. Melton *et al*. (2015) observed widespread abandonment or desertion of arable lands due to severe drought and rising temperatures. The IPCC (2007), and Taylor *et al*. (2015) identified the conversion of agricultural lands to open water in coastal areas due to heavy rainfall, flooding, and sea-level rise. Fischer *et al*. (2005), IPCC (2013; 2019), projected a significant decrease in suitable rain-fed agricultural land in Africa by 2030, 2050, and 2080. Similarly, there have predicted longer growing periods in temperate regions due to global warming, which have the potential to increase the suitability and availability of land for crop production in those areas (Fischer *et al*.; IPCC, 2014; Ramankutty *et al.,* 2002).

According to the IPCC (2019) and FAO (2010), prolonged periods of dry and hot conditions in the US grain belt, parts of Asia, and Australia have had negative impacts on agriculture. In Sub-Saharan Africa, FAO (2008) and Niasse (2005) found that increasing drought conditions have worsened the already dry conditions, leading to the drying up of major rivers that support agriculture. The rapid decline of Lake Chad has also affected agricultural production and the livelihoods of millions of people in the region. Niasse (2005) further revealed that the flow of many African agriculture-supporting rivers decreased by approximately 40% between 1970 and 2000. All natural resources-based systems are affected (IPCC, 2014; FAO & UNEP, 2020).

According to the IPCC (2014) and FAO (2013), changes in AEZs have led to increased grain yields in high and mid-latitude regions, but decreased yields in tropical and subtropical regions. Crop yields in Central and South Asia are projected to decrease by 30% by 2050, with India experiencing an 18% LGPs in rainfed cereal production. In Africa, rainfed agriculture is expected to see a potential 50% decrease in crop yields by 2050. Countries in Sub-Saharan Africa like Sudan, Nigeria, Somalia, Ethiopia, Zimbabwe, Chad, and Ghana may face a reduction in cereal production potential by 2080 (Ray *et al.*, 2019).

The changes in AEZs have also impacted species habitats, plant distribution, and the spread of diseases and pests (IPCC, 2013). Climate change has introduced destructive insects and invasive species in Canada and the US, such as the mountain pine beetle that harms agricultural production (Fischer *et al*., 2005). In Africa, the alteration of AEZs due to climate change has led to a

25-42% LGPs of species habitat, affecting both food and non-food crop production (Department for International Development, DFID, 2005; FAO, 2010; FAO & UNEP, 2020; her *et al*.; Ray *et al.,* 2019). Climate change impacts on AEZs and agricultural land uses have severe consequences for global food security, both now and in the future (FAO, 2020; UNDP, 2015). It is estimated that by 2080, around 768 million people worldwide could face undernourishment due to the instability and reduced productivity of AEZs (Fischer *et al*., 2009). In Bangladesh, for instance, sea level rise has led to a significant 16% decrease in national rice production, affecting the livelihoods of over 13 million people (FAO, 2008; UNDP, 2006; IPCC, 2014).

According to Parry *et al*. (2004) and FAO (2020), the majority of malnourished individuals in the coming decades will be from developing countries, particularly Sub-Saharan Africa and Southern Asia. Even under a low emissions scenario and a 2°C rise in global temperatures, it is warned by Easterling *et al*. (2007), Fischer *et al*. (2006), IPCC (2013), Stehfest *et al*. (2009), World Bank (2010), and Lin *et al*. (2013) that outdated AEZs could severely impact agricultural policies, agro-economic investments, and farming systems unless proactive measures are taken. Hence, reclassifying Ghana's national AEZs is an important venture.

3.10 Urgency for Revision of Global, Sub-regional and National AEZs

In order to effectively address the susceptibility of AEZs to the impacts of climate change and variability, regular monitoring and periodic revision of AEZ parameters are essential (Fischer *et al*., 2006; Mücher *et al*., 2016; Mugandani, 2012; Lin *et al*., 2013). The recognition of climate change impacts on AEZs coupled with the limitations of previous AEZ methods (Patel, 2003;

Steven, 1993) and advancements in geographical information systems and remote sensing technology (Bisht *et al*., 2019; Patel, 2003; Quiroz *et al*., 2001), justifies the revision of outdated national AEZs. This revision is considered an adaptation strategy to mitigate climate change impacts and enhance the resilience of systems and economic activities within the AEZs (Chikodzi, *et al.*, 2013; Fischer *et al*.; Pate; Mugandani *et al*., 2012).

Existing national AEZs, as highlighted by Steven (1993), Fischer *et al*. (2006), Patel *et al.* (2005) and Mugandani *et al*. (2012), suffer from limitations such as being sketchy, macro-scale, lacking precision, and unable to effectively guide agriculture development planning and land use appraisal. In response to historical climate change impacts on AEZs, Mugandani *et al.* reclassified Zimbabwe's AEZs using local climatic data to address these shortcomings. Kurukulasuriya and Mendelsohn (2008) observed significant local differences between FAO's observed AEZ distribution and calculated distribution based on climate data.

A study by Lin *et al*. (2013) on the future impacts of climate change in China revealed a decadal shifting pattern in AEZs, calling for regular revisions as a positive adaptation response to climate change and global food security. Similarly, Mugandani *et al*. (2012) emphasized the need for reclassification of Zimbabwe's outdated AEZs due to climate change. They recommended reclassification as a holistic adaptation strategy to address the impacts of climate change. Kurukulasuriya and Mendelsohn (2008) found that climate change has led to shifts in AEZs in Africa, which have dire consequences on food security, livelihoods, income, and economic growth.

The need to revise national AEZs is urgent and supported by modern

GIS and RS technologies (Fischer *et al*., 2002 ; Pater *et al, 2005* ; Paladini, 2013 ; van Wart *et al*., 2013). Previous methods relied on limited ground station data and lacked advanced processing facilities (Carter & Corbett, 1997). Remote sensing and GIS enable the capture, storage, analysis, and manipulation of climatic, soil, and land resources at large scales. Fischer *et al*. and Pater argue that the availability of digital global databases, facilitated by RS, calls for improved calculation procedures and expanded assessments of AEZs, crop suitability, and land productivity. By combining climatic data interpolation with other land resources in GIS, a comprehensive approach to agro-ecological zoning is achievable. Considering the impacts of climate change on AEZs, regular revision of national AEZs is crucial (Fischer *et al*.; Bisht *et al*., 2019).

3.11 Climate Change Impacts on Ghana's AEZs and Agriculture

In Ghana, sustainable agricultural production and agro-economic investment are crucial for achieving the Sustainable Development Goals (SDGs), including poverty reduction, food security, good health, gender equality, economic growth and environmental conservation (FAO, 2020; UNDP, 2006; 2013; World Bank, 2010). Agriculture plays a significant role in Ghana's economy, employing a large portion of the workforce and contributing significantly to GDP and export earnings (MoFA, 2016; UNDP, 2013; World Bank, 2007). Agricultural production in Ghana is profoundly rainfed, practiced by smallholder rural farmers, and primarily planned informed by the national AEZs (EPA, 2008; FAO, 2013; Stanturf *et al.*, 2011; UNDP, 2013; World Bank, 2010). Consequently, the impacts of historical climate change and changes in land use have possibly altered the existing FAO agro-ecological zones, affecting their suitability and potential for agricultural production and for planning agro-economic investment in Ghana (Aquastat-Ghana, 2005; Darfour & Rosentrater, 2016; EPA, 2010; IPCC, 2018; Klutse *et al*., 2013).

Studies by Asante and Amuakwa-Mensah (2015), Asare-Nuamah and Botchway (2019), and Nkrumah *et al* (2014) have shown rising temperatures, increasing PET, and decreasing or erratic rainfall patterns across all the existing AEZs in Ghana. From studies (Amekudzi *et al*., 2015; Gbangou *et al*., 2020; Klutse *et al*., 2020; Yamba *et al.*, 2023), climate change has affected the timing and duration of rainfall, shifting the onset and cessation dates. There is now longer dry seasons and shorter wet seasons, disrupting agricultural productivity (Asante and Amuakwa-Mensah; FAO, 2013; MoFA, 2016; Owusu *et al*).

Studies by EPA (2008), CIAT (2014), FAO (2005), MoFA (2016), and the World Bank (2010) have shown that Ghana's AEZs are gradually shifting. Changes in AEZs have challenged the growing of staple food crops like rice, sorghum, maize, potato, yam and cocoyam etc., and other cash crops such as cocoa, palm, coffee, and cashew (Asare-Nuamah & Botchway, 2019; Amekudzi *et al*.,2015; EPA, 2010; MoFA,2016; World Bank, 2007). The CIAT (2014) reported rising temperatures have negatively shifted cocoa-growing areas in Ghana. Furthermore, climate change has led to a significant LGPs of arable land, with EPA reported a 35% conversion of arable land. There is a merging up of the Transitional and Guinea Savanna AEZs gradually (Asante & Amuakwa-Mensah, 2015; Bessah *et al*., 202; EPA, 2008; Stanturf *et al*., 2011). Farmers in Ghana are facing difficulties in crop production and farm management due to the changing AEZs (Amekudzi *et al*., 2015; Aniah, Kaunza-Nu-Dem, & Ayembilla, 2019; Asante & Amuakwa-Mensah, 2015; MoFA, 2016; UNDP, 2013; Owusu *et al*., 2008). Unpredictable shifts in rainfall patterns and growing periods make it challenging for farmers to plan, prepare land, and select suitable crop varieties (Asante and Amuakwa-Mensah; Asare-Nuamah and Botchway). These changes in AEZs and crop production have had severe impacts on poor farmers and rural communities, increasing their vulnerability to climate change (Anim-Kwapong & Frimpong, 2008; Darfour, & Rosentrater, 2016; EPA, 2010; World Bank, 2010).

Consequently, the shifting AEZs pose great threats to the achievement of sustainable economic growth and agricultural development, as highlighted by Asante and Amuakwa-Mensah (2015), FAO (2005), UNDP (2006) World Bank (2007). In recent times, agricultural production has become difficult, putting food security at risk; rural livelihoods have become more vulnerable, and several disruption of economic investments. Everywhere in Ghana, the socio-economic impacts of the changes in AEZs are evident, including food shortages, rising food prices, increased hunger, and worsening poverty among the vulnerable rural folks. (Asante & Amuakwa-Mensah; EPA, 2010; Ghana News Agency, GNA, September 2011; UNDP, 2015; World Bank, 2010).

Asante and Amuakwa-Mensah (2015), UNDP (2013), and the World Bank (2010) have concluded that achieving the Sustainable Development Goals (SDGs) in Ghana will be difficult unless the negative impacts of climate change on agricultural ecological zones (AEZs), agriculture production, and agro-economic investments are addressed. Reclassifying Ghana's AEZs is seen as a crucial strategy to promote sustainable agriculture, enhance food security, and reduce rural poverty in the face of global warming (Mugandani *et al*., 2012; Yamba *et al*., 2023)

3.12 Reclassification of Ghana's AEZs as Adaptation to Climate Change

In Ghana, the government, local farmers, and other stakeholders face challenges in achieving desirable outcomes in agriculture production and agro-economic investments. This is explained in part, by the impacts of climate change, and significantly due to the continuous use of existing but obsolete AEZs classifications in planning agriculture and agro-economic investments. Studies by Fischer *et al*. (2006), The Herald News (2011), Lin *et al*. (2013), and Mugandani *et al*. (2012) have highlight potential failures in agriculture and disservice done to farmers in agrarian economies, including as researchers, scientists, and extension technicians continue to advise farmers, government and agro-economic investors based on potentially altered AEZs. Reclassification of Ghana's a relevant adaptation option.

Reclassifying Ghana's AEZs is a proactive response to addressing the impacts of climate change and changes in land use to boost agriculture and agro-economic investment planning, now and in the future. Studies by FAO (2005), Fischer *et al*. (2006), Kurukulasuriya and Mendelsohn (2008), Mugandani *et al*. (2012), UNDP (2011), and Lin *et al*. (2013) have shown significant changes in AEZs, having severe adverse implications for food security and the use of natural resources. Kurukulasuriya and Mendelsohn found that the existing FAOAEZs of the Africa have shifted due to the impacts of climate change and land use, affecting food security, rural livelihoods, and economic growth. From the findings of Lin *et al*. (2013) in China, regular revisions of national AEZs, at least on a decadal time interval, is a positive response to climate change impacts. Similarly, Chikodzi et al. (2013) and Mugandani *et al*. proposed reclassifying existing but obsolete agro-ecological regions in Zimbabwe, and the other developing Sub-Saharan agrarian economies as a holistic approach to building the resilience of agrarian economies to the direct impacts of climate change and variability, and to achieve food security.

Like elsewhere, reclassifying Ghana's AEZs offers several benefits. It provides up-to-date information for governments, NGOs, farmers and researchers to plan agriculture and agro-investments, and series of economic activities more effectively Yamba *et al.*, 2023. This effort will potentially reduce crop production failures, boost food security and livelihoods, and reduce rural poverty (Chikodzi *et al.*, 2013; Mugandani *et al.*, 2012; Lin *et al*. 2013; UNDP, 2011; Yamba *et al.*, 2023).

Many existing AEZs classification in agrarian economies like Ghana's is vulnerable and requires revision due to limited use of geospatial data and low application of GIS and RS in the past AEZ, a serious methodological flaw (Steven, 1993; Patel *et al*., 2005). The analysis of past AEZs Ghana appears to be too macro and categorical, denying zonal variability and appreciation of differences in local factors such as rainfall, altitude, water resources, soil, and vegetation types. With advancement in modern geospatial techniques, Ghana needs to revise existing but obsolete national AEZs. Regular updates can be made easier with GIS and satellite RS, enhancing overall accuracy (Chikodzi *et al.*, 2013; Patel *et al*., 2005).

Reclassifying Ghana into AEZs also supports agricultural development by guiding the implementation and monitoring of various innovations, such as irrigation schemes, crop fields, nature reserves, aquariums, and agro-forestry (Chikodzi et al., 2013; FAO, 2005; Mugandani et al., 2012). This classification enables the adoption of tailored practices aimed at preserving the fertility and sustainability of arable land. Extension officers and researchers can utilize this information to plan adaptation strategies, including the adoption of suitable agro-technologies that align with socio-cultural factors, thereby minimizing disruptions of AEZs (Chikodzi et al.; FAO, 2005; Mugandani et al.; Yamba et al., 2023).

3.13 Chapter Summary

This chapter provided an overview of the evolution of AEZs and the AEZ methodology, along with their practical uses. It highlighted challenges in previous AEZ and agro-climatic classifications, emphasizing the need for simpler zoning approaches, limited RS and GIS use, and reliance on a few parameters, mainly related to climate, for AEZ and land suitability assessments. In the late 1970s and 1980s, the FAO introduced the global AEZ methodology, bringing significant advancements to land evaluation systems. Today, thanks to modern GIS and RS techniques, many methodological and data limitations have been resolved, enabling the reclassification of existing AEZs. Given the impact of climate change on AEZs, regular updates are crucial. Changing climate patterns, especially in countries like Ghana, have made existing AEZs outdated, making it necessary to urgently reclassify Ghana's AEZs in response to climate change.

CHAPTER FOUR

PROFILE OF STUDY AREA

4.1 Introduction

Chapter Four provides a detailed overview of the study area, covering its geographical location, population, administrative regions, soils, topography, climate, and agricultural land use patterns. In the context of reclassifying Ghana's AEZs, it also describes the existing six FAO AEZs in the country. Understanding the agro-climatic and edaphic conditions in the country is crucial for achieving the study's specific objectives. The chapter summary highlights the key points covered.

4.2 Study Area

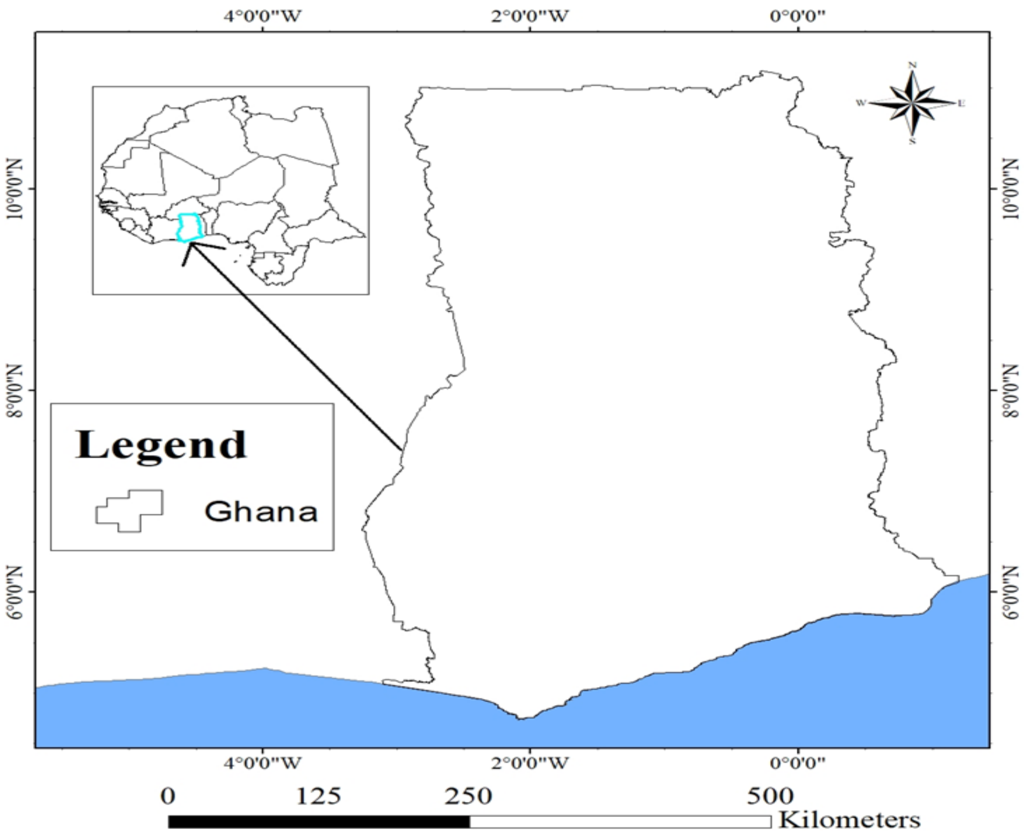

Figure 4.5: Map of Study Area (Republic of Ghana)

4.3 Location

Ghana, located on the Guinea coast of West Africa, lies between Latitude 4° 44′N and 11° 11′N and Longitude 3° 11′ W and 1° 11′E. It shares borders with Burkina Faso in the north, Togo in the east, La Côte D'ivoire in the west, and the Gulf of Guinea in the south. (Aquastat-Ghana, 2005; Ministry of Local Government and Rural Development, Environment and Science (MLG & RD/ES, 2018). The Latitudinal and longitudinal location influences the distribution of climate (rainfall, temperature, LGP, and PET, etc) within Ghana’s AEZs in the country (EPA, 2008; Amekudzi *et al*., 2015)

4.4 Population and Political Regions

Republic of Ghana, with a total land area of 243,438 square kilometers, is divided into 16 regions. Within these regions are 260 Metropolitan, Municipal, and District Assemblies (MMDAs). According to the 2021 National Population and Housing Census (NPHC), Ghana has a total national population of 30.8 million, with an annual growth rate of 2.1%. The population structure of Ghana is characterized by a slight majority of females (50.7%), a significant youth population (57%), and an urban population of 57% (GSS, 2021). The population distribution, structure, density and growth rate have direct and indirect implications for reclassifying Ghana’s AEZs. Increasing population causes changes in LULC, climate and thus, the existing AEZs. Knowing these population indices help to plan land suitability, assess population carrying capacity, and monitor natural resources.

4.5 Topography

Generally, Ghana's topography is characterized by a low-lying and undulating terrain, with slopes of less than 1%. Across the country, there are scattered interior plateaux surfaces at various heights. The average peak heights range from 460 meters to 885 meters. Ghana can be divided into five primary physical relief regions: the Coastal Low Plains, Akwapim-Togo Range, Forest Dissected Plateau; Ashanti Uplands, Voltaian Sandstone Basin, and Northern Savana High Plains. The Coastal plains consist of flatlands, undulating hills, valleys, and a coastal river system. Moving inland, the Akwapim-Togo Range extends from the mouth of the Densu River to the northeastern border with Togo. The Forest dissected plateau comprises the undulating forested southern Ashanti uplands and the Kwahu plateau. The Voltaian Basin serves as the primary drainage system, housing Lake Volta and numerous tributaries. Lastly, the Northern high plains are characterized by dissected escarpments and plateau surfaces. These distinct topographic features shape the landscapes and water resources, determining the agricultural potential and crop suitability across different agro-ecological zones of the country (Aquastat-Ghana, 2005).

4.6 Soils and Vegetation

The Interim Ghana Soil Classification system, developed in the late 1950s and early 1960s, identified approximately 42 Great Soil Groups for Ghana (Brammer, 1962). Among these, the dominant types include Forest Oxyzols, Forest Ochrosols, Savannah Ochrosols, Groundwater Laterites, Tropical Black Clays, and Tropical Grey Earths, as shown in Table 2.3. These soil groups are strongly associated with local climate, vegetation, and parent materials, reflecting the interplay of environmental factors. The prevailing soil and climate conditions significantly shape agricultural production in Ghana, underscoring their importance in AEZs and/ or AEZ (FAO, 2005; MoFA, 2016; Oppong-Anane, 2006).

In correlation with the WRB-RSGs presented in Table 2.3, the Forest Oxyzols (Ferrasols) are found in the Tropical Humid Forest zone. These acidic soils are ideal for acid-tolerant tree crops, including cocoa, rubber and oil palm. The Forest Ochrosols (Acrisols), located in the semi-deciduous forest and forest-savanna transition zones, are alkaline and support crops like cocoa and plantain. Mainly found in the northern and coastal savanna regions, the Savannah Ochrosols, are alkaline and nutrient-rich, making them suitable for yams, cassava, maize, and groundnuts. Similarly, Groundwater Laterites (Plinthosols or Ferric Acrisols), pale brown-grey soils in the woodland savanna belt, are waterlogged and nutrient-poor but can grow maize and sorghum. In the coastal savanna, Tropical Grey Earths (Gleysols) are mainly used as grazing fields, while Tropical Black Clays are heavy soils, challenging to cultivate, but suitable for wetland rice and sugarcane.

In addition to the major soil groups, Ghana has minor soil groups with varying agricultural potentials. Lithosols (Leptosols), found in forest and savanna zones, are shallow soils limited by steep slopes and rocky exposures. Regosols and Arenosols, acidic and nutrient-poor soils along the coast, are suitable for coconut plantations. Cambisols, located near major rivers, support vegetables, sugarcane, and grazing. Solonchaks and Solonetz, saline soils near coastal lagoons, are mainly used for sugarcane. The Alluviosols (Fluvisols), found along rivers and streams, consist of recent alluvial deposits influenced by flooding and varying in texture (FAO, 2005; Oppong-Anane, 2006).

Changes in climate and vegetation (natural cover) overtime alter soil quality, crop suitability, and land productivity of prevailing AEZs in Ghana. Thus, understanding the intricate associations helps to adapt to shifts in Ghana’s

AEZs. The spatial correlated WRB-RSGs classification for Ghana have been shown in Figure 4.6, while and Figure 4.7 represent vegetation zones.

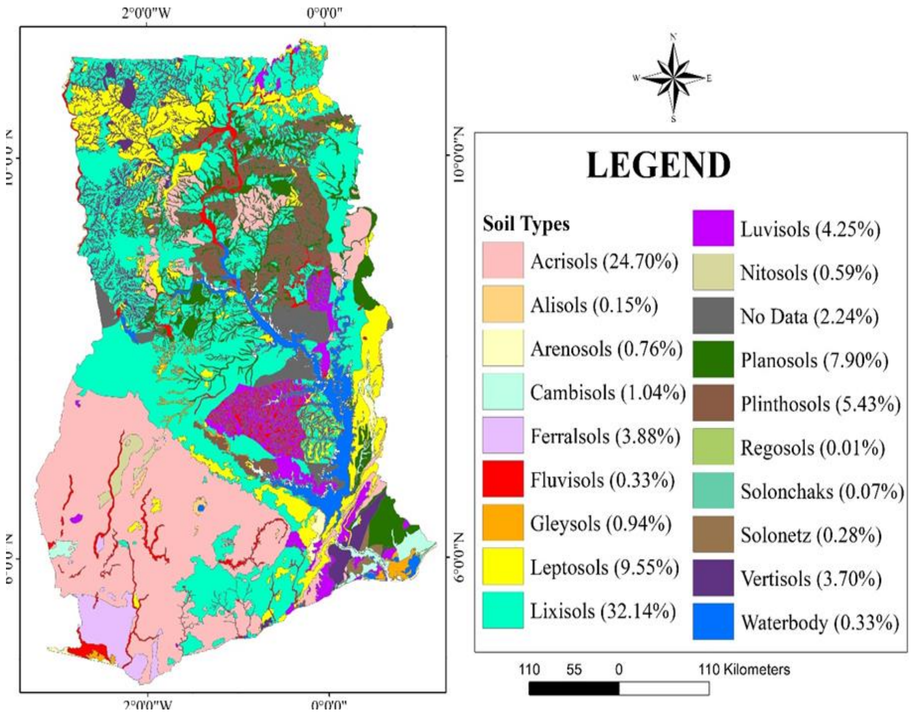

Figure 4.6: Digitized Soil map of Ghana (RSGs-WRB correlated)

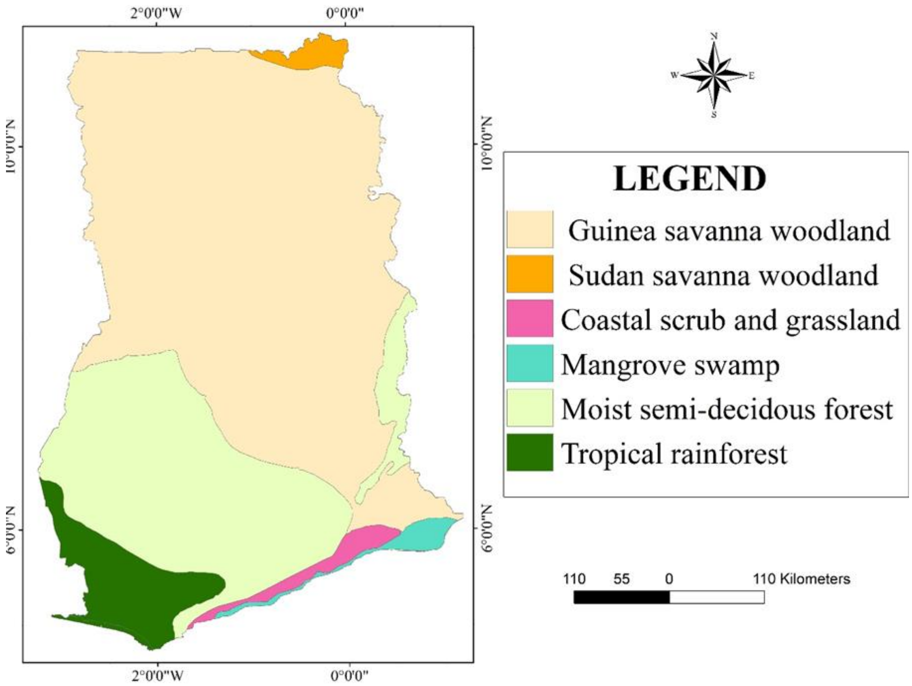

Figure 4.7: Vegetation zones of Ghana.

4.7 Climate

Ghana has a Tropical Monsoonal climate. It is characterized by a warm-dry season and a wet-humid season (Acheampong, 1982; Asare-Nuamaha & Botchway, 2019; Asante & Amuakwa-Mensah, 2015; EPA, 2008). There are two rainfall seasons: double maxima are experienced in the south from March to July and September to October; and the single maxima in the north from May to October, followed by a long dry season from November to May (Amekudzi *et al*., 2015; Asante & Amuakwa-Mensah; Owusu & Waylen, 2013; EPA, 2010; Manzanas, Amekudzi, Preko, Herrera & Gutiérrez, 2014a). The seasonality of Ghana's climate is explained by three climatic processes: the variations in the movement and intensity of the Inter-Tropical Convergence Zone (ITCZ), the variations in timing and intensity of the West African Monsoon wind system, and the variations in the El Niño Southern Oscillation events (Acheampong, 1982; Asante & Amuakwa-Mensah; Asare-Nuamaha & Botchway; Janicot *et al*., 2005; Manzanas, Frías, Cofiño, & Gutiérrez., 2014b).

Ghana experiences high temperatures, ranging from 24°C to 30°C on average, with variations across AEZs. Sometimes, temperatures can be as low as 18°C or less in the south, and above 40°C in the north (Amekudzi *et al*.; Asante & Amuakwa-Mensah, 2015; Barry *et al*., 2005). Generally, rainfall decreases from the wet humid southwest coast to the hot dry northern savannah parts of the country. The wettest part of Ghana is found on the extreme southwest coast with a mean annual rainfall of 2,200 mm the lowest value of 800 mm is recorded on the warm southeast coast of Ghana. The extreme north of the country has a mean annual rainfall of less than 1100 mm. The length of the growing season days is lowest in the Coastal Savana in the south and highest in the transitional forest-savanna zone to the north. Similarly, relative humidity decreases from the south to the north, and there is a general increase in evapotranspiration (ET_0) in the north relative to the south of Ghana (Acheampong, 1982; Barry *et al*.; FAO, 2005; Oppong-Anane, 2006). In Ghana, the seasonality of climate influences the farming and planting seasons. From studies (Asare-Nuamaha & Botchway; EPA; IPCC, 2013; Owusu & Waylen, 2013; Stanturf *et al*., 2011; Yamba *et al*., 2023), the impacts of anthropogenic climate change have altered the country's climate and LULC characteristics, rendering the existing national AEZs and agriculture vulnerable.

4.8 Agriculture

Ghana's agriculture sector, which includes the production of food and cash crops, livestock, and fisheries, is a significant contributor to the country's economy. It supports the livelihoods of a majority (60%) of the population and accounts for a substantial portion (44%) of the Gross Domestic Product (GDP) (GSS, 2021; MoFA, 2016; UNDP, 2013; World Bank, 2010). Staple food crops such as cassava, maize, plantain, rice, yams, and cocoyam are grown, alongside cash crops like cocoa, sheanut, oil palm, rubber, coffee, cashew, cotton, tobacco, pineapple, pawpaw, coconut, and mango (EPA, 2008; FAO 2005; MoFA, 2013).

Agriculture in Ghana relies heavily on rainfall, making it predominantly rain-fed (FAO, 2013; IPCC, 2014; Owusu & Waylen, 2013; UNDP, 2013). The climate-sensitive nature of the agricultural sector thus makes it very vulnerable to the impacts of ongoing climate change. Changes in land use and land cover have also coupled to disrupt climatic and edaphic conditions of the AEZs affecting agriculture production in Ghana (EPA, 2010; MoFA, 2016). Through changes in rainfall patterns and temperature, climate change has affected crop yields, livestock productivity, and overall agricultural production structures. Apart from the direct impacts of climate, most farming practices are characterized by subsistence systems, involving limited technology, and having small landholdings (FAO, 2013, UNDP, 2013; World Bank, 2010). Similarly, rapid urbanization, deforestation, illegal mining, and accelerated population growth have coupled to limit the availability of arable land for agricultural production in Ghana. Extreme climate events and the location of farms in disaster-prone areas threaten the adaptive capacity of farmers (EPA, 2010; FAO, 2010; IPCC, 2014; World Bank, 2007).

Similarly, the continuous reliance of researchers, scientists, and extension officers on obviously altered AEZs to advice and inform the decisions, policies and practices of farmers, government and other stakeholders in planning agriculture and economic investment present affect the sector (Chikodzi *et al*., 2013; EPA, 2010; Yamba *et al*., 2023). With climate change direct impacts on the existing AEZ, the lack of comprehensive revision and reclassification of national AEZ, threatened Ghana's efforts to ensure high agricultural productivity, food security, reduced unemployment, and to achieve sustainable socio-economic development.

To mitigate these challenges, the existing but obsolete national FAO AEZs ought to be revised. This will help to prioritize adaptation strategies and promote sustainable agricultural production, plan investments in irrigation infrastructure, promote climate-resilient crop varieties, and adopt efficient water management techniques. Finally, it will build the resilience of the agricultural sector, boost farmers’ adaptive capacity, and thus ensure long-term food security and economic stability in Ghana.

4.9 Existing National AEZs / FAO AEZ Classification of Ghana

Ghana's AEZs were delineated by climate to reflect the natural vegetation and soil conditions in the country (*Aryee et al.,* 2017; EPA, 2008; FAO, 2005; MoFA, 2016). The existing six national AEZs in Ghana are the Guinea Savanna, Sudan Savanna, Transitional zone, Semi-deciduous Forest zone, Tropical Forest zone, and Coastal Savanna zones (MoFA, 2016; FAO, 2005). The AEZs in Ghana are characterized by key agro-climatic variables, mainly MAR and LGP with distinct zonal thresholds (in Table 4.4). Since their inception, the country's national AEZs has served as important decision framework for guiding farmers, Non-Governmental organizations (NGOs), government ministries, department and agencies, and other stakeholders in determining suitable crops to plant, land preparation timelines, appropriate farming systems, and planning economic investments (Asilevi *et al*., 2019; EPA, 2010; MoFA, 2011; World Bank, 2010).

The impacts of climate change and changes in land use and land cover have possibly rendered the existing national FAO AEZs. Similarly, any changes in Ghana's AEZs have potential challenges to achieving food security and sustaining livelihoods of many rural folks and local agrarian communities (EPA, 2008; MoFA, 2016, World Bank, 2010). Therefore, with the main objective of the study, reclassification of Ghana's AEZs is very relevant to keep the zones in tandem with current climatic and land cover patterns. Table 4.4 and Figure 4.9, present the tabular description and spatial representation of the existing six national AEZs of Ghana, which have been referenced to the FAO; delineated mainly by climate to reflect the country's vegetation, and also influenced by the soils of Ghana.

Table 4.6: Existing FAO Agro-ecological Zones of Ghana

Existing AEZs	MAR (mm)	MAJ-LGP (Days)	MIN-LGP (Days)	Major LULC
GSAEZ	1100	190	N/A	Agricultural, Rangeland
SSAEZ	1,000	155	N/A	Agricultural, Rangeland
TAEZ	1,300	190	60	Agricultural, Woodland
THAEZ	2,200	155	100	Forest, Plantation
DFAEZ	1,500	155	90	Forest, Plantation
CSAEZ	800	105	50	Savanna-woodland, Wetland

GSAEZ (Guinea Savanna AEZ), SSAEZ (Sudan Savanna AEZs), TAEZ (Transitional Zone AEZ), THAEZ (Tropical Humid AEZ), DFAEZ (Deciduous Forest AEZ), and CSAEZ (Coastal Savanna AEZ). Similarly Mean Annual Rainfall (MAR), Length of Growing Season (LGP); Length of Growing Period (LGP), Major Season (MAJ.), Minor Season (MIN.), Land Use and Land Cover (LULC), Not applicable (N/A).

Similarly, Figure 4.8 presents the spatial distributions of the existing six national agro-ecological zones in Ghana, according to the FAO classification.

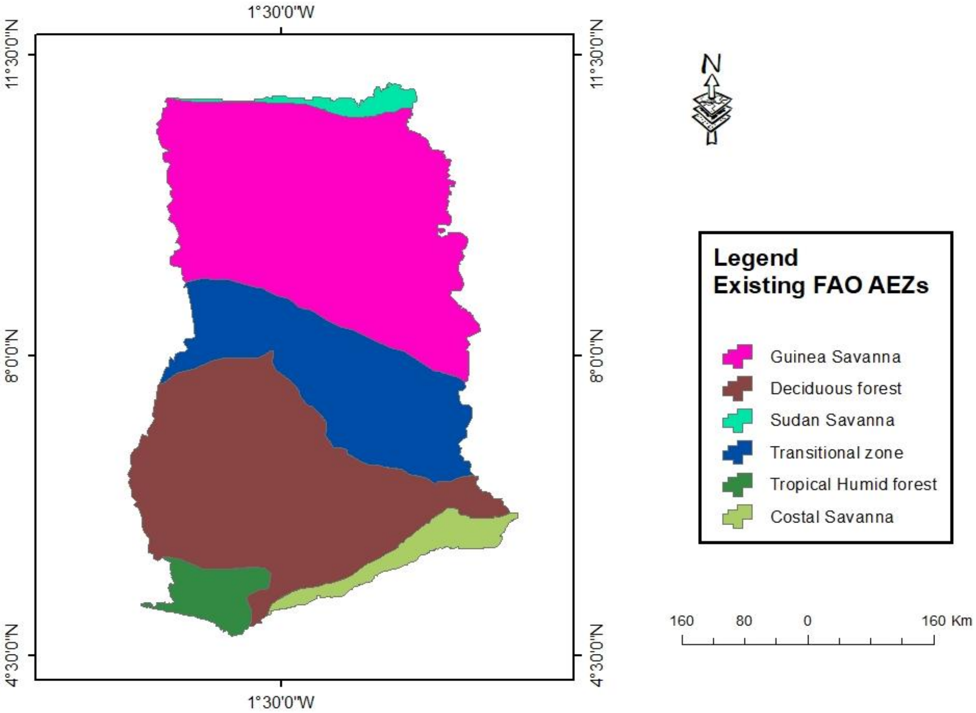

Figure 4.8: Spatial distribution of existing AEZs in Ghana (FAO, 2005)

In the study, the existence of inherent inconsistencies in the choice and use, poor conceptualisation and sheer interchangeability in the use of existing classifications related to AEZs, including ACZ(s), Ecological zone (s) and vegetation classification schemes and applications, presents real challenges. In many studies and from literature, vegetation map or classification is referenced as ecological, while ecological maps as described as AEZs. Similarly, ACZs are misconstrued as AEZs because of so called similarity in applications in agriculture. An attempt is thus made in Table 4.7 to describe, differentiate and align the popular classifications along the following criteria: Nature, types, rationale, parameters, methods, agricultural and land use Potentials.

Table 4.7: Detailed description of AEZs and related classifications

Descriptive Variables	Agro-Climatic Classification	AEZS Classification	Ecological Classification	Vegetation Classification
Nature	Focuses on climate as the primary determinant for agricultural activities.	Integrates climate, soil, and land use to assess agricultural potential holistically.	Emphasizes ecosystems, their components, and interactions.	Centers on plant communities and their distribution based on climatic and soil conditions.
Types	Coastal zone, Transitional, Savannah zone, Forest zone	CSAE, TRAEZ, DFAEZ, THAEZ, GSAEZ, SSAEZ,	Tropical Rainforest Zone, Semi-Deciduous Forest Zone, Savannah Zone, Mangrove Zone.	Grasslands, Forest Vegetation, Mangroves.
Rationale	Identifies areas suitable for specific crops and farming systems using climatic data.	Combines climate and soil properties to delineate areas for sustainable farming.	Categorizes regions based on natural ecosystems and biodiversity conservation.	Classifies regions by dominant vegetation types and associated ecological conditions.
Parameters	Rainfall, temperature, length of growing period, evapotranspiration.	Climate (rainfall, temperature), soil type, fertility, drainage, topography, land use.	Climate, soil, flora, fauna, hydrology, physiography.	Plant cover, structure, biomass, climatic, soil moisture, NDVI

Table 4.7 Continued

Descriptive Variables	Agro-Climatic Classification	AE Classification	Ecological Classification	Vegetation Classification
Methods	Analysis of climatic data, including precipitation, temperature, and growing seasons.	Soil and climate mapping, land-use assessments, crop suitability analysis.	Ecosystem mapping using biophysical data, species composition, and environmental conditions.	Vegetation surveys, satellite imagery, mapping plant communities.
Agricultural Potentials	Guides crop zoning, irrigation planning, and selection of climate-resilient crops.	Supports crop diversification, sustainable farming, and land-use optimization.	Biodiversity conservation and management of natural resources.	Identify regions suitable for specific vegetation management practices, such as forestry or rangeland restoration.
Applications	Used for crop selection, irrigation systems design, and mitigation of climate impacts.	Applied in agricultural planning, land evaluation, and policy-making for sustainable farming.	Ecosystem conservation, wildlife protection, environmental impact assessments.	Forest management, rangeland restoration, ecological conservation.

Adapted EPA (2010); FAO, 200; UNEP (2006); Van Wart et al, (2013)

4.10 Chapter Summary

Chapter Four provides a comprehensive description of the study area (Ghana), including its geographical location, population, political administrative regions, topography, soils, climate, existing agro-ecological zones, and agricultural potentials. The description of the edaphic and climatic characteristics of the study has several implications for achieving the specific objectives. Ghana’s existing AEZs have possibly changed due to the impacts of climate and LULC changes.

CHAPTER FIVE

RESEARCH METHODS

5.1 Introduction

Chapter Five outlines the research philosophy, research design, and research approach that guide the realization of the study's main purpose and the specific objectives. It describes the types of data and /or material used as well as their sources, further detailing data collection procedures and methods of results presentation. This chapter also covers data cleaning, formatting, and organization processes done to prepare and achieve reliability of the datasets and validity of results analyzed. Moreover, it describes the various statistical testing and analytical tools employed in data analysis such as standardization (z-scores), trend analysis, correlation analysis, hypothesis testing, and tests of significant differences. These methods are applied to analyze the parameters studied for any significant changes, variations or shifts.

The chapter systematically explains the methods for processing all the agro-edaphic and agro-climatic parameters as input raster layers compatible for GIS multi-criteria Analytical Hierarchical Process (AHP) classification. Ethical considerations and limitations of the methodology are discussed, followed by a description of the flow model (a GIS process-based AEZ methodology) used for the reclassification of Ghana's new AEZs. The summary chapter is finally presented. This chapter aims to provide a clear and coherent methodological framework for the study, and which can also be adopted for further and related studies in Ghana and elsewhere.

5.2 Research philosophy

In reclassifying Ghana's AEZs, this study adopted the positivist philosophy, emphasizing empirical research using observable facts and numerical data (Crotty, 1998; Lincoln *et al.*, 2011; Mertens, 2010). Underpinned by positivist approach, this study aims to create a robust AEZ methodology for Ghana, integrating a wide range of real quantitative and geospatial datasets (Lincoln *et al.;* Mertens). The study aligns with the positivist methodology, analyzing land use changes and agro-climatic shifts using statistical tools and testing techniques, and geospatial techniques (Creswell, 2014). The study prioritizes objectivity, replicability, and quantitative analysis of numerical and spatial datasets (Creswell, 2014; Phillips & Burbules, 2000), thus ensuring the understanding of the reality of changes in Ghana's AEZs, the rationale for reclassification, and the suitability of quantitative methods.

5.3 Research design

Research design serves as a structured plan for addressing research questions (Babbie, 2003; Bryman, 2014; Kumar, 2005; Silverman, 2005). In the context of reclassifying Ghana's Agro-Ecological Zones (AEZs), an analytical research design was chosen. This design is suitable due to its quantitative and empirical nature, aligning with the positivist approach (Kumar, 2005). Analytical research involves the systematic analysis of existing data, emphasizing numerical analysis, hypothesis testing, comparisons, and objective conclusions through statistical or analytical methods (Kumar, 2005). The analytical research design fits well for reclassifying AEZs in Ghana, allowing quantitative analysis of historical land use changes, examination of spatio-temporal variations in agro-climatic factors, and the creation of a new AEZ map through statistical and GIS methods.

5.4 Research approach

This study uses quantitative research approach, involving measurements of numerical and spatial data, statistical methods including trend analysis, significance testing, and drawing of inferences (Kumar, 2005; Yin, 2003). This approach aligns with the study's objectives, analytical design, and the positivist philosophy. In establishing a reliable context for this study, it supports the spatial and quantitative analyses of land use changes and agro-climatic variations using numerical and spatial datasets. It provides clear, measurable spatio-temporal results, aiding in drawing valid conclusions about changes occurring in Ghana’s AEZs. Thus, the use of quantitative methods ensures the replicability of Ghana’s AEZ methodology.

5.5 Data, Material and sources

In this study, a variety of data sources, including point and geospatial datasets were accessed to conduct a range of quantitative, statistical, and spatial analyses, all aimed at achieving the main objectives. The data, as summarized in Table 5.5, encompass relevant agro-climatic and agro-edaphic parameters essential for the reclassification of Ghana's AEZs. Specifically, the climatic data can be categorized into three sub-groups. The first group comprises observed ground-based climate data, such as daily rainfall, maximum and minimum temperature, wind speed, solar radiation, sunshine hours, and relative humidity.

Table 5.8: Data and Sources

Categories	Parameters	Periods	Sources
Observed climatic	Rainfall,	1991-2020	GMET
	Minimum temperature	1991-2020	GMET
	Maximum temperature	1991-2020	GMET
	Wind speed	1991-2020	GMET
	Solar radiation	1991-2020	GMET
	Sunshine hours	1991-2020	GMET
	Relative humidity	1991-2020	GMET
Satellite modeled	CMIP-6 climate data	1951-2100	ESGF

Table 5.8 Continued

Categories	Parameters	Periods	Sources
Derived climatic	MAR, LGP, PET, RDAYS and TMEAN,	1991-2020	Results
Agro-edaphic	Digitized soil map	2021	WRB-FAO,
	30 m DEM	2021	ASTER-USGS
	30 m LULC	2001, 2010, 2019	MODIS 16
	10 m LULC	2021	Sentinel 2
Materials	Literature review		E-Journals

The observed climate datasets came from the twenty-two synoptic stations manned by the Ghana Meteorological agency (GMET). Figure 5.9 shows the current spatial distribution of the 22 stations across the six AEZs in the country.

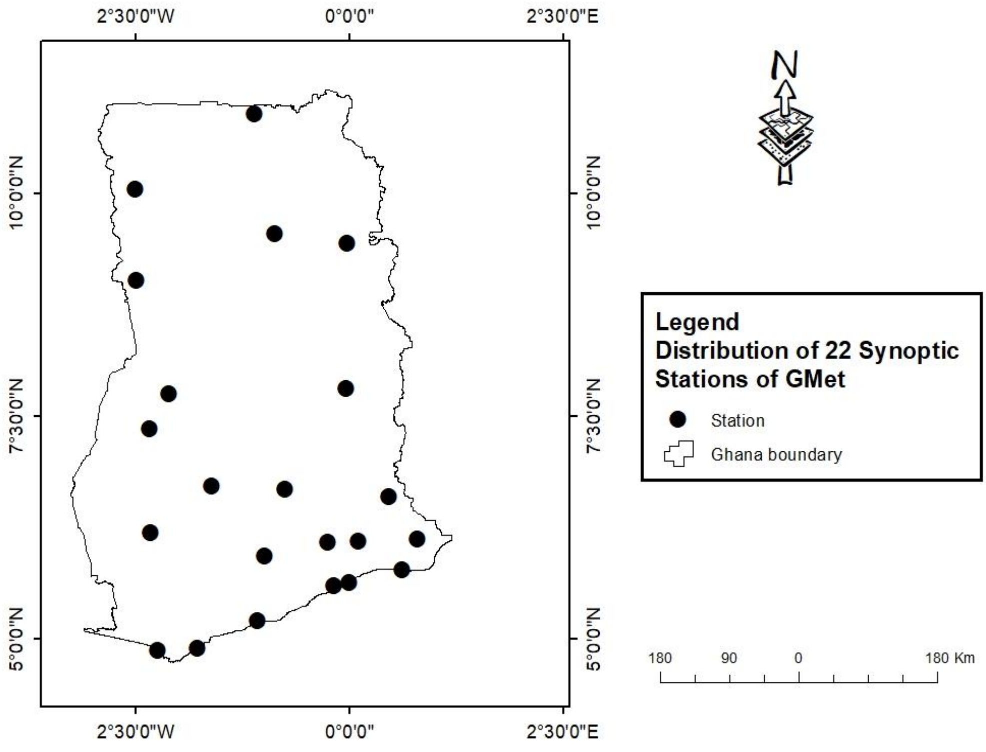

Figure 5.9: Map of 22 Synoptic Stations of Ghana Meteorological Agency

In addition to the observed climate data from the synoptic stations, the study also utilized a second group of data: ensemble modeled climate data known as CMIP-6 (Coupled Model Intercomparison Project Phase 6). This data includes daily rainfall and temperature records from 1951 to 2100. These CMIP-6 datasets have been integrated to enhance data reliability through statistical interpolation, essentially bridging possible data gaps in ground-based synoptic station datasets. The final agro-climatic dataset included mean annual rainfall (MAR), mean temperature (TMEAN), potential evapotranspiration (ET_0), the number of rainy days (RDAYs), and the length of the growing season (for Major and Minor seasons). These datasets were derived from a statistical analysis of daily observed ground climate data provided by GMET. They served multiple purposes, including the assessment of agro-climatic changes within the existing six AEZs and the creation of agro-climatic maps for Ghana's agro-ecological classification. These datasets covered the period from 1991 to 2020, reflecting both current conditions and the impacts of climate change on AEZs.

Furthermore, secondary geospatial data included Digital Elevation Model (DEM) imagery, historical Land Use and Land Cover (LULC) data sourced from MODIS-16 for the years 2001, 2010, and 2019, as well as Sentinel-2 data for 2021. Soil maps, classified according to WRB classification, were obtained from sources such as FAO and local agencies. In addition to these geospatial datasets, secondary literature materials related to agro-ecological zoning, climate change, and land use were utilized to provide comprehensive information for the study.

Finally, the study extensively utilized secondary data from reputable research organizations, government agencies, and experts published in electronic journals online. This includes relevant theoretical and conceptual issues related to AEZ and the methodology guiding the reclassification of Ghana's AEZs.

5.6 Data Collection Procedure

Firstly, observed station climate datasets were obtained from GMET, following official protocols. An introductory letter was acquired from the University of Cape Coast's Department of Geography and Regional Planning and sent to the Director-General. This letter conveyed the study's purpose and requested assistance in collecting climate data and essential information. Relevant ground climate data, including daily records of maximum temperature, minimum temperature, rainfall, relative humidity, solar radiation, and wind speed, were collected. This data spanned from 1991 to 2020.

Secondly, the satellite remotely sensed geospatial data (imageries), encompassing LULC, DEM, digitized soil maps of Ghana, ensemble CMIP6 modeled climate datasets, and relevant literature, were primarily downloaded from open online sources. The specific geospatial data sources included NASA's EOSDIS website (https://earthdata.nasa.gov) for 250m MODIS-16 LULC imagery, Sentinel 2 (https://scihub.copernicus.eu) for 10m LULC geospatial data, the USGS Earth Explorer website (http://Edcsns 17.cr.usgs.gov/EarthExplorer) for the 30m ASTER DEM of Ghana, FAO (http://www.fao.org) and ISRIC (https://www.isric.org) for the digitized soil map of Ghana, and ESGF (https://esgf-node.llnl.gov) for CMIP6 modelled climatic data. Data retrieval occurred mainly between April 2020 and June 2023, covering the entire thesis preparation period.

5.7 Methods of data processing/analysis and rresults presentation

The study adopted a structured approach aligned with the research objectives, rooted in a positivist epistemological framework, an analytical research design, and a quantitative methodology, supported by carefully selected datasets. Data analysis involved statistical testing and the application of analytical tools and GIS techniques, generating key metrics such as means, standard deviations, and standardized (z-scores) values for summarizing datasets and presenting findings effectively. Results were visualized through various formats, including charts, tables, time series graphs, and spatial maps, to illustrate data patterns and trends comprehensively. Each research objective was addressed in a dedicated chapter (Chapters 6, 7, and 8), facilitating focused analysis and in-depth discussions of the results. Findings were critically compared with existing literature and expert opinions, leading to robust conclusions and actionable recommendations to guide policy-making and stakeholder decisions in Ghana

5.8 Statistical and Analytical Framework

This study employed a combination of statistical tools and analytical techniques to analyze the agro-climatic variables and LULC datasets. Specifically, standard deviations quantified variability, while standardization enabled z-scores for consistent comparisons within stations in the same AEZs and across different zones. GIS-based spatial analysis detected trends, percentage changes, and spatial variability in LULC, providing insights into land-use dynamics. Similarly, trend analysis identified temporal patterns in agro-climatic variables, including MAR, MAJ-LGP, MIN-LGP; while correlation analysis explored relationships between and among these parameters within stations and across all six AEZs. Single-factor ANOVA tested significant differences in the long-term and inter-decadal means, trends, and correlations for stations within same zones (intra-zonal), and across different AEZs (inter-zonal) using the standardized FAO-Zmean and CLT-Zmean agro-climatic datasets (z-scores). Kappa statistics with confusion matrix accuracy also assessments validated post LULC classifications. These methods provided a comprehensive understanding of spatial and temporal variability, supporting robust conclusions for resource management and agricultural planning.

5.8.1 Means

Statistical testing focuses on the mean, which is the average of a dataset, showing where most of the data falls. The mean helps with things like understanding data variability and comparing different sets of data. In the study, FAO-zonal mean thresholds (such as MAR, MAJ-LGP, MIN-LGP) are compared with CLT-zonal means for existing AEZs to identify significant differences through tests like ANOVA, Z-Test, and T-Test. These tests unveil crucial insights

5.8.2 Variance

Variance is crucial for testing significance between means of multiple datasets. It measures how spread out the data is, representing the average of the squared differences between each data point and the mean. The equation for variance is defined as:

$$\text{Var} = \frac{\Sigma((X - \mu)^2)}{N} \qquad Eqn\ (5.3)$$

where, $\boldsymbol{X}$ represents the individual data points; $\boldsymbol{\mu}$ the mean of the dataset, $\boldsymbol{\Sigma}$ represents the sum of the squared differences between each data point and the mean, and $\boldsymbol{N}$ is the total number of data points. In this study, variance assisted in interpreting the ANOVA results.

5.8.3 Standard deviations

Standard deviation (σ) is important statistics calculated in the study. It indicates the variability in data from the average (μ). It helps with advanced analysis, like standardization, which normalizes data by showing each point's distance from the mean through this formula:

$$\sigma = \sqrt{\left(\frac{\Sigma((X - \mu)^2}{N}\right)} \qquad Eqn\ (5.4)$$

where, X represents the individual data points, μ represents the mean of the dataset, Σ represents the sum of the squared differences between each data point and the mean, and N represents the total number of data points.

5.8.4 Standardization (z-scores)

Standardization (z-scores) was essential in the data analysis in this study. It compared datasets by converting them to a common scale with a mean of 0 and a standard deviation of 1. This process calculated the standardized value Z for each data point using the formula:

$$Z = \frac{X - \mu}{\sigma} \qquad Eqn\ (5.5)$$

where Z is the standardized value, X is the original value, μ is the mean, and σ is the standard deviation.

The study standardized the derived datasets on MAR, MAJ-LGP, MIN-LGP, PET, and Tmean. It found important trends, correlations, and mean differences between FAO-Zmean and CLT-Zmean thresholds, as well as between stations and FAO-Zmean data for MAR and LGP. Two criteria were used: the ANOVA test (comparing p-value with alpha 0.05) and z-scores. Changes were considered significant if z-scores consistently went above or below ±1 standard deviation (±1σ) or consistently increased or decreased within ±1σ across all four periods. These findings show significant changes due to current climate and land use dynamics

5.8.5 Correlation test (Pearson R)

In this study, the Pearson correlation was employed to analyze the strength of relationships between various datasets and variables. This approach was used to assess connections between FAO-Zmean and CLT-Zmean datasets, FAO-Zmean and station datasets, as well as MAR and LGP with other climate factors. The simple equation for the Pearson correlation coefficient (r) is:

$$r = \left(\frac{\Sigma\left((X - \bar{X})(Y - \bar{Y})\right)}{\sqrt{(\Sigma((X - \bar{X})^2)} * \Sigma((Y - \bar{Y})^2)} \right) \qquad Eqn\ 5.6$$

where, X and Y represent the variables, $\bar{X}$ and $\bar{Y}$ represent their respective means. The correlation coefficient ranges from -1 to 1, where 1 indicates a strong positive linear relationship, -1 indicates a strong negative linear relationship, and 0 indicates no linear relationship between the variables. In this study, the strongest (a perfect positive) correlation was not interpreted to mean causation between variables.

5.8.6 Trend analysis (LINEST regression)

In this study, trend analysis was conducted to describe changes in variables (e.g., MAR, LGP) using historical time series climate data and land use land cover images. LINEST and TREND functions, based on linear regression, were commonly used methods to measure trends. The equation for LINEST and TREND is underpinned by:

$$Y = \beta 0 + \beta 1X + \varepsilon \qquad \text{Eqn } 5.7$$

In this context, Y represents the variable under study (e.g., rainfall), X signifies the independent variable (e.g., year), and β0 serves as the intercept, while β1 acts as the slope determining the relationship. The coefficients β0 and β1 are estimated using statistical techniques such as the least squares method.

5.8.7 Hypothesis testing

In quantitative analysis, hypothesis testing assesses variations between datasets or samples. It compares them to find significant differences in means, trends, or correlations. This study formulated and tested six primary hypotheses. Each included a null hypothesis (H_0) assuming no differences and an alternative hypothesis (Ha) suggesting variations. These three hypotheses are as follows:

3. Hypothesis:

   H_0: The CLT-Zmeans for MAR have not significantly changed from the existing FAO-Zmeans.

   Ha: The CLT-Zmeans for MAR have significantly changed from the existing FAO-Zmeans

4. Hypothesis:

   H_0: The CLT-Zmeans for LGP have not significantly changed from the existing FAO-Zmeans.

   Ha: The CLT-Zmeans for LGP have significantly changed from the existing FAO-Zmeans

3. Hypothesis:

   H_0: There is no significant intra-zonal difference in the stations from the standardized FAO-Zmeans for MAR across the AEZs.

   Ha: There is significant intra-zonal difference in the stations from the standardized FAO-Zmeans for MAR across the AEZs

4. Hypothesis:

   H_0: There is no significant intra-zonal difference in the stations from the standardized FAO-Zmeans for LGP across the AEZs.

   Ha: There is significant intra-zonal difference in the stations from the standardized FAO-Zmeans for LGP across the AEZs

5. Hypothesis:

   H_0: There is no significant inter-decadal and long-term variability and shifts in the standardized FAO-Zmeans for MAR across the AEZs

Ha: There is significant inter-decadal and long-term variability and shifts in the standardized FAO-Zmeans for MAR across the AEZs

6. Hypothesis:

H_0: There is no significant inter-decadal and long-term variability and shifts in the standardized FAO-Zmeans for LGP across the AEZs

Ha: There is significant inter-decadal and long-term variability and shifts in the standardized FAO-Zmeans for LGP across the AEZs

In each hypothesis, the p-value, indicating the likelihood of extreme test statistics assuming the null hypothesis, was pivotal. It was compared to a significance level (alpha, $\alpha = 0.05$ or 0.1). A p-value smaller than alpha led to null hypothesis rejection; otherwise, it was retained. Two key tests, ANOVA and T-Test, assessed differences in parameters like MAR, MAJ-LGP, and MIN-LGP.

5.8.8 Test of significance of difference

The significance test is a statistical method used to compare datasets. In this study, the single-factor ANOVA was employed to assess significant differences in FAO-zonal mean and CLT-zonal mean thresholds for key agro-climatic parameters. The objective was to detect significant changes or variations in the data, which could inform the reclassification of AEZs in Ghana. Significance was determined using the p-value, a probability measure, and comparing it to a predetermined level (alpha, 0.05 or 0.1). This process determined whether to accept or reject the null hypothesis. Conclusions regarding significant changes or variability in the data were drawn from the ANOVA test results.

5.8.9 Kappa statistical testing

Kappa coefficient expressed the proportionate reduction in error generated by a classification process compared with the error of a completely random classification. It accounts for all elements of the confusion matrix and excludes the agreement that occurs by chance. Kappa coefficient was thus computed for the four multi-temporal (2001, 2010, 2019 and 2021) reclassified LULC maps to test the accuracy of the results. Kappa is underpinned by mathematical formula or equation given by Congalton and Green (2019):

$$\hat{K} = N\sum_{i=1}^{r} x_{ii} - \sum_{i=1}^{r}(x_{i+} - x_{+i}) \;/\; N^2 - \sum_{i=1}^{r}(x_{i+} - x_{+i}) \qquad \text{Eqn}(\mathbf{5.8})$$

where,

r = the number of rows in the error matrix

Xii = the number of observations in row i column i (along the diagonal)

Xi+ = is the marginal total of row i (right of the matrix)

X+i = the marginal total of column i (bottom of the matrix)

N = the total number of observations included in the matrix

5.9 Secondary Literature Materials

The study began with the systematic processing of online journal materials to support its literature review and analysis. References were verified and corrected for accuracy using Mendeley Desktop and the APA Online reference generator, ensuring citation integrity and preventing plagiarism. All quotations, ideas, and facts drawn from other authors were appropriately acknowledged and referenced. Through careful analysis, paraphrasing, and synthesis, the original context and meaning of the literature were preserved. Consistent in-text citations and properly formatted APA references were employed throughout, upholding ethical research practices and maintaining academic rigor.

5.10 Observed Daily Climatic Datasets

The study rigorously processed and analyzed observed daily ground climate data, including rainfall, temperature (minimum and maximum), relative humidity, wind speed, solar radiation, and rain days. Steps like statistical cross-checking, editing, and correction ensured data accuracy. To address data gaps and inconsistencies, the "last-observation-carried-forward" (LOCF) method and the RClimdex framework were used. LOCF filled missing values by assuming trends similar to previous observations, while RClimdex estimated missing values based on historical patterns. Spline interpolation enhanced rainfall and temperature analysis by creating smooth curves integrating observed data with CMIP6 datasets. GIS spatial analyst spline interpolation improved spatial representation for areas with limited data, making the climate data spatially robust for AEZ of Ghana.

5.11 Derivation of key agro-climatic parameters

In this study, the corrected daily observed climatic datasets were further analyzed to derive the key agro-climatic parameters such as MAR, MAJ-LGP, MIN-LGP, Tmean PET, RH, and RDAYS. The generation of these variables aligned with the study's purpose and the specific objective one. The subsequent sections provide descriptions of specific procedures employed in processing analyzing, and generating maps of the essential agro-climatic parameters for AEZ.

5.11.1 Length of the growing period/ season

The process of deriving the length of growing season (LGP) dataset began by restructuring the original daily rainfall data, converting it from a day-month format to a Julian calendar format suitable for Instat + computer programming analysis. This format organized the data continuously across 366 days in a year using Microsoft Excel's Pivot Table tool. Subsequently, the data was refined using Excel's Replace tool to address anomalies, including leap years (replaced with 9988), missing data (replaced with 9999), and other irregularities (replaced with 8888).

With rainfall data in Julian calendar format, it was ready for advanced analysis in Instat+ to derive the onset, cessation, and length of the growing season. The Instat + called the effective onset and cessation dates, using the onset and water balance models, and based on the fuzzy logic approach (Laux et al., 2007; Odekunle, 2006). This approach defines onset (SOS) dates when: a total of at least 20 mm of rainfall should be observed, within a 5- day period, the starting day and at least two other days in this 5-day period should be wet (at least 1 mm of rainfall recorded), and no dry period of 7 or more consecutive days occurring in the following 30 days. SOS is shown as:

$$SOS = n\,(20-F)/r \qquad \text{Eqn. (5.9)}$$

where, SOS (onset), n (number of days in the first month with at least 20 mm of rain), MER (the first month where rainfall exceeds 20 mm), F (accumulated rainfall from previous months), and R (total rainfall in MER). Similarly, end of season (EOS) is dated from 1st October when there are more than 7 consecutive days of rainfall significantly less than 50% of the soil water capacity. EOS equation is shown as:

$$EOD = n+275 \qquad \text{Eqn. (5.10)}$$

where, EOS (end of season), n (number of days in the first month with at least20 mm of rain. Thus, LGP is derived by subtracting the onset date from the cessation date. The equation for LGP in this study is shown:

$$\text{LGP} = \text{Card}\left\{\frac{(\text{Ta}_i, \text{P}_i)}{\text{Ta}_i} > 5°\text{C}, \text{P}_i > 0.5\ \text{PET}_i\right\} = \text{P} > \frac{1}{2}\ \text{PET} \qquad \text{Eqn. (5.11)}$$

Where, T_{ai} (^{0}C) is the average daily temperature of the ith day in the year; P_i (mmday^{-1}) is the precipitation plus moisture stored in the soil of the ith day in the year; PET$_i$ (mmday^{-1}) is potential evapotranspiration of the ith day in the year; Card is simply the cardinality function of counting the number of elements of a set.

5. 11.2 Potential evapotranspiration

In this study, the monthly evapotranspiration (PET/ET0) dataset was derived using the FAO Cropwat 8.0 model. This Cropwat model is based on the FAO reference grass evapotranspiration equation which is a modified Penman-Monteith equation (Allen et al., 1998; FAO, 2005). Equation (2.3) presents the statistical representation:

$$\text{ET}_\text{O} = 0.408 * \Delta * (\text{Rn} - \text{G}) + \gamma * \left(\frac{900}{I + 273}\right) * \text{u2} * \frac{\text{es} - \text{ea}}{\Delta + \gamma * (1 + 0.34 * \text{u2})} \ \text{Eqn}(\mathbf{2.3})$$

where, ETo is the reference evapotranspiration (mm/day); Δ is the slope of the saturation vapor pressure-temperature curve (kPa/°C); Rn is the net radiation at the crop surface (MJ/m^2/day); G is the soil heat flux density (MJ/m^2/day); γ is the psychrometric constant (kPa/°C); T is the mean air temperature at 2 meters height (°C); u2 is the wind speed at 2 meters height (m/s); es is the saturation vapour pressure (kPa); ea is the actual vapor pressure (kPa). The PET dataset was derived from the PET equation, involving the processing and analysis of minimum temperature, maximum temperature, relative humidity, wind speed, sunshine hours, solar radiation, and vapor data spanning from 1991 to 2020. This dataset was prepared for further analysis in the study.

5. 11.3 Number of Rain Days

In this study, the number of rainy days (RDAYS) was calculated using the Microsoft Excel conditional function. The COUNTIFS function was utilized, allowing the counting of cells that met specific criteria. The RDAYS function (fx) was conditioned as follows: (=COUNTIFS (RANGE, "> 0.85")). In this case, the criteria were set to count cells with rainfall values greater than 0.85 (GMeT rainfall threshold). This function was applied to the range of daily data points in the column structure (Julian calendar format). Summing up all the events with rainfall values exceeding 0.85 mm within each of the 30 years generated the RDAYS climate dataset for the study. This procedure facilitated the analysis of rainfall events and frequency throughout over the past years

5.12 Creation of Agro-climatic maps

In this study, ArcGIS spatial analyst tools were employed to process agro-climatic parameters and generate map layers. The process included reformatting and converting mean agro-climatic datasets from Excel (.xls) to CSV (comma delimited) to ensure compatibility with GIS. Point-based agro-climatic datasets were then transformed into spatial raster layers using ArcGIS's spline interpolation method, accurately depicting the spatial distribution of agro-climatic data. These raster layers were further analyzed to produce spatio-temporal maps, illustrating parameters like mean annual rainfall, relative humidity, rain days, evapotranspiration, mean temperature, onset of the rainy season (SOS), cessation of the rainy season (EOS), and length of the growing season (LGP). These maps were categorized into specific classes using the natural break classification tool, offering a comprehensive view of Ghana's agro-climatic conditions. Subsequent sections present all key agro-climatic maps created considered for AEZ in this study

5.12.1 Mean annual rainfall (MAR) map

Following the GIS-process based spline interpolation and subsequent application of natural break classification, six MAR classes have been defined for Ghana, and shown in Figure 5.10. These six MAR regimes in Ghana are characterized by the following ranges: < 700 mm, 700-940 mm, 941-1,181 mm, 1,181-1,422 mm, 1,423-1,664 mm, and >1,665 mm. This map is important for understanding the rainfall patterns in Ghana over the recent period (1991 - 2020) and for assisting in crop suitability assessment.

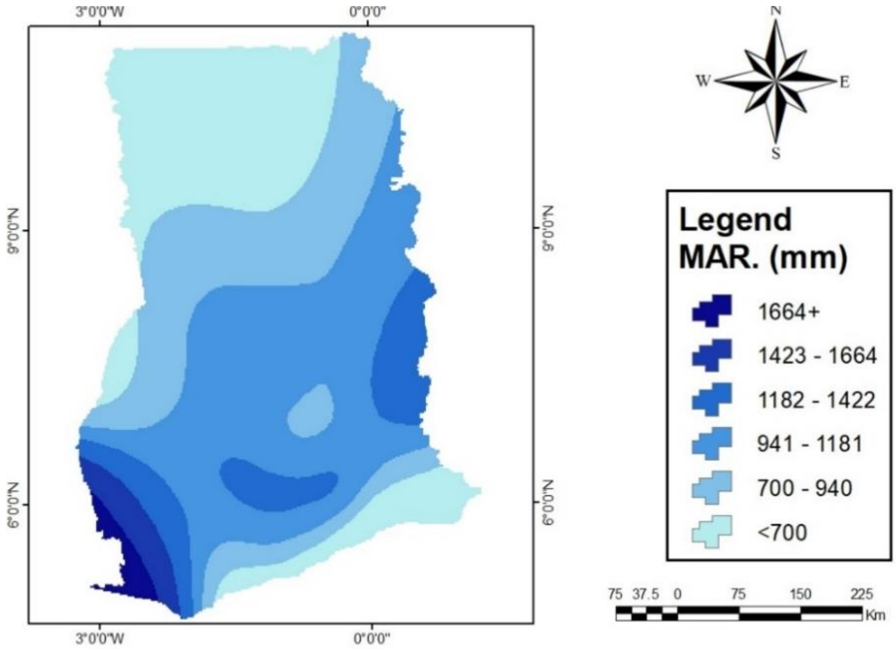

Figure 5.10: Mean annual rainfall map of Ghana

5.12.2 Thermal regime map

Ghana's temperature classification map consists of six classes, as illustrated in Figure 5.11. These thermal regimes are categorized as follows: < 20.1°C, 20.1 - 22.5°C, 23.6 - 26.1°C, 27.1 - 28.6°C, 30.6 – 32.1°C, and > 32.1°C. Temperature plays a critical role in influencing crop growth, regulating humidity (RH) and potential evapotranspiration (PET), and determining land use and land cover (LULC) patterns in Ghana's agro-ecological zones

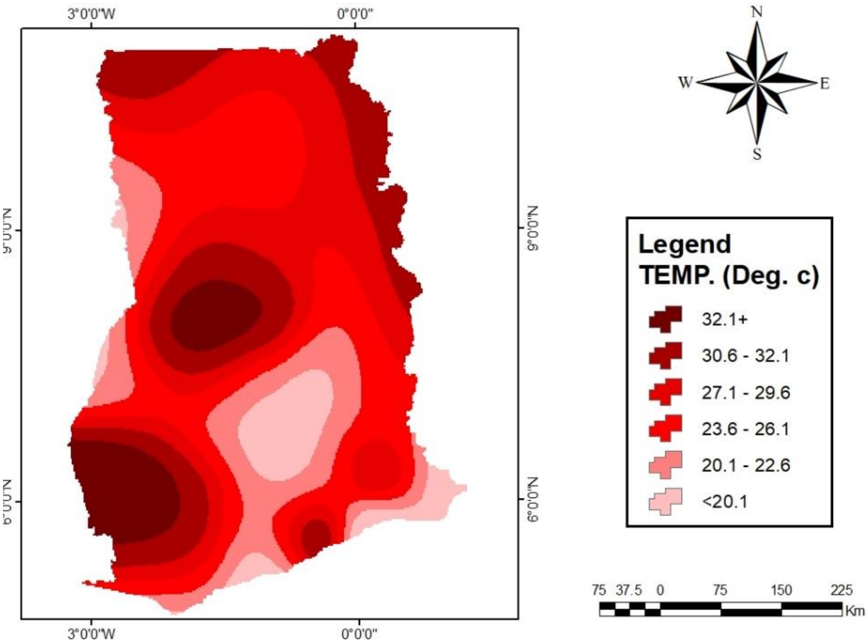

Figure 5.11: Mean Annual Temperature map of Ghana

5.12.3 Potential evapotranspiration map

The potential evapotranspiration (PET) map of Ghana is a vital agro-climatic parameter utilized in the reclassification of the country's agro-ecological zones. This significant map is illustrated in Figure 5.12. It outlines six distinct PET class ranges: < 1,730; 1,731-1,871; 1,872-2,013; 2,013-2,154; 2,154-2,295, and 2,296+). Understanding these PET classifications is crucial for the assessment of agricultural suitability and water management in Ghana. Similarly, GIS spatial analysis tools (spline interpolation and natural break classification) generated PET map.

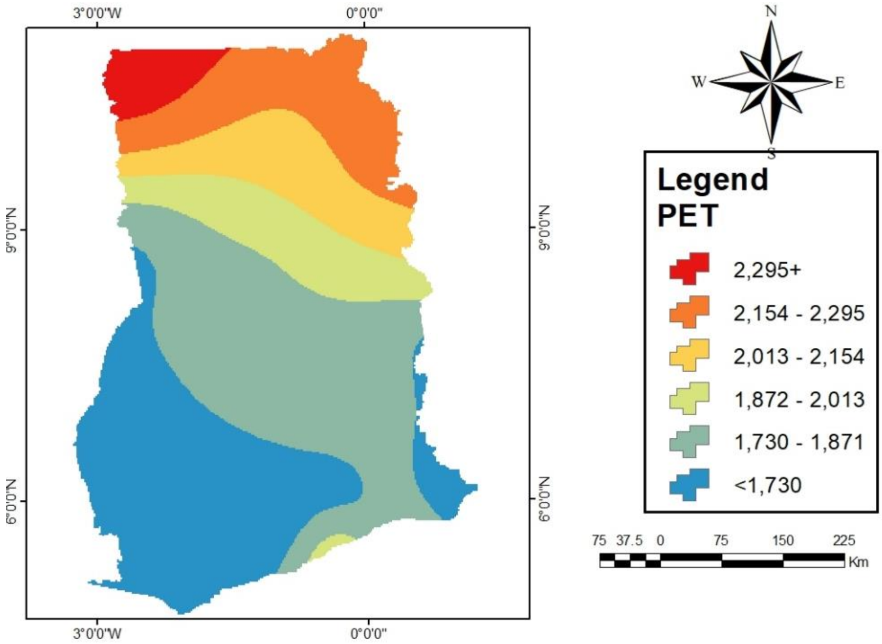

Figure 5.12: Mean annual potential evapotranspiration Map

5. 12.4 Rain days map

Rain days, an important moisture regime parameter, was included in the analysis, and the resulting map used for defining the agro-ecological zones is displayed in Figure 5.13. This Rain days map is divided into six classes: (< 30 days; 31-60 days; 61-70 days; 71-80 days; 81-90 days, and >90 days). These classifications are a valuable component of the current agro-ecological zones as they provide insights into rainfall frequency and distribution, aiding in the assessment of moisture conditions within local areas (AEZs) across Ghana. Such information is essential for evaluating the suitability of these areas for various agricultural and economic activities.

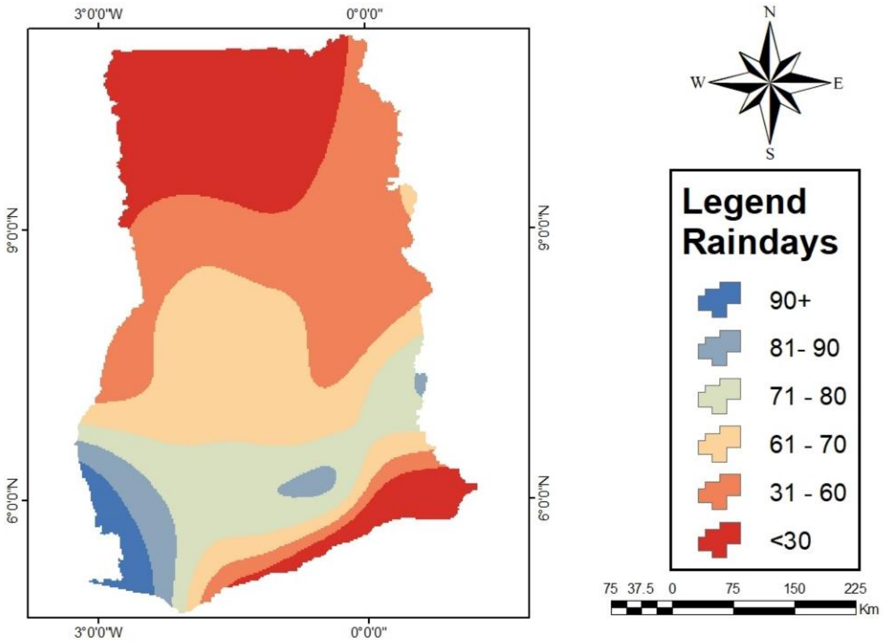

Figure 5.13: Number of rain days map

5. 12.5 Relative Humidity map

A map illustrating the relative humidity across Ghana was generated and is displayed in Figure 5.14. This relative humidity map underwent rasterization using a GIS spline interpolation model, followed by classification using the natural break classification tool. Figure 5.14 presents the RH map divided into six distinct classes: < 49%; 50-59%; 60-69%; 70-79%; 80-89; > 90. This parameter plays a crucial role in the analysis of moisture regimes within Ghana's agro-ecological zones. Additionally, it aids in evaluating the overall moisture conditions within local areas and their potential impact on various economic activities.

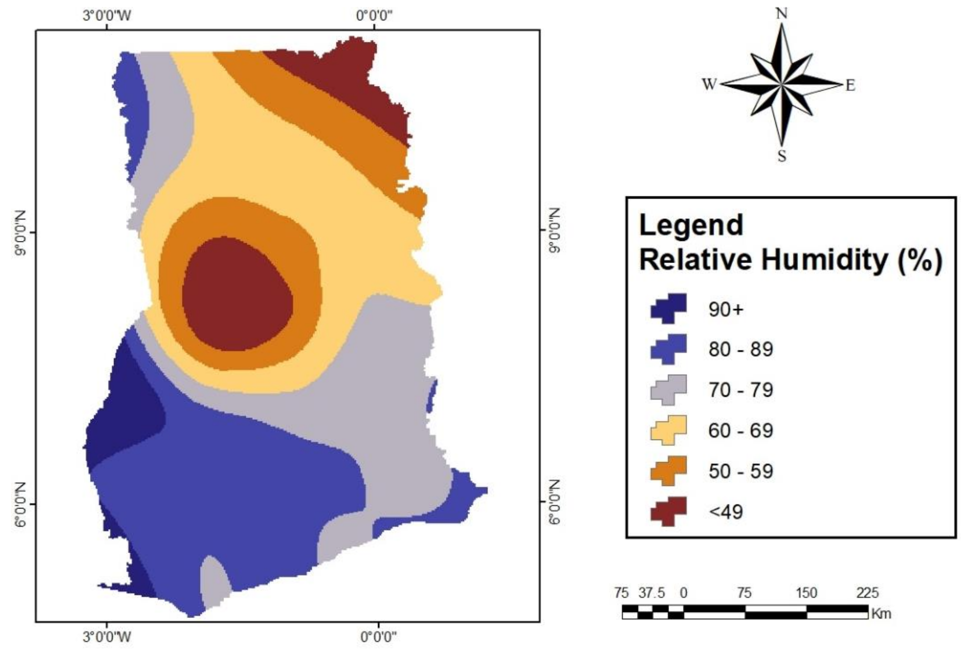

Figure 5.14: Relative Humidity Map

5.12.6 Length of major growing season map

The map displaying the length of the growing season or growing period, as seen in Figure 5.15, was created using the Instat+ software and GIS-based spline interpolation. This parameter is crucial in evaluating seasonality within ACZs and AEZs, guiding decisions related to land preparation, planting schedules, crop variety selection, land use practices, and agricultural management. It also plays a role in assessing moisture conditions in local areas. Figure 5.15 illustrates the LGP map, which categorizes the length of the growing season into six classes: < 60 days; 61-90 days; 91-120 days; 121-150 days; 151-180 days; > 181 days.

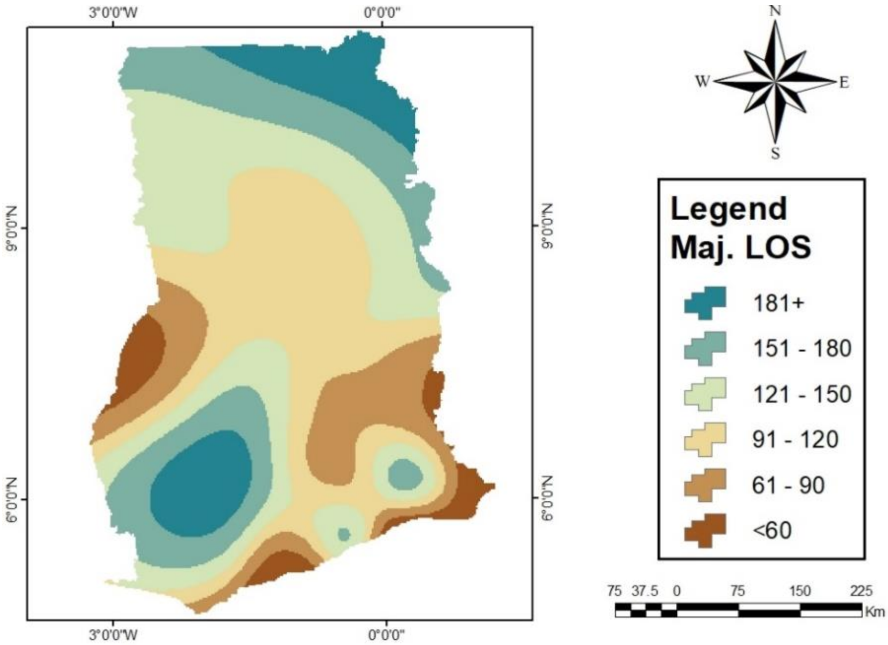

Figure 5.15: Length of major growing season map

5.12.7 Start of major growing season (SOS) map

The commencement of the growing season, known as the Start of Season (SOS), is a vital factor considered in characterizing Ghana's new AEZs. Utilizing GIS spatial analyst spline interpolation and natural break classification, the SOS map has been divided into six distinct class-ranges, as depicted in Figure 5.16. These six SOS classes, represented by monthly Julian dates, are as follows: < 78; 78-108; 109-139; 140-170; 171-201; and > 201. These dates mark the effective beginning of the rainy season, serving as critical information for crop cultivation and land preparation in the region

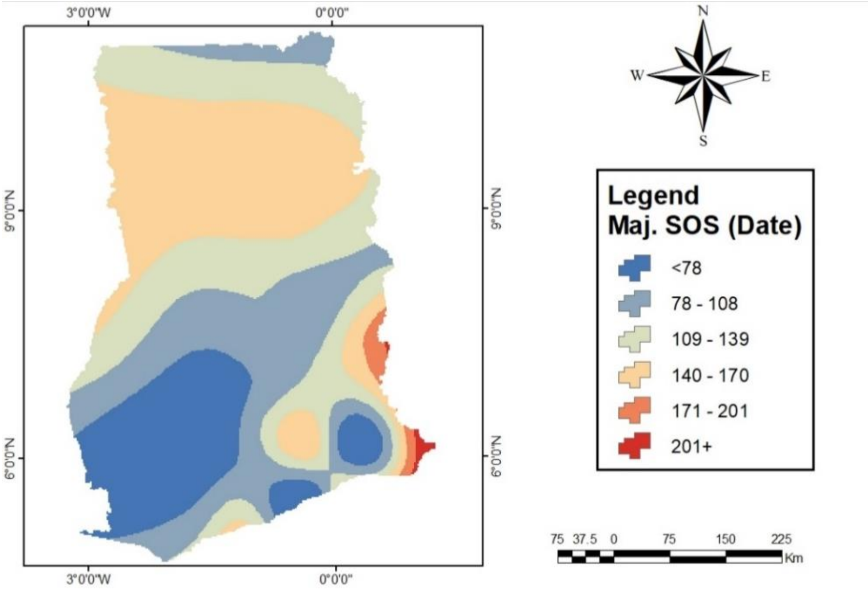

Figure 5.16: Start of major growing season map

5.12.8 End of major growing season (EOS) map

The end of the growing period is another vital agro-climatic variable considered in the AEZ. The EOS map was also created with the GIS spline interpolation and natural break spatial analyst tools. Figure 5.17 shows the map of the cessation of the rainfall regime, which helps to select the right cultivar and plan for irrigation or conserve moisture. The EOS map of Ghana has six classes, representing Julian dates: <160; 160-195; 196-231; 231 - 266; 267-302; < 302). This EOS map was considered for the AEZ of Ghana.

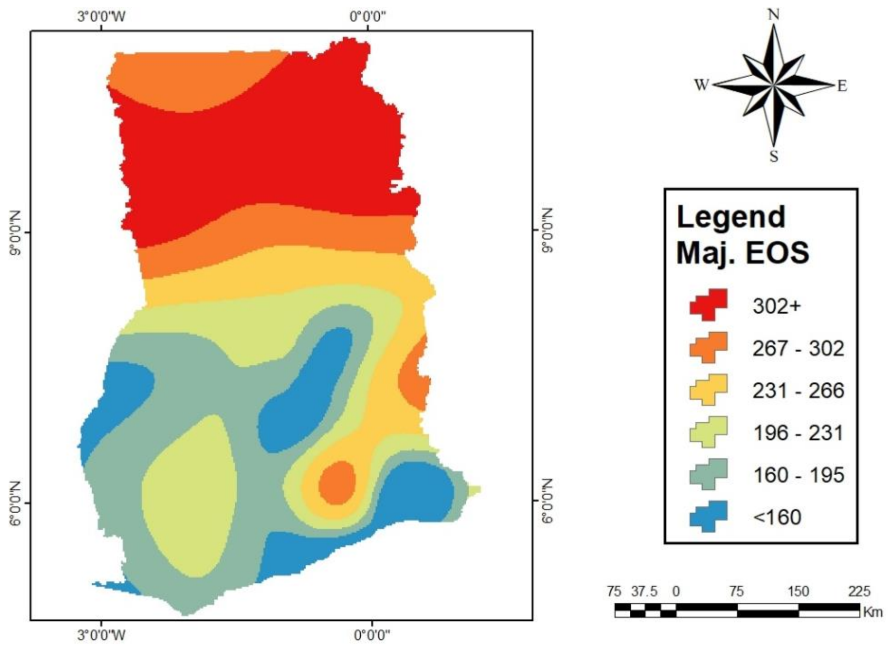

Figure 5.17: End of major growing season map

5.12.8 Agro-climatic map.

Using the weighted overlay multi-criteria analysis technique, a composite agro-climatic map (input) was also created. The GIS overlay analysis combines the multi-criteria (variables) such as mean annual rainfall, relative humidity, potential evaporation, length of the rainy growing period, number of rain days, and the start and end of the rainfall season parameters. Each criterion was given a weight based on its importance in agriculture. The weighted criteria were then overlaid to generate the agro-climatic map (Figure 5.18). This shows five homogeneous classes, suggesting different suitability zones for agriculture. These zones represent a combination of climate factors that are relevant to agriculture.

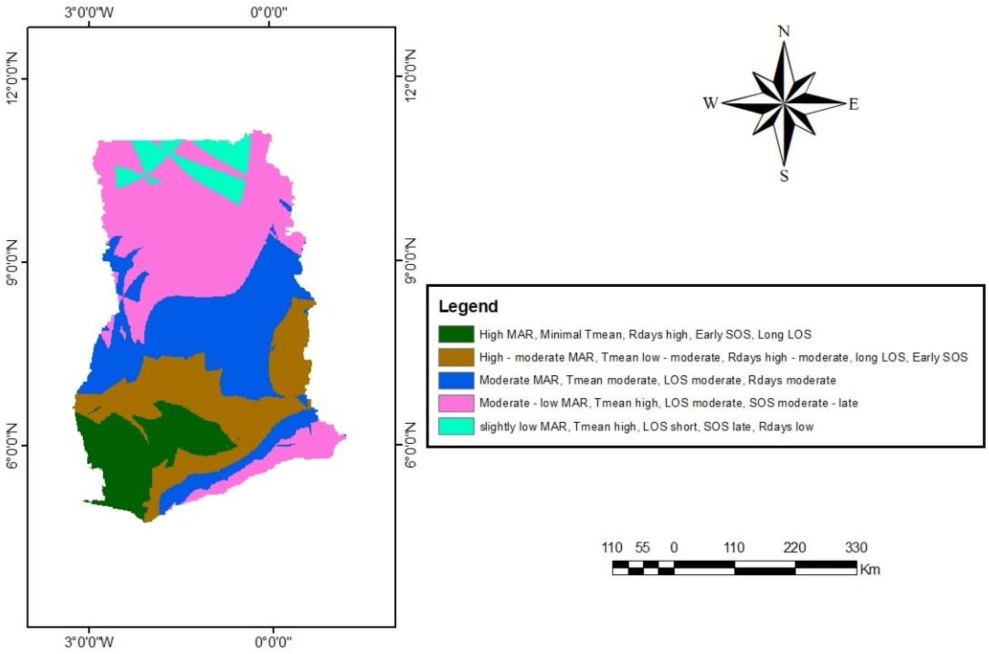

Figure 5.18: Agro-climatic map

5.13 Creation of Agro-edaphic maps.

This section outlines the systematic procedures followed for the processing and analysis of the different satellite geospatial imageries employed for the delineation of the key agro-edaphic map layers. The agro-edaphic map layers created for the agro-ecological reclassification of Ghana, the main objective of this study, include the generalized LULC, generalized elevation, generalized slope, generalized aspect, and generalized soil types. The specific parameters and their processing and analysis procedures employed to create the map layers of these are described in the following sections.

5.13.1 Land use and Land cover classification and Accuracy Assessment

In this study, the three multi-temporal (2001, 2010 and 2019) Post LULC classification maps (imageries) of Ghana, having spatial resolution of 250 m from MODIS-16, were reclassified and analyzed for historical spatio-temporal change detections or dynamics in Ghana LULC. Similarly, the 10 m Sentinel 2 Post LULC classification was reclassified and used as LULC input raster for the reclassification of Ghana obsolete AEZ; systematically processed and analyzed using the ArcGIS. In the absence of a direct national survey for acquiring detailed LULC data in this study, works by Behera et al. (2012), Foody (2002), and) support the use of post classifications as reliable.

By adopting the Anderson (1976) and the FAO (2016) LULC schemes, the 3-multi-temporal historical LULC (2001, 2010 and 2019) were reclassified into seven main classes, including Forest land, Rangeland, Wetland, Agricultural land, Built-Up, and Barren Land and water bodies. Figure 5.19 presents the three LULC maps used for the spatio-temporal shifts, a basis for reclassification of Ghana's AEZs.

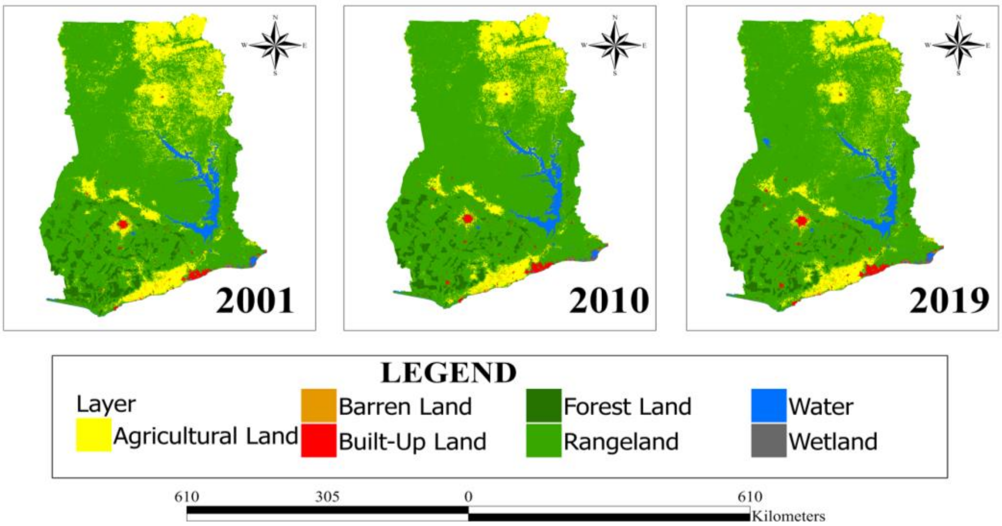

Figure 5.19: 3 Multi-temporal Historical LULC Maps of Ghana

Concerning the main and final LULC used for the reclassification of Ghana's AEZs, the study adopted the 10 m Sentinel-2 LULC map (2021), reclassifying into six major LULC classes, including Forest land, Rangeland, Agricultural land, Wetland, Water and Settlement (combined Built-Up and Barren Land). This was based on the FAO and Anderson LULC classification systems. Figure 5.20 show the final reclassified LULC input raster used.

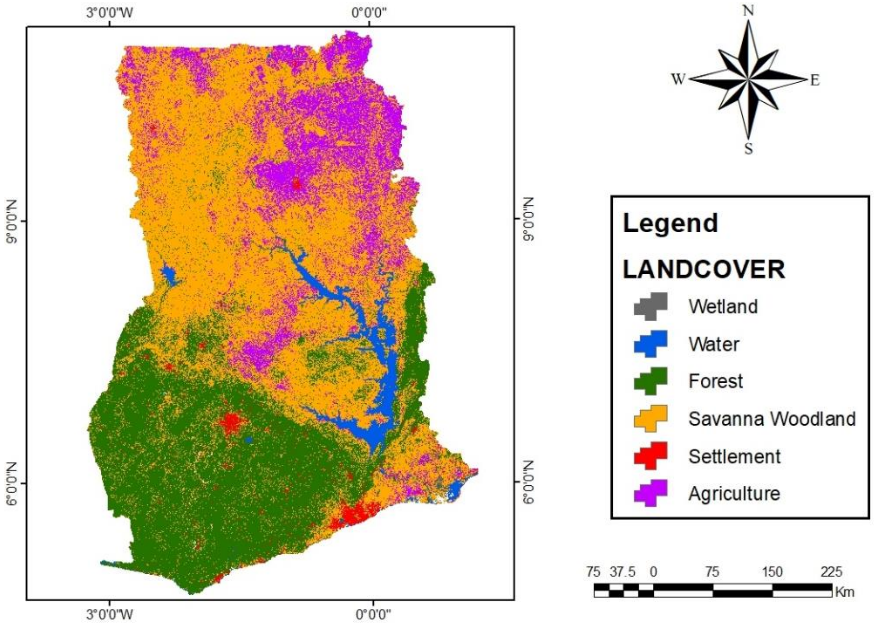

Figure 5.20: Land use and Land cover map

Kappa statistics and accuracy assessment or Confusion matrix

In this study, though the various source missions and organizations from which the current the historical LULC had performed spatial data quality control, the performance of accuracy assessment or confusion matrix and kappa test statistics was relevant (Behera et al., 2012; Congalton & Green, 2019; Foody, 2002). These statistical analyses were crucial to ascertain if, the reclassified LULC classes were accurate representation of realities, or compatible with what is on the ground; thus, ensure the reliability of our post-classification spatio-temporal LULC change detections and related statistical analysis, and in the final AEZ.

With respect to accuracy assessment, representative samples of 100, 102 and 103 points generated from the 2001, 2010 and 2019 LULC reclassified maps, respectively. There were converted into kml format for validation and/or ground-truthing using Global Positioning System (GPS) reference points in the Google Earth Pro (GEP) software. In relation to Figures (5.19 and 5.20), Table

5.9 presents a summary of LULC accuracy evaluation matrix performed for the four post LULC classifications, analyzed in terms of producer's accuracy (PA), user's accuracy (UA) and overall accuracy (OA) and overall kappa statistics (Kc).

Table 5.9: Summary of Accuracy Assessment and Kappa co-efficient (%)

Periods	**2001**		**2010**		**2019**		**2021**	
LULC classes	**UA**	**PA**	**UA**	**PA**	**UA**	**PA**	**UA**	**PA**
Agriculture	66.7	80	87.5	100	90.9	83.3	91	89
Bare Area	80	66.7	40	66.67	40	66.7	100	50
Built Up	100	100	80	66.7	83.3	83.3	100	77
Forest	100	100	100	75	100	90	94	96
Rangeland	100	100	88.9	88.9	77.8	77.8	91	96
Water	75	75	83.3	100	100	87.5	94	100
Wetland	75	75	100	80	66.7	100	100	91
OA	**84.9**		**83.7**		**84**		**93**	
Kc	**81.9**		**80.8**		**80.8**		**93**	

Result, 2023

The overall accuracy (OA) Kc for the 2001, 2010, 2019 and 20121 LULC maps were 84.85% (81.93 %), 83.72% (80.82%), 84.00% (80.81%) and 93% (93%) respectively. This results, (0A > 81) and the kappa statistics (Kc > 81%), put our LULC classifications in at very good range from the standard classification accuracy scale approved by Anderson (1979), Congalton and Green (2019), Monserud and Leamans (1992), and Moriasi et al. (2007).

5.13.2 Slope map

In this study, the 30 m Digital Elevation Model (DEM) imagery from the ASTER satellite mission, covering the entire land area of Ghana, was processed and analyzed to generate different maps for elevation, slope and aspect for the study. Using the surface model and reclassify tools in ArcGIS

10.5 software, the initial 7 slope classes were reduced into three classes based on the classification of the FAO (1991). The initial seven slope classes in the DEM were 0-4% (level to gently rolling); 4-9% (undulating to rolling); 9-15% (rolling to hilly); 15-21% (hilly to moderately steep); 21-31% (moderately steep to steep); 31-45% (steep); 45-100% (very steep) as shown in Figure 5.21

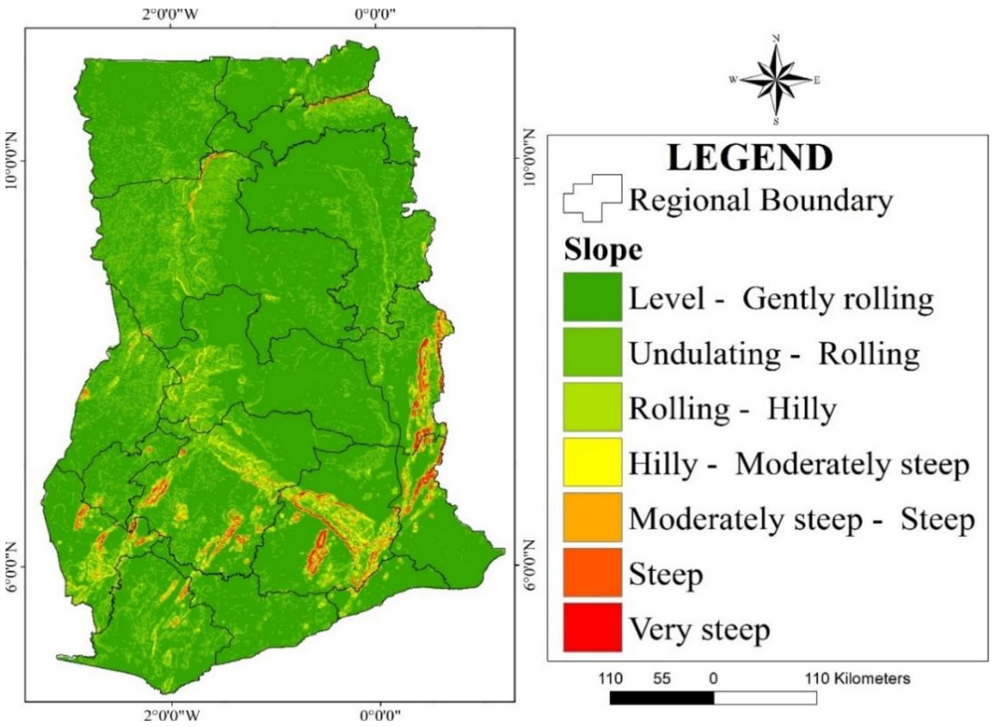

Figure 5.21: Initial seven slope classes

These were then reduced to three main classes based on the classification of the Food and Agriculture Organization of the United Nations (FAO, 1991). The three resulting generalized elevation classes are: Level to gently undulating0-8%), Rolling to hilly (8-30%), and steeply dissected to mountainous (> 30%).

The final generalized slope map input layer is shown in Figure 5.22.

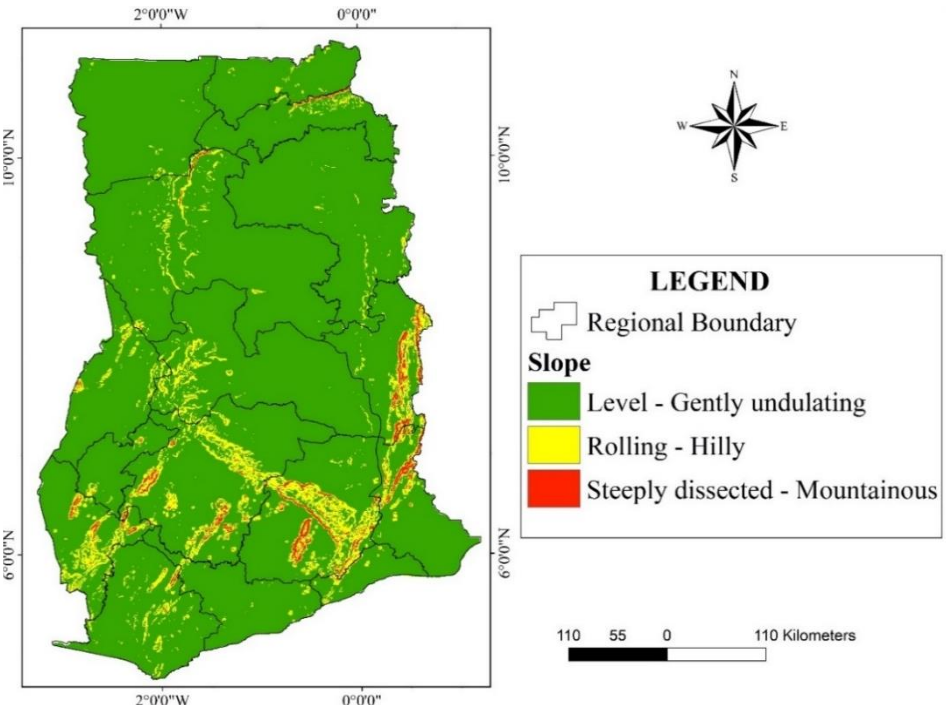

Figure 5.22: Generalized Slope Map

In agro-ecological zoning, slope classes are considered very important since it describes the suitability, challenges, and possible agricultural management practices in different AEZs. Generally, from Figure 5.22, Ghana's terrain is relatively flat. This has implications for agriculture and other land uses.

5.13.3 Description of Aspect map layer

Using the same 30 m DEM of Ghana, the GIS process-based aspect tool was used to process the spatial imagery and created 9 initial Aspect classes (Figure 5.23). Then, using the reclassify tool, the nine Aspect classes were further reclassified into four main cardinal points (North, South, East and West) in Figure 5.24.

In the current study, reclassification of Ghana's AEZs, it is the final generalized four aspect map layer that was used, enabling description of the direction of the reclassified slope across the zones. The initial 9 Aspect map

(5.23) and final generalized four cardinal points Aspect maps (Figure 5.24) are shown here.

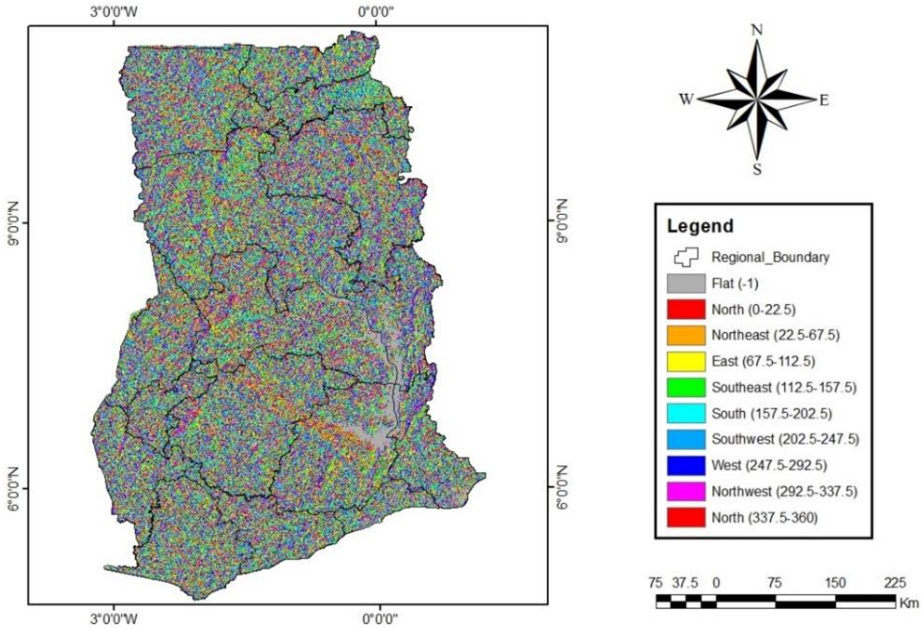

Figure 5.23: Initial 9 Aspect classes map

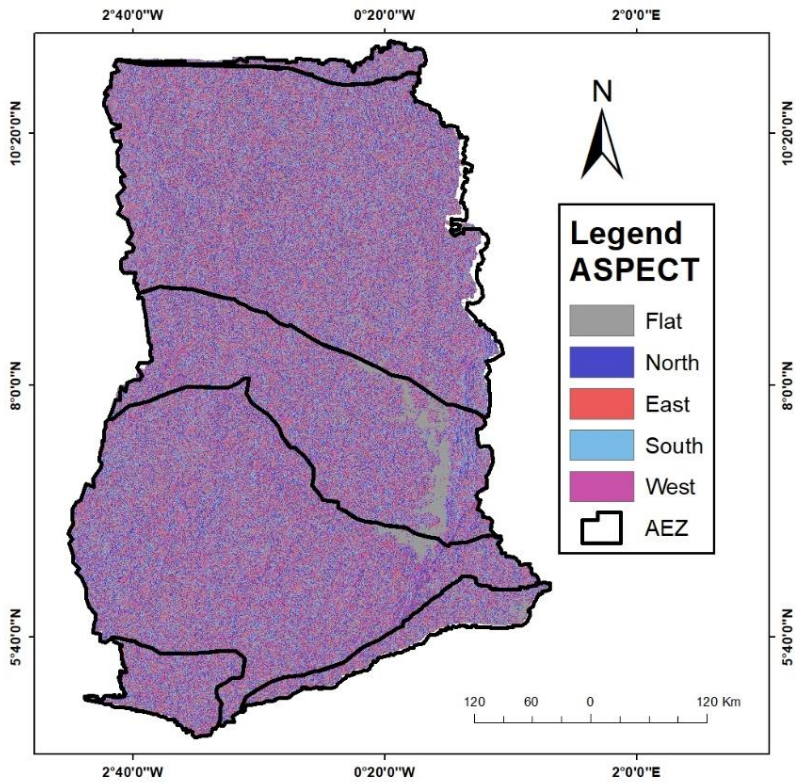

Figure 5.24: Final 4Aspect classes

5.13.4 Elevation map

Similarly, in current agro-ecological zoning, the inclusion of elevation classes is considered very important. This is because, it combines with other parameters to comprehensively describe the suitability, challenges, and possible agricultural management practices of different AEZs. Still, using the same 30 m DEM of Ghana, the GIS spatial analyst tool, the imagery was again analyzed for elevation. The initial analysis showed produced elevation classes. This result is presented in Figure 5.25.

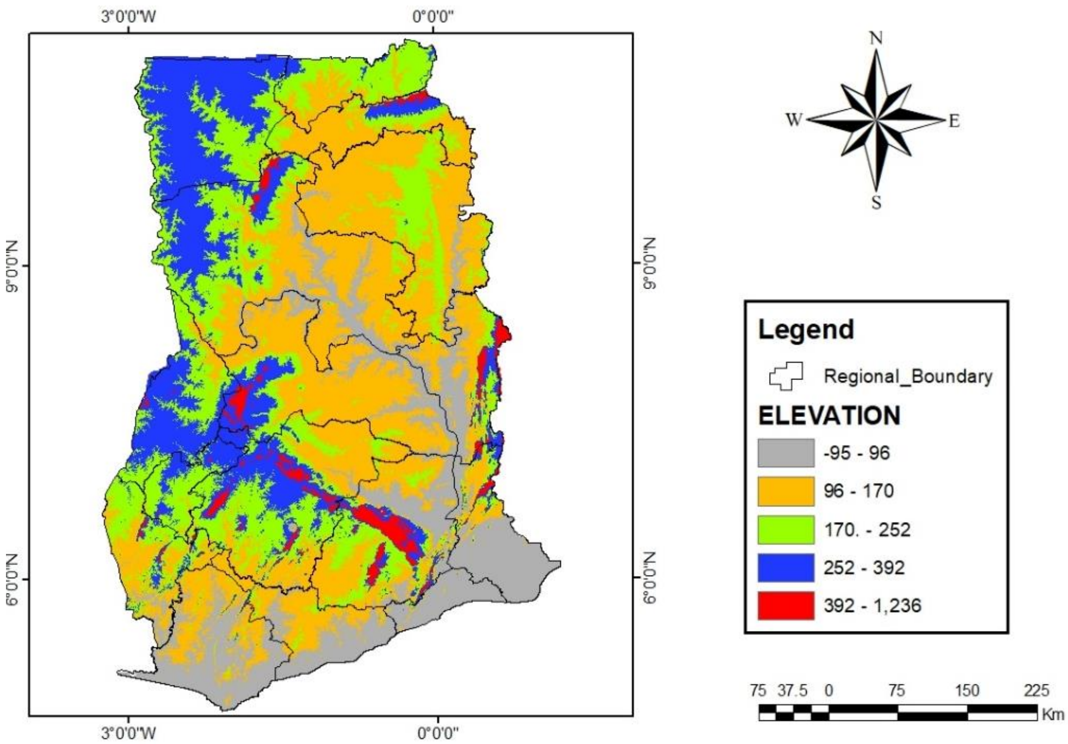

Figure 5.25: Initial five elevation classes

Subsequently, the reclassify tool assisted in the reclassification of the five classes into two main classes based on FAO threshold: <100 m (lowland) and above (>100 m).

The final generalized elevation map layer is presented in Figure 5.26.

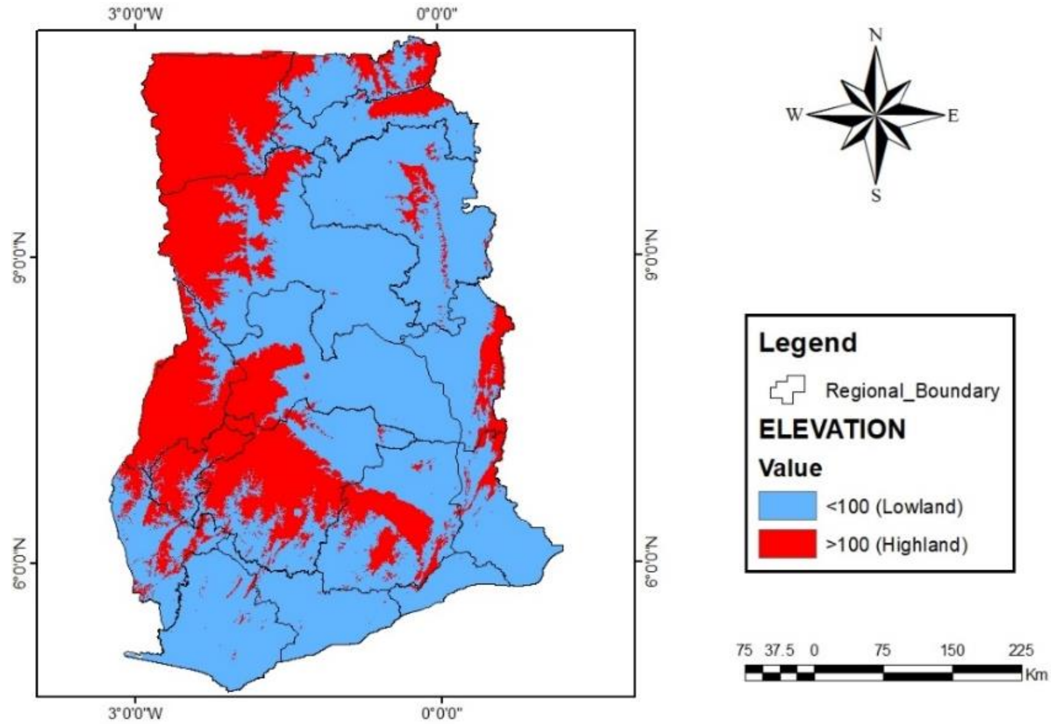

Figure 5.26: Elevation map of Ghana

5.13.5 Description of soil map

To achieve a comprehensive agro-ecological classification of Ghana, the inclusion and processing of soil types map is considered important. The soil map layer was combined with other parameters to describe the suitability, challenges, and the possible agricultural management.

The delineated soil map of Ghana, which was used as input for the new GIS AEZ of Ghana, involved a digitization processes. The soil map of Ghana was digitized from the RGS-WRB in Google Earth engine, a classification that offers international standard, having improved soil dataset, and highly compatible with GIS. The digitized soil map was correctly geo-referenced using the image-to-image registration technique and the image processing software in ArcGIS-10.5.

The final soil map used as a GIS layer for the agro-ecological classification was created with an attribute file. The initial digitization process produced a-16 WRB-RSGs correlation with the Interim Ghana Great soil groups. The initial 16 soil groups are in presented in Figure 5.27.

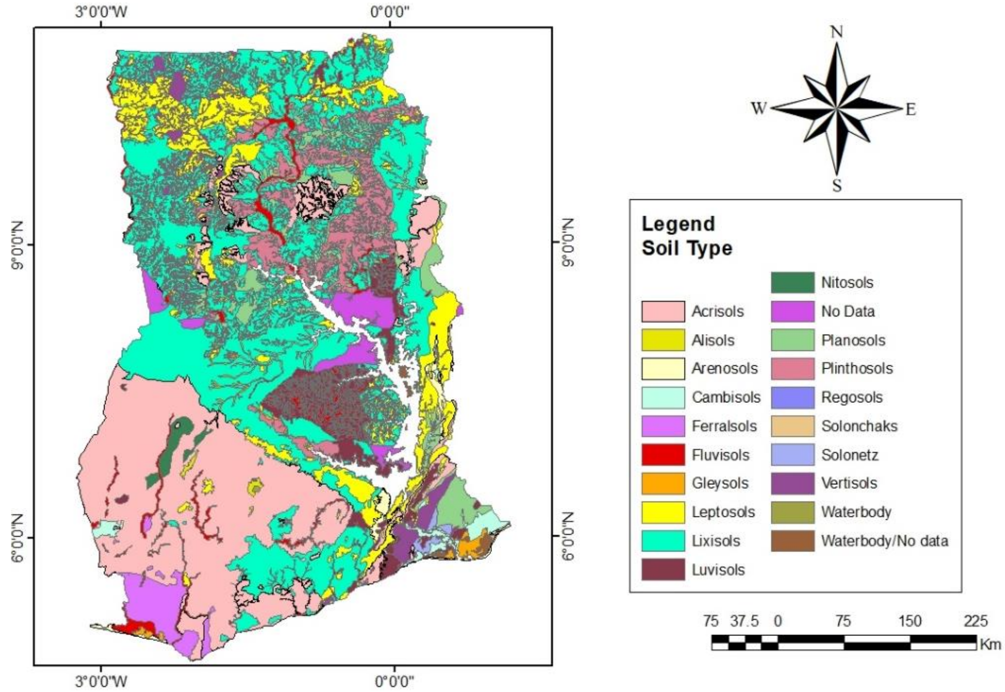

Figure 5.27: Initial 16 soil classes of Ghana

Subsequently, the reclassify tool, again, assisted in a systematic reclassification of the 16 classes into five soil unit classes. The soil classes were grouped based on their homogenous climatic, vegetation, potential agricultural suitability, and assessment of management practice in relation to FAO (1991) criteria.

The five soil units are: Very suitable for agriculture (Alisols, Nitisols, and Luvisols); Suitable with proper management (Acrisol, Ferrasols, Lixisols, cambisols, and Fluvisol); Management-intensive agriculture (Planosol and Regosols); Management-intensive with limitations (Arenosls, Glyesols, and Vertisols); and finally, Limited agricultural potentials (Plinthosols, leptosols, Solonchaks and Solonetz).

The generalized elevation map layer is presented in Figure 5.28.

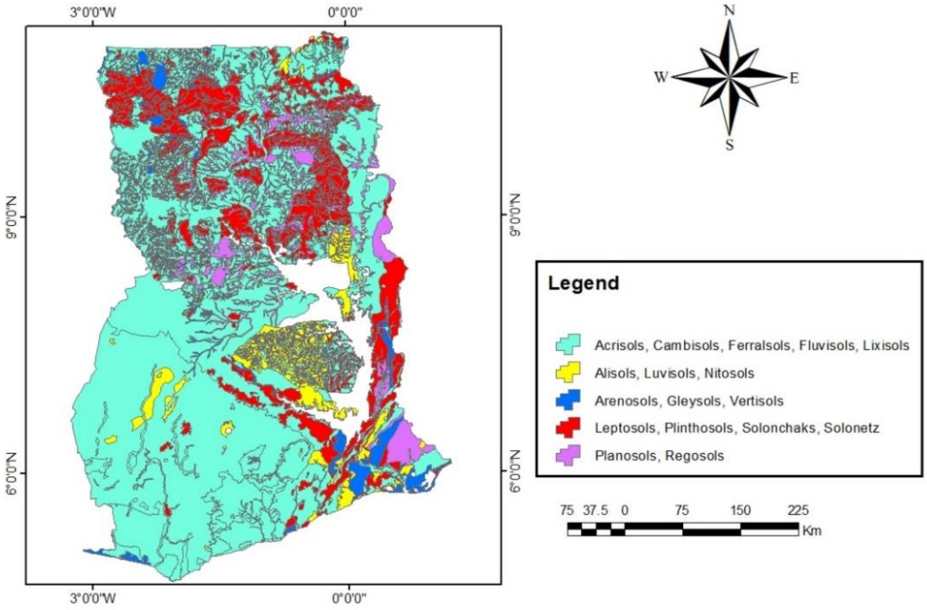

Figure 5.28: Generalized Soil unit map of Ghana

5.13.6-edaphic map

Similarly, following the same multi-criteria over-lay analysis criteria, the individual maps of the key agro-edaphic variables were also weighted and systematically overlaid. The individual agro-edaphic parameters included generalized soil unit types, generalized slope, generalized elevation, and generalized land use land cover layers. The resultant agro-edaphic map was delineated into six classes or zones. This is shown in Figure 5.29.

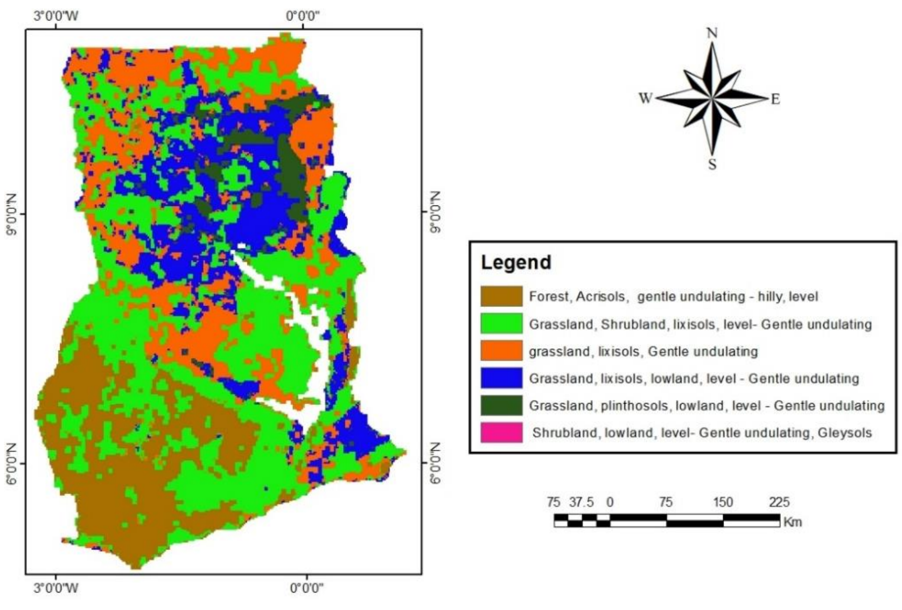

Figure 5.29: Agro-edaphic map of Ghana

5.14.1 A Step-by-Step Dynamic AEZ Methodology for Ghana

To develop a dynamic and sustainable methodology for reclassifying Ghana's Agro-Ecological Zones (AEZs), the study employed an integrated process combining agro-climatic, edaphic, and topographic data within a GIS-based Analytical Hierarchical Process (AHP) framework. The approach systematically incorporated data acquisition, preprocessing, standardization, and multi-criteria spatial analysis to delineate spatially homogeneous zones that are adaptive to future changes in climate, land use, and technology.

The methodology began with the acquisition of agro-climatic variables, including Mean Annual Rainfall (MAR), Length of Growing Period (LGP), End of Season (EOS), Start of Season (SOS), Mean Temperature (TMEAN), Relative Humidity (RH), Potential Evapotranspiration (PET), and Rainy Days (RDAYS). These datasets were converted into raster layers for spatial analysis. MAR was categorized into six classes (<700 mm, 700–940 mm, 941–1181 mm, 1181–1422 mm, 1423–1664 mm, >1665 mm), while LGP was classified into six ranges (<60 days, 60–90 days, 90–120 days, 120–150 days, 151–180 days, >180 days). Similarly, TMEAN was grouped into five ranges (<20.1°C, 20.1–22.5°C, 23.6–26.1°C, 27.1–28.6°C, >32.1°C), and RH was categorized into six intervals (0–49%, 50–57%, 60–69%, 70–79%, 80–89%, >90%). PET values were grouped into six ranges (<1730 mm, 1731–1871 mm, 1872–2013 mm, 2014–2154 mm, 2155–2295 mm, >2296 mm), and RDAYS were divided into six classes (<30 days, 31–60 days, 61–70 days, 71–80 days, 81–90 days, >90 days).

Edaphic datasets included reclassified soil types grouped into five management and suitability classes: very suitable (e.g., Alisols, Nitisols, Luvisols), suitable with proper management (e.g., Acrisols, Ferralsols, Lixisols), management-intensive agriculture (e.g., Planosols, Regosols), management-intensive with limitations (e.g., Arenosols, Gleysols, Vertisols), and limited agricultural potential (e.g., Plinthosols, Leptosols). Topographic parameters were derived from DEM and reclassified into slope classes (0–8%, 8–30%, >30%), elevation classes (lowlands <100 m, highlands >100 m), and aspect classes (North, South, East, West). Land Use and Land Cover (LULC) was reclassified into six categories: forest land, rangeland, wetland, agricultural land, water bodies, and built-up/barren land.

To standardize and harmonize these diverse datasets, all raster layers were resampled to a uniform spatial resolution of 30m. Continuous data like MAR and TMEAN were interpolated using bilinear resampling, while categorical data such as soil types and LULC classes were processed with nearest-neighbor resampling to preserve classification accuracy. Normalization followed using min-max scaling, transforming all parameter values into a range of 0 to 1 for comparability. This process ensured that data with varying units and ranges could be integrated seamlessly.

The Analytical Hierarchical Process (AHP) was applied to assign weights to each parameter based on their relative importance to AEZ delineation. Saaty's pairwise comparison matrix (1–9 scale) facilitated the calculation of normalized weights, which were aggregated using GIS-based spatial modeling. The weighted parameters were overlaid to produce composite maps that represent the interactive relationships among agro-climatic, edaphic, and topographic factors.

The final AEZ delineation, presented in Chapter Eight, reflects spatially homogeneous zones optimized for agricultural productivity and sustainable resource management. This methodology not only updates Ghana's AEZ classification but also provides an adaptable framework for future revisions, ensuring resilience to climatic, land-use, and technological changes. It offers a robust tool for policymakers, researchers, and practitioners to guide decision-making at local and national levels.

5.15 Flow Chart for Reclassification of Ghana's AEZs

In the process of reclassifying Ghana's Agro-Ecological Zones (AEZs), this study employed a GIS-RS process-based flow model (Figure 5.29) that addresses existing criticisms and challenges associated with previous AEZ methods in Ghana and elsewhere. The model emphasizes a dynamic and systematic approach to AEZ classification, allowing for regular updates under changing climatic conditions, land use patterns, methodological improvements, and advancements in data and technology. This adaptability ensures that AEZs remain relevant and responsive to evolving environmental and agricultural needs.

The flow chart begins with a critical decision point, the "start," which assesses whether the current AEZ or its methodology has become obsolete. This decision is triggered by significant changes in key factors such as climate, land use, technological advancements, or the availability of improved datasets. If the need for reclassification is identified, the next step involves identifying essential agro-climatic and agro-edaphic parameters. These datasets are sourced from observed ground-based data provided by GMET stations and remotely sensed satellite data.

Geospatial imagery and raster datasets from satellite missions, including

ASTER, MODIS-16, and Sentinel-2, are used to generate relevant inputs such as DEM, digitized soil maps, and LULC imagery. Rigorous data correction, validation, and smoothing techniques are applied to both observed and remotely sensed data. Statistical and GIS-based spatial analysis tools such as interpolation, classification, reclassification, and boundary cleaning ensure the accuracy and consistency of the datasets during processing.

The reclassified raster maps representing different parameters are then standardized using Saaty's pairwise comparison approach. Criteria are weighted and aggregated through the Analytical Hierarchical Process (AHP), which serves as a multi-criteria decision-making tool. This process integrates and balances the diverse parameters, creating spatially homogenous zones that reflect Ghana's new AEZs

The flow model is also designed to evaluate the need for future revisions. If significant changes in climate, land use patterns, data availability, or technological advancements are observed, the process loops back to initiate a new cycle of reclassification. However, if no substantial changes are detected, the process concludes with an "end".

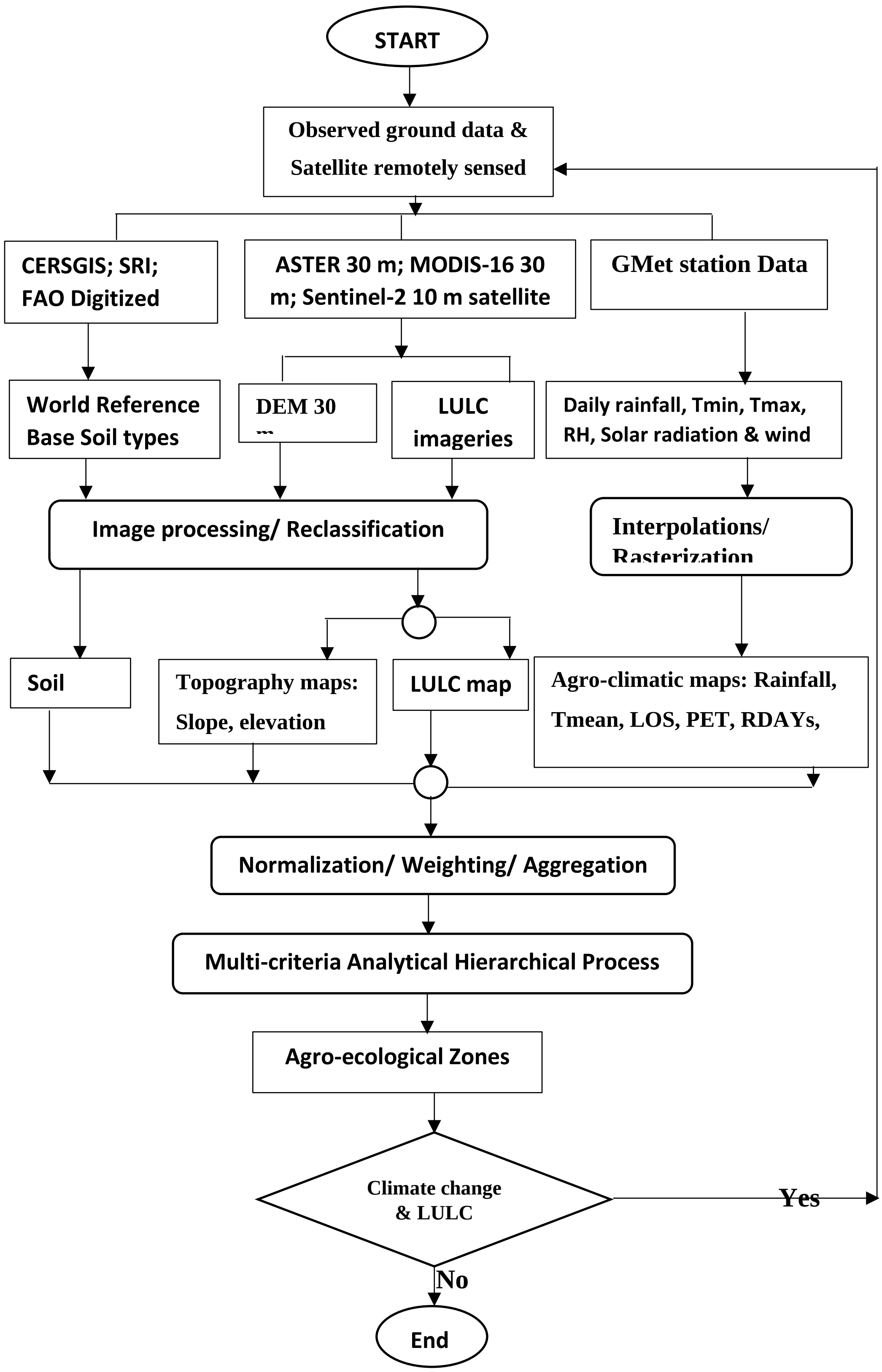

Figure 5.30: Flow chart for dynamic AEZ of Ghana

5.16 Ethical considerations

The researcher took ethical considerations seriously to uphold academic integrity and ensure the success of the study. To establish trust and gain consent from relevant authorities at the Ghana Meteorological Agency, an informed consent document detailing research objectives and ethical observations, such as data protection, anonymity, and privacy handling, was designed and sent to the Managing Director. This collaboration with GMET facilitated access to the necessary climatic datasets for the study. The researcher avoided plagiarism by acknowledging all authorities, organizations, and agencies whose works, reports, or data were used or cited in the study. Proper citations and references were provided in the text and reference section, ensuring the acknowledgment of primary and secondary data sources accessed during the literature review

5.17 Limitations

This study focused on reclassifying Ghana's agro-ecological zones (AEZs) primarily using secondary quantitative data related to agro-climatic and agro-edaphic variables. The conduct of nationwide surveys to gather direct quantitative and qualitative data from the six national AEZs, though ideal was limited by obvious time and financial constraints. Instead, but proactively, remotely sensed datasets thus provided the quantitative information (geo-spatial data), which were analysed and interpreted to understand the changes and the spatial characteristics of the existing national AEZs. While qualitative data could offer additional subjective insights, the use of remotely sensed data allowed for quantitative analysis, focusing on measurable variables and spatial patterns. This approach was chosen as a cost-effective alternative to overcome the limitations and still provide valuable information about the AEZs in Ghana.

Similarly, the study used only the 22 synoptic stations, despite their uneven distribution. These stations were selected based on their reliability and adequacy of data within the chosen climate window of 1991-2020. They represented the geo-climatic stations of the AEZs and provided the most reliable results for examining changes in the AEZs under the current climatic and LULC change.

To address challenges with data gaps and anomalies in the climate datasets, the study employed the last-observation-carried-forward (LOCF) approach and GIS process-based spline interpolation using CMIP 6 for gap correction and consistency. These methods ensured the derivation of a more reliable climate dataset for subsequent analysis and the generation of map layers for the final agro-ecological classification of Ghana. The availability of historical LULC data for analysis was limited, but the two decades' worth of LULC imageries were considered climatologically adequate and suitable for assessing changes in LULC and their impacts on AEZs within the chosen climate window. By leveraging available data and employing suitable techniques, the study aimed to develop robust datasets that could support an efficient AEZ methodology for the effective reclassification of Ghana's agro-ecological zones. The insights gained from this research will be valuable for stakeholders' decision-making processes.

5.18 Chapter summary

This chapter details the methods for data processing, statistical testing, and analysis, including standardization, trend analysis, and significance testing. It introduces a new AEZ methodology for Ghana, designed to address climatic, LULC, and technological changes, offering a sustainable adaptation framework for dynamic environmental and data-driven challenges

CHAPTER SIX

CHANGES IN GHANA'S AEZS: EVIDENCE FROM THE ANALYSIS OF KEY AGRO-CLIMATIC PARAMETERS

6.1 Introduction

Chapter Six examines spatiotemporal changes in the key agro-climatic parameters, MAR, MAJ-LGP, and MIN-LGP across, used to define Ghana's old FAO AEZs. In this analysis, the study adopted current 30-year (1991–2020) long-term zonal mean (CLT-Zmean) with the old FAO zonal mean (FAO-Zmean) thresholds to standardize the derived MAR and LGP datasets for all stations and zonal aggregates, deriving z-scores for comparative analysis against FAO thresholds. This method identifies long-term mean shifts (CLT-Zmean vs. FAO-Zmean), inter-decadal variations (within long-term trends and means), and intra-zonal differences (stations vs. FAO-Zmean) across all AEZs.

Key methods, including ANOVA, assessed significant differences in trends and means, while Pearson's correlation analyzed relationships between FAO-Zmean, CLT-Zmean, and station-level datasets. Additional analyses explored the relationships of MAR, MAJ-LGP, and MIN-LGP with PET, RDAYS, TMEAN, RH, SOS, and EOS to evaluate the broader impacts of climate variability. Time series graphs, column bar charts, tables, and spatial maps showed results, and providing insights into temporal and spatial dynamics.

The chapter presents results by first providing an overview of FAO thresholds, climatological mean shifts, inter-decadal variations, and intra-zonal differences in MAR and LGP, zonal summaries, inter-zonal spatio-temporal result discussions, concluding with chapter summary emphasizing implications for adaptive agricultural planning and climate resilience in Ghana's AEZs.

6.2 Evidence for Changes in the Sudan Savannah Agro-ecological zone

According to the existing FAO agro-ecological classification, the Sudan Savanna AEZ (SSAEZ) is defined by a 155-day Length of Growing Period (LGP), a unimodal rainfall season from May to September, and a Mean Annual Rainfall (MAR) of 1,000 mm. Analysis of a 30-year (1991–2020) historical climate dataset established updated long-term (CLT) mean thresholds for the zone, revealing a reduced MAR of 966 mm (± 153) and an extended LGP of 183 days (± 21) for both MAJ-LGP and MIN-LGP.

6.2.1 Climatological shifts in the FAO zonal MAR and LGP thresholds

To establish climatological changes in the existing FAO-zonal mean thresholds for MAR and LGP, 30-year standardized FAO-Zmean and CLT-Zmean datasets were analyzed for long-term trends and means using ANOVA to test for significant differences and Pearson correlation to evaluate relationships between datasets. Time series line graphs were employed to visualize yearly and long-term trends in MAR and LGP for SSAEZ. Figure 6.31 illustrates the long-term trends observed in MAR, represented by the FAO-Zmean and CLT-Zmean z-scores.

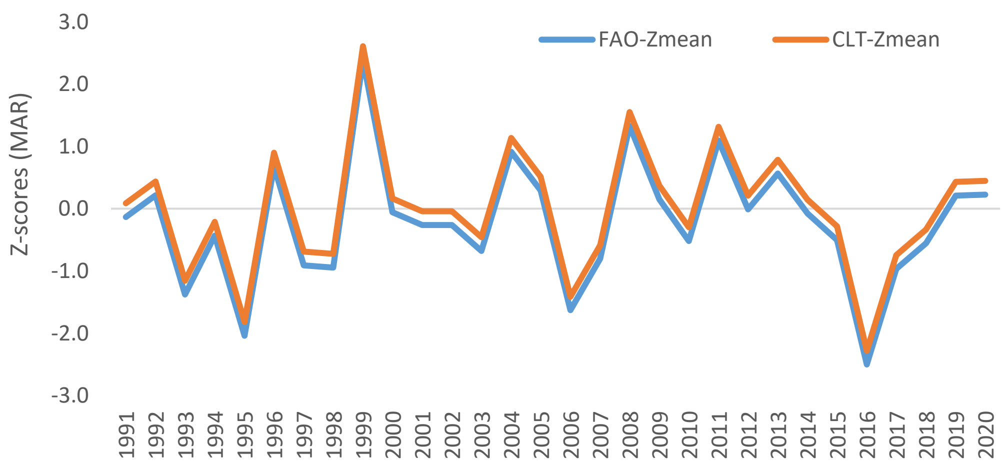

Figure 6.31: Standardized FAO-Zmean and CLT-Zmean MAR trends.

From Figure 6.31, the long-term trend in mean annual rainfall (MAR) shows a general decreasing pattern for both the FAO-Zmean (-0.25) and CLT-Zmean (-0.03) datasets. The Pearson correlation coefficient reveals a perfect positive correlation (1.0) between the two zonal datasets, indicating consistency in their observed trends. The climatological long-term mean for the FAO-Zmean dataset also shows a decrease (-0.22), while the CLT-Zmean z-scores dataset remains stable (0.00). The decreases (trend and mean) in the FAO-Zmean dataset align with the observed difference of -34 mm between the existing FAO-Zmean (1,000 mm) and CLT-Zmean (966 mm) MAR thresholds.

To test for significant differences in the climatological means and trends between the FAO-Zmean and CLT-Zmean datasets, the single-factor ANOVA yielded a p-value of 0.397 at an alpha of 0.05. This indicates that the observed differences in long-term means and trends are not statistically significant.

While the findings suggest that the existing FAO-Zmean for MAR has decreased over the past 30 years, the reduction is not statistically significant. However, it is crucial to consider revising the old MAR threshold to better align with the current climate dynamics, environmental conditions, and LULC changes in the SSAEZ. This would provide more accurate information for agricultural planning and sustainable land management in the zone.

Similarly, Figure 6.32 was used to present the results analyzed for long-term trends in the standardized FAO-Zmean and CLT-Zmean LGP datasets. From Figure 6.32, the 30-year analysis of LGP trends shows an increase of 1.1 in the FAO-Zmean z-scores dataset, while the CLT-Zmean dataset indicates a slight decrease of -0.3. Similarly, for the climatological long-term mean, the FAO-Zmean z-scores show a significant increase of 1.3, compared to a slight increase of 0.01 in the CLT-Zmean dataset.

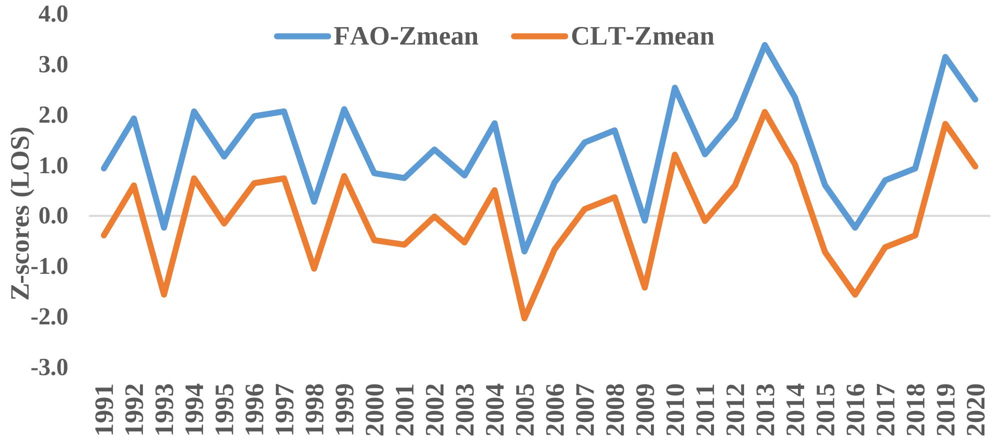

Figure 6.32: Standardized FAO-Zmean and CLT-Zmean LGP trends LGP Anomalies

The Pearson correlation coefficient reveals a perfect positive relationship (1.00) between the two datasets. A single-factor ANOVA test yielded a p-value of 4.95×10^{-6} at an alpha level of 0.05, indicating statistically significant differences in the means and trends between the FAO-Zmean and CLT-Zmean LGP datasets. These findings align with the observed mean difference of +28 days between the existing FAO threshold (155 days) and the CLT threshold (183 days), confirming that the FAO-LGP threshold no longer accurately represents the SSAEZ,

The increase in LGP underscores climate change impacts and the need for updated strategies. Policymakers and farmers should adjust planting schedules, optimize crop choices, and refine management practices to leverage benefits and address challenges

6.2.2 Inter-decadal and long-term variability in MAR and LGP

The analysis of temporal variability provided critical insights into inter-decadal patterns (1991–2000, 2001–2010, 2011–2020) compared to the long-term means and trends (1991–2020) in the standardized FAO-Zmean MAR and

LGP datasets. Figure 6.33 illustrates the inter-decadal and long-term differences in means and trends for the FAO-Zmean MAR z-scores, with results visually represented through column bars and ANOVA tested temporal variability.

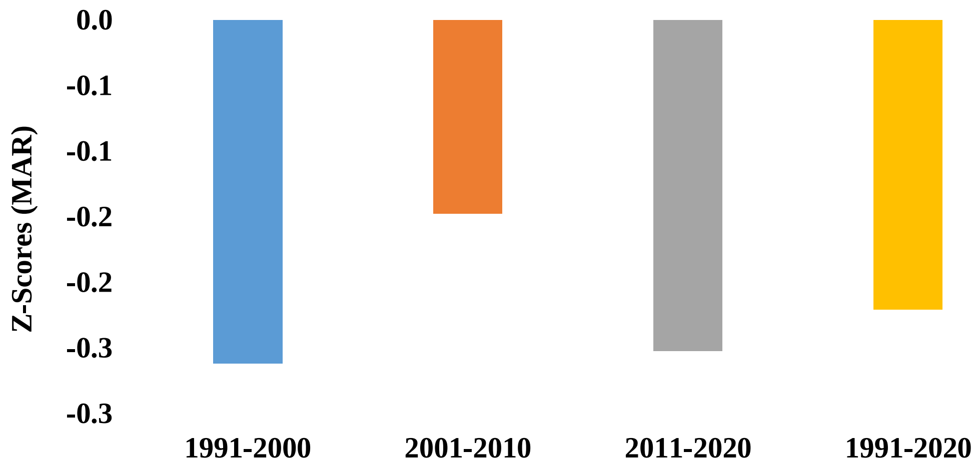

Figure 6.33: Standardized FAO-Zmean MAR Decadal and Long-term anomalies.

Based on Figure 6.33, the inter-decadal and long-term means for the FAO-Zmean z-scores indicate consistent decreases in the MAR agro-climatic parameter across all four periods (-0.3, -0.12, -0.3, -0.2). LINEST regression analysis shows a decreasing trend in MAR across all four-analysis period. ANOVA test reveals a statistically significant difference in both the means and trends across the four periods, with a p-value of 3.33E-10 at an alpha level of 0.05. The consistent inter-decadal and long-term decreasing trends in the MAR z-scores justify the need to revise the existing FAO zonal threshold for the SSAEZ. Similarly, the ANOVA test for inter-decadal variability further emphasizes the need for a regular and dynamic agro-ecological classification methodology that would guide the decision making of stakeholders.

Likewise, Figure 6.34 reveals the results analyzed for the inter-decadal and long-term means and the trends observed in the standardized FAO-zonal

LGP mean (z-scores) dataset.

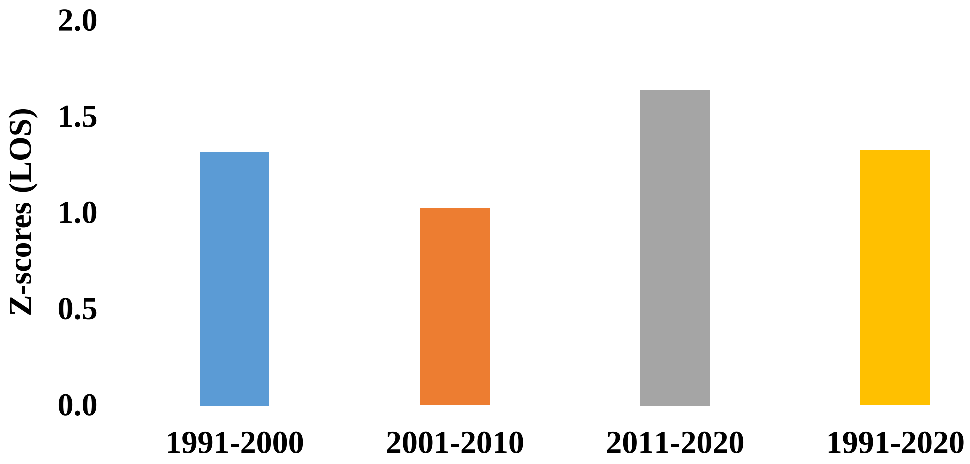

Figure 6.34: Standardized FAO-Zmean LGP Decadal and Long-term anomalies

The results in Figure 6.34 reveal significant inter-decadal and long-term increases in the standardized FAO-Zmean LGP z-scores, with trends of 1.2, 0.7, 1.6, and 1.1 for the periods 1991–2000, 2001–2010, 2011–2020, and 1991–2020, respectively. Similarly, increasing mean values of 1.3, 1.0, 1.6, and 1.3 were observed for the same periods. The Pearson coefficient (1) indicates a perfect positive correlation, reinforcing the consistent increases in both trend and mean over the three decades and long-term period. ANOVA results, with a p-value of 0.0003 at a significance level of 0.05, confirm significant temporal differences in the FAO-Zmean LGP z-scores across the four periods.

These findings highlight clear temporal variability and substantial changes in the FAO zonal LGP over time. It is recommended that a regular decadal revision approach be adopted for updating SSAEZ thresholds.

6.2.4 Multiple correlations for the key agro-climatic variables

Additionally, the analysis for changes in SSAEZ included testing correlations between key agro-climatic variables (MAR, MAJ-LGP, and MIN-LGP) and other relevant parameters, such as PET, RDAYS, TMEAN, SOS, and

EOS. This approach aimed to uncover associations and trends among these variables, providing a deeper understanding of the interactions influencing the agro-climatic conditions in the zone. The results of the multiple Pearson correlations are presented in Figure 6.35

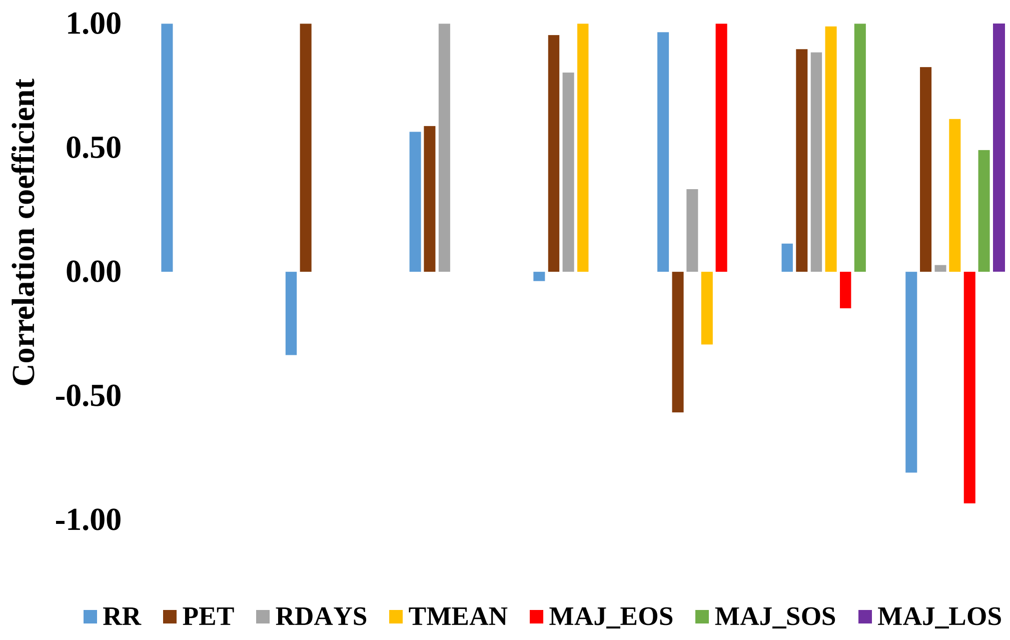

Figure 6. 35: Multiple Pearson correlation for agro-climatic parameters

From Figure 6.35, MAR (RR) exhibits a positive correlation with RDAYS (0.6) and EOS (0.97), indicating that higher MAR is associated with more rainy days and a later cessation of rainfall. Conversely, MAR shows a strong negative correlation with MAJ-LGP (-0.8), suggesting that as MAR decreases, the length of the growing period increases.

Furthermore, MAJ-LGP is positively correlated with PET (0.8), TMEAN (0.6), and SOS (0.5), implying that longer growing periods are associated with higher potential evapotranspiration, increased mean temperatures, and delayed rainfall onset. However, MAJ-LGP displays a strong negative correlation with MAR (-0.8) and EOS (-0.9), indicating that as the growing period lengthens, MAR and EOS tend to decrease within the SSAEZ.

6.2.5 Summary of zonal decadal and long-term MAR and LGP trends

The results of integrated analysis for changes in the SSAEZ involved combining and comparing the means and trends in the long-term and decadal FAO-Zmean MAR, MAJ-LGP, and MIN-LGP standardized datasets over the four periods. Figure 6.36 presents the summary results.

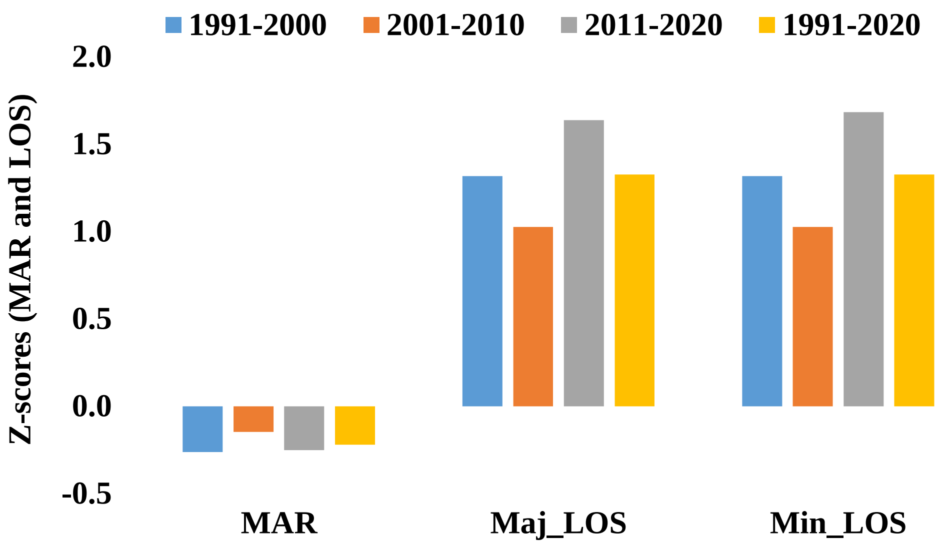

Figure 6.36: Summary decadal and long-term FAO-zonal MAR and LGP anomalies.

From Figure 6.36, the analysis shows a continuous decrease in FAO zonal mean annual rainfall (MAR) z-scores over inter-decadal and long-term periods, with a long-term mean reduction of -0.25. ANOVA results indicate no significant differences in climatological means and trends between FAO-Zmean and CLT-Zmean z-scores (p-value = 0.396) but reveal significant temporal variability across periods (p-value = 0.005).

Similarly, LGP z-scores (MAJ-LGP and MIN-LGP) show significant increases, with a long-term mean of 1.3 and a trend of 1.1. ANOVA tests for LGP means and trends yielded p-values of 0.0003 and 0.002, confirming notable changes in FAO LGP thresholds for the SSAEZ.

The results highlight a -34 mm difference between the old FAO-Zmean MAR threshold (1,000 mm) and the new CLT-Zmean (966 mm), alongside a +28-day increase in LGP from 155 to 183 days. These changes confirm that the SSAEZ still experiences a single growing season but underscores the obsolescence of the current FAO thresholds.

It is concluded that the FAO thresholds for MAR and LGP should be updated to reflect current climatic and land-use patterns. These findings provide crucial insights into the impacts of climate change on rainfall and growing periods in the SSAEZ, supporting better agricultural planning and climate adaptation strategies.

6.3 Evidence for Changes in the Guinea Savanna Agro-ecological zone

The Guinea Savanna AEZ, traditionally characterized by a mean annual rainfall (MAR) of 1,100 mm and a single rainy season spanning May to September, had its length of growing period (LGP) set at 190 days under the FAO classification. Based on a 30-year historical climate analysis, this study established updated thresholds, revealing a revised MAR of 1,103 mm (±140) and a significantly reduced LGP of 135 days for both major and minor growing periods.

6.3.1 Climatological shifts in old FAO zonal MAR and LGP thresholds

To assess changes in the FAO thresholds for MAR and LGP, the 30-year standardized FAO-Zmean and CLT-Zmean datasets were analyzed for long-term trends and means. ANOVA and Pearson’s correlation were employed to evaluate differences and relationships in the trends and means between the datasets. Figure 6.37 presents the trends observed for the MAR z-scores

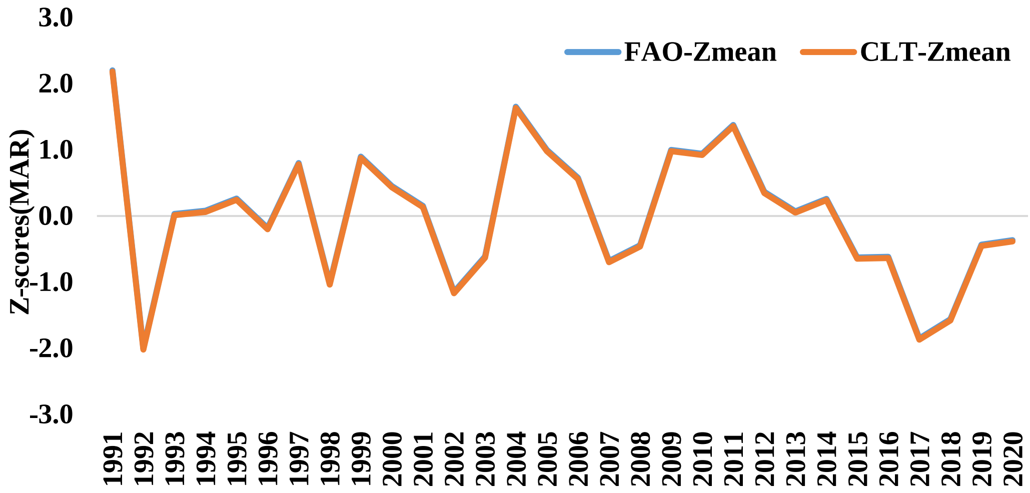

Figure 6.37: Standardized FAO-Zmean and CLT-Zmean MAR trends

Over the long term (1991-2020), Figure 6.37 reveals a decreasing trend in mean annual rainfall (MAR) for both the FAO-Zmean and CLT-Zmean z-scores datasets. The FAO-Zmean dataset shows a slight increase in the trend (0.38), while the CLT-Zmean dataset shows a slightly higher increase (0.40). In terms of climatological means, the FAO-Zmean dataset shows a minor increase (0.02), while the CLT-Zmean dataset shows no change (0.00). This confirms the small mean difference (3 mm) between the existing FAO-zonal mean (1,100 mm) and the current long-term zonal mean (1,103 mm) for MAR in the GSAEZ.

The Pearson correlation coefficient between the long-term means and trends for the FAO-Zmean and CLT-Zmean z-scores shows a perfect positive correlation (+1), indicating consistency in the decreasing MAR trends. The ANOVA test, with a p-value of 0.940 at a 0.05 alpha level, shows no statistically significant difference in the long-term means and trends for the FAO-Zmean and CLT-Zmean MAR datasets.

These results suggest that while the FAO zonal MAR threshold has changed, the change is not statistically significant. However, in light of ongoing climatic, environmental, and land-use changes, it is appropriate to consider updating the MAR threshold for GSAEZ to provide more accurate agro-climatic data for agricultural planning.

Likewise, Figure 6.38 was used to present the results of the analysis performed for long-term trends observed in the FAO-Zmean and CLT-Zmean LGP Z-scores datasets.

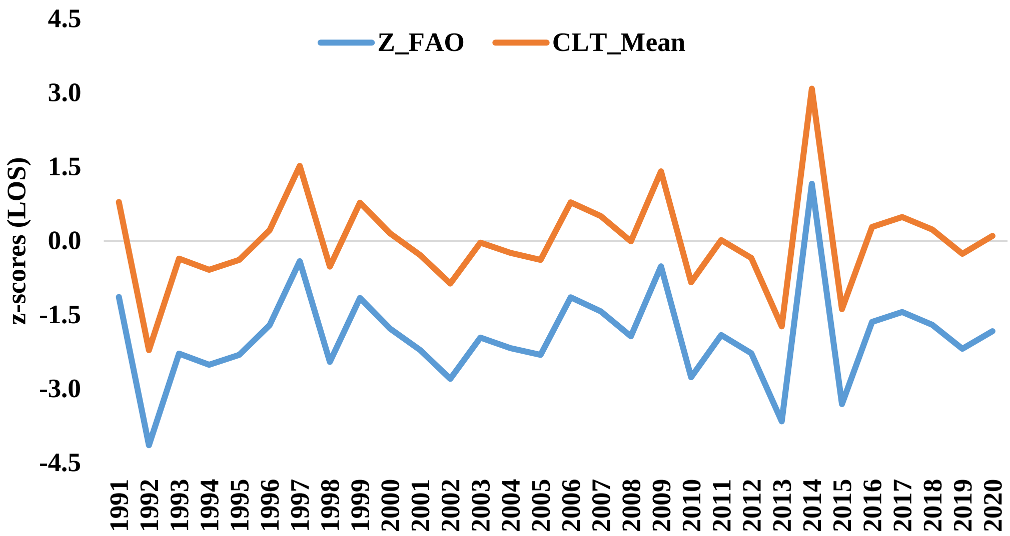

Figure 6.38: Standardized FAO-Zmean and CLT-Zmean MAR trends

The results in Figure 6.38 reveal a general increase in the length of growing period (LGP) days over the past three decades. However, over the long term, the FAO-Zmean z-scores dataset shows a decreasing trend (-2.2) in LGP, while the CLT-Zmean z-scores dataset exhibits a smaller decreasing trend (-0.2). In terms of long-term means, the FAO-Zmean z-scores indicate a significant increase (-1.9) in LGP days, whereas the CLT-Zmean z-scores reflect a relatively small decrease (-0.01).

The Pearson coefficient (+1) indicates a strong positive correlation between the trends and means observed for the FAO-Zmean and CLT-Zmean datasets. Additionally, the ANOVA p-value (1.13E-09) at an alpha level of 0.05 confirms a statistically significant difference in the long-term trends and means between the FAO-zonal and CLT-zonal mean z-scores for LGP. These findings are consistent with the observed LGP mean difference (-65 days) between the FAO-zonal and CLT-zonal thresholds.

The results indicate that the existing FAO zonal LGP threshold is outdated and no longer reflects the GSAEZ. Revising the LGP threshold is crucial to align with current climatic, environmental, and land-use changes, enabling farmers, extension officers, and policymakers to address the challenges of a decreasing LGP effectively

6.3.2 Intra-zonal (FAO-zonal vrs stations) variability in MAR and LGP

Another significant analysis to describe the changes in the GSAEZ was the test for intra-zonal variability or shift in stations in the zone. By analyzing for the trend, correlation and ANOVA for the standardized FAO-zonal and stations MAR and LGP (MAJ-LGP and MIN-LGP) datasets, the evidence for any significant intra zonal variability (inconsistencies) in the zone was determined. In study, the GSAEZ was geo-climatic represented by Bole, Tamale, Wa and Yendi synoptic station for the four zonal stations for the GSAEZ. The analysis for intra zonal variability was thus done by calculating the long-term and inter-decadal trends and means for the individual stations and compared to their combined FAO-Zmeans z-scores.

Figure 6.39 presents the results of intra-zonal variability.

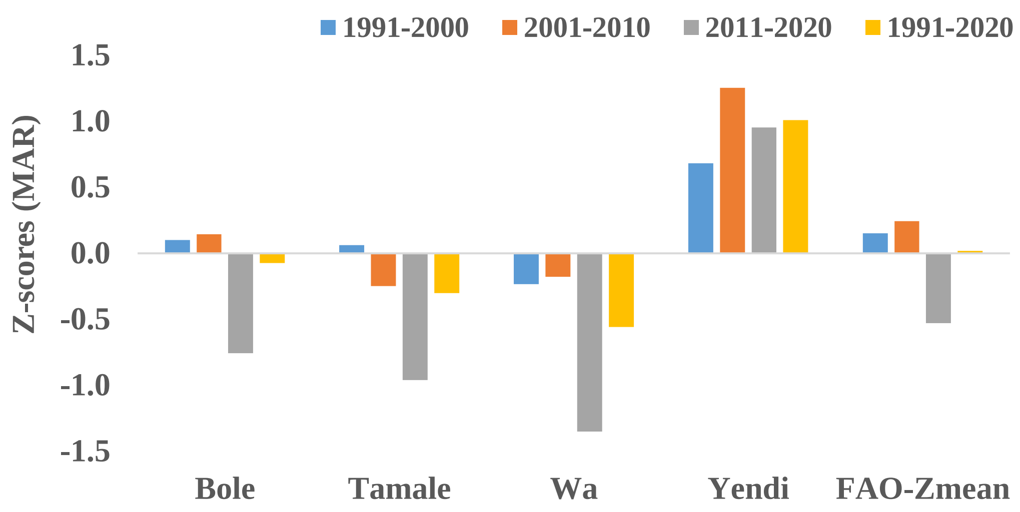

Figure 6.39: Standardized FAO-zonal and Stations Decadal and Long-term MAR anomalies

From Figure 6.39, the long-term climatological means observed for three stations (Bole, -0.1; Tamale, -0.3; and Wa, -0.6) show a decreasing MAR relative to the FAO-Zmean Z-scores dataset, which shows a slight increasing (0.02) mean annual rainfall. Similarly, relative to the FAO-Zmean, the Yendi station show a significant increase (1.0) in rainfall within the same zone. In the last and current decade, Bole, Tamele, and Wa stations all relate to the decreasing FAO-Zmean, but the Yendi station shows no association. In addition, for the first two decades, Bole and Yendi show an increasing means similar to the FAO, but still Yendi behaved significantly different.

The Pearson correlation matrix showed a strong positive correlation between the FAO-Zmean and Bole (0.8), Tamale (0.8) and Yendi (0.7); however, while the Wa observed a negative correlation (-0.6) with FAO-Zmean dataset. The ANOVA p-value (0.0001) at 0.05 alpha show a significant difference (variability) in the long-term means for the FAO-Zmean and the four stations analyzed. These results show significant intra-zonal discrepancies in the rainfall pattern observed within the GSAEZ.

Similarly, the standardized LGP (z-scores) was further analyzed to describe the intra-zonal variability of the GSAEZ. Figure 6.40 presents the intra-zonal variability results for the LGP.

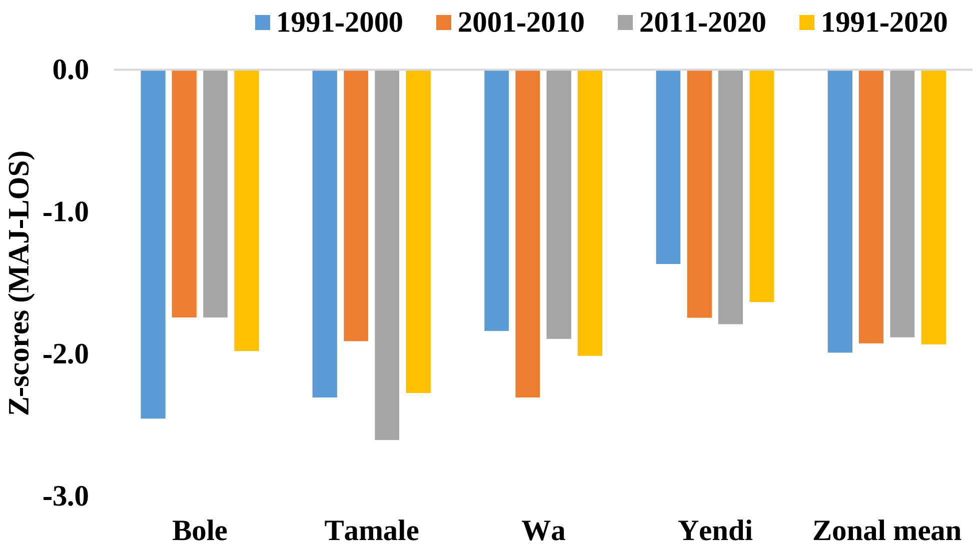

Figure 6.40: Standardized FAO-zonal and Stations Decadal and Long-term MAJ-LGP anomalies

From Figure 6.40, the findings showed a significantly consistent decreasing LGP days over the long-term from the stations z-scores and the FAO-Zmean z-scores datasets. Specifically, the Bole station showed a decrease of -2.0; Tamale, -2.3; Wa, -2.0; Yendi, -1.6, and FAO-Zmean, -1.9. Similarly, the inter-decadal periods reveal consistent significant decreasing means trend for all the groups.

The Pearson correlation showed a perfect positive (1) correlation between the FAO-Zmean datasets and the station's datasets). The ANOVA p-value (0.61) at an alpha (0.05), indicated no statistically significant intra-zonal differences or variability since all the five groups showed uniform decreasing long-term means. However, the results indicate that the FAO-Zonal mean LGP threshold for the GSAEZ has changed significantly, with direct consequences on agricultural and series of economic activities. The GSAEZ needs a reclassification based on the current LGP.

6.3.3 Decadal and long-term changes or variability in MAR and LGP

The analysis reveals significant inter-decadal and long-term changes in MAR and LGP patterns across the GSAEZ. From Figure 6.40, MAR trends show variability, with Yendi consistently increasing (0.7, 1.3, 1.1, 1.0), Wa decreasing (-0.2, -0.2, -1.3, -0.6), and mixed patterns for Bole and Tamale. The FAO-Zmean z-scores reflect a general increase in MAR during the first two decades (0.2, 0.2), a decrease in the third decade (-0.3), and a slight long-term increase (0.02). Pearson correlation tests show perfect positive correlations for Bole (1.0), strong correlations for Tamale (0.9), moderate for Yendi (0.8), and weaker for Wa (0.5). ANOVA results (p = 9.28E-05) confirm statistically significant inter-decadal and long-term variability in MAR across stations and the FAO-Zmean.

For LGP (Figure 6.40), all stations and the FAO-Zmean show consistent decreases across decades. For instance, Bole (-2.5, -1.7, -1.7, -2.6), Tamale (-2.3, -1.9, -2.6, -2.3), Wa (-1.8, -2.3, -1.9, -2.0), and FAO-Zmean (-2.0, -1.9, -1.9, -1.9) highlight significant temporal reductions. Pearson correlations confirm strong positive associations between Bole (1.0), Tamale (1.0), moderate for Yendi (0.8), and Wa (0.5). ANOVA (p = 0.02) indicates significant differences in LGP patterns across periods.

The findings reveal temporal shifts in MAR and LGP across the GSAEZ, with Yendi and Wa diverging and Bole and Tamale aligning with FAO-Zmean trends. Revising obsolete FAO thresholds through decadal reclassification is crucial to reflect current climatic and land-use conditions,

6.3.4 Multiple Pearson correlation for key agro-climatic variables

Additionally, the analysis for changes in GSAEZ included the test for correlations between the key agro-climatic (MAR, MAJ-LGP and MIN-LGP) and other relevant variables such as PET, RDAYS, TMEAN, SOS, and EOS. This analysis was done to better understand the associations and trends between and among the agro-climatic variables. The results for the multiple Pearson (R) correlation are shown in Figure 6.41.

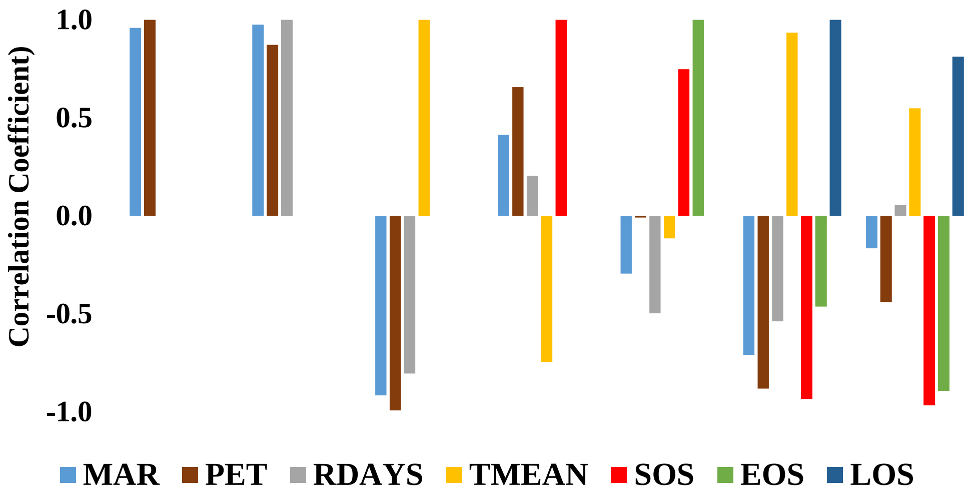

Figure 6.41: Multiple correlation for key agro-climatic parameters

From Figure 6.41, the results from the correlation matrix showed that MAR has a strong positive correlation with both PET (1.0) and RDAYS (1.0), and a weak SOS (5U 0.4). This means that higher values of MAR tend to be associated with more RDAYS and large PET values. However, MAR has a strong negative correlation with LGP (-0.7), Tmean (-0.9), and EOS (-0.3), indicating that as the MAR decreases, the LGP and Tmean increases. In the case of the LGP, the results showed a strong positive association with Tmean (0.9) and RDAYS (0.1), but it indicated a negative correlation with MAR, PET, RDAYS, SOS, and EOS; with Pearson correlation coefficients of -0. 7, -0.9, -0.5, -0.9 and 0.5 respectively.

6.3.5 Summary of decadal and long-term FAO-zonal MAR and LGP

The results of the coupled analysis to examine the changes in the FAO zonal MAR, MAJ-LGP, and MIN-LGP mean thresholds set for the Guinea Savanna agro-ecological zones have been shown in Figure 6.43. This analysis involved combining and comparing the long-term and decadal means and trends observed for the key agro-climatic parameters used to describe the GSAEZ from the FAO agro-ecological classification of Ghana. Figure 6.42 presents the final summary results.

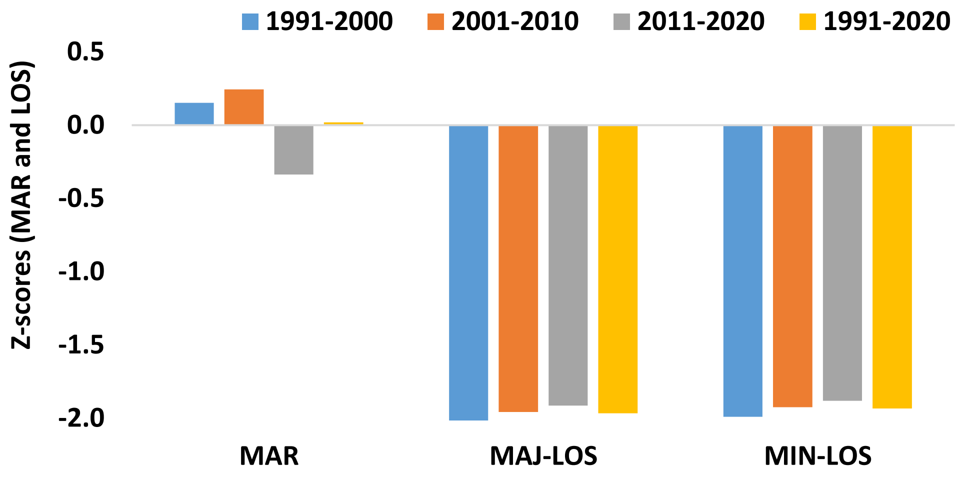

Figure 6.42: Summary decadal and long-term FAO-zonal MAR and LGP

From Figure 6.42, the FAO-Zmean standardized MAR dataset revealed an increasing trend during the first two decades, followed by a decrease in the third decade, resulting in a slight overall increase above the existing FAO-Zmean threshold. However, ANOVA results (p = 0.940) indicate no statistically significant difference in the long-term MAR between the FAO and CLT thresholds. Additionally, Figure 6.42 demonstrates significant uniform decreases in MAJ-LGP and MIN-LGP means across both inter-decadal and long-term periods. ANOVA results (p = 0.02) highlight a statistically significant shift in the LGP thresholds, emphasizing temporal variability and changing growing season dynamics. These findings indicate that the current FAO thresholds for the GSAEZ no longer accurately represent the zone's agro-climatic conditions. Revising the thresholds is essential to reflect the impacts of climate variability and land-use changes

6.4 Evidence for Changes in the Tropical Humid Agro-ecological Zone

According to the FAO classification, the Tropical Humid Forest AEZ is characterized by a mean annual rainfall (MAR) of 2,200 mm, a major rainfall season from March to July, a minor rainfall season from September to October, and a length of growing period (LGP) of 155 days for the major season and 100 days for the minor season. However, after analyzing a 30-year historical climate dataset, the updated long-term (CLT) thresholds for the zone were found to be 1,876 mm (± 367) for MAR, 134 days (± 37) for the major season LGP, and 73 days (± 17) for the minor season LGP. These new values reflect the changing climatic conditions in the Tropical Humid Forest AEZ.

6.4.1 Changes in FAO-zonal and CLT-zonal MAR and LGP thresholds

Similarly, to analyze climatological changes in the existing FAO-zonal mean thresholds for MAR and LGP, the 30-year standardized FAO-Zmean and CLT-Zmean datasets were examined for long-term trends and means. Time series line graphs were used to visualize both yearly and long-term trends in the MAR and LGP z-scores. Figure 6.43 presents the long-term trends observed in the FAO-Zmean and CLT-Zmean z-scores for the mean annual rainfall (MAR) datasets. ANOVA was performed to test for significant differences in the means and trends between the FAO-Zmean and CLT-Zmean datasets, while Pearson’s correlation was used to assess the strength and direction of the relationships between the two datasets

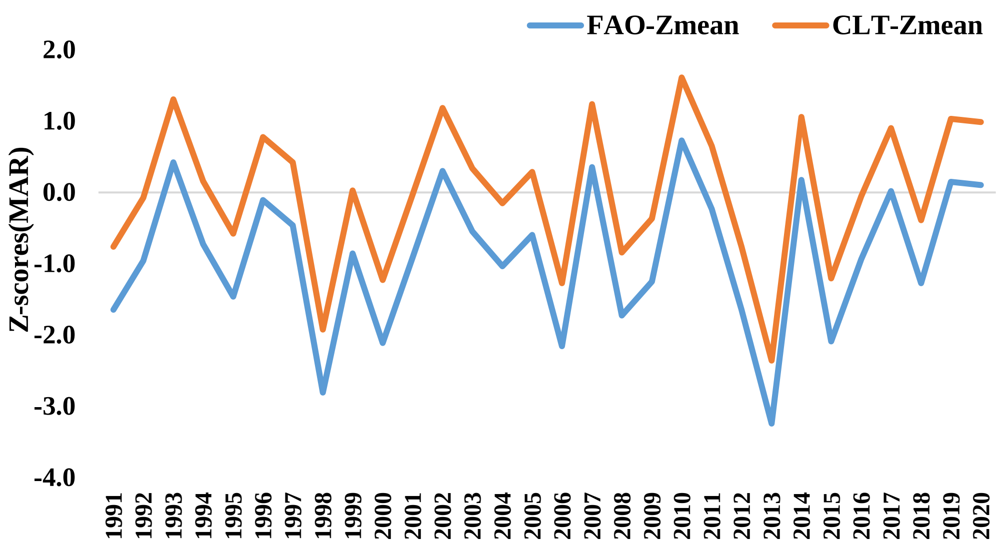

Figure 6.43: Standardized FAO-Zmean and CLT-Zmean MAR trends

The findings presented in Figure 6.43 reveal an increasing mean annual rainfall trend observed from the standardized yearly means for both the FAO-Zmean and CLT-Zmean z-scores datasets. Over the past 30 long-term years, the FAO-Zmean dataset shows a trend (-1.0), indicating a significant decreasing pattern in the MAR agro-climatic parameters over the long-time.

However, the CLT-Zmean dataset exhibits a trend coefficient of -0.1, suggesting a slight or unnoticeable trend over the long-term. Concerning the climatological means analysis, the standardized FAO-Zmean z-scores dataset reveals a long-term mean decrease (-0.9) in MAR. The CLT-Zmean dataset showed no obvious change (0.0) from the current climate data analyzed.

The Pearson correlation coefficient (1) showed a perfect correlation between the standardized FAO and CLT zonal MAR datasets. The ANOVA p-value of 0.001 at an alpha level of 0.05 revealed a significant difference in the means of FAO and CLT MAR datasets. This shows a significant change in the existing MAR threshold set for THAEZ under current climatic conditions. These results validated the difference in MAR of -325 mm observed between the existing FAO zonal threshold (2,200 mm) and the CLT zonal mean (1,875 mm) for the THAEZ

Similarly, Figure 6.44 was used to present the results analyzed for long-term trends in the standardized FAO-Zmean and CLT-Zmean MAJ-LGP datasets.

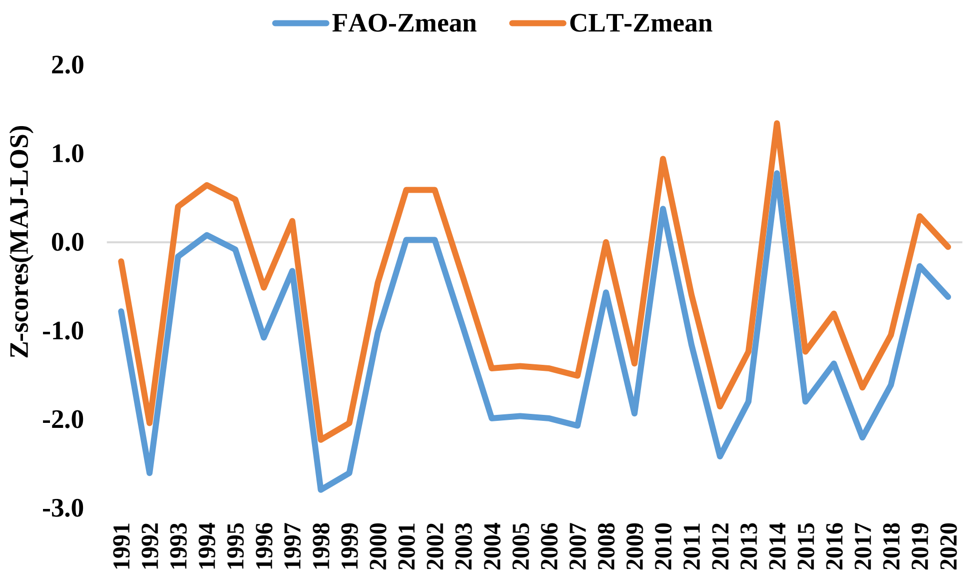

Figure 6.44: Standardized FAO-Zmean and CLT-Zmean MAJ-LGP trends

From Figure 6.44, the standardized yearly mean LGP anomalies indicated a decreasing trend for both the FAO-Zmean (-1.2) and CLT- Zmean (-0.6) datasets. Specifically, the FAO-Zmean dataset exhibited a significant decreasing trend (-1.1), while CLT-Zmean showed a slight (-0.5). The Pearson coefficient of +1 indicated a perfect positive correlation in the decreasing trends of both FAO and CLTM standardized mean MAJ-LGP. Additionally, the ANOVA test with an alpha value of 0.05 showed a statistically significant difference in the means of the standardized FAO-Zmean and CLT-Zmean MAJ-LGP (Z-scores) datasets, with a p-value of 0.033. This result validates the mean LGP difference (-21) of days reduction between the existing FAO (155 days) and CLT (134) MAJ-LGP for THAEZ.

In the same way, Figure 6.45 was used to present the results analyzed for long-term trends in the standardized FAO-Zmean and CLT-Zmean MIN-LGP (Z-scores) datasets.

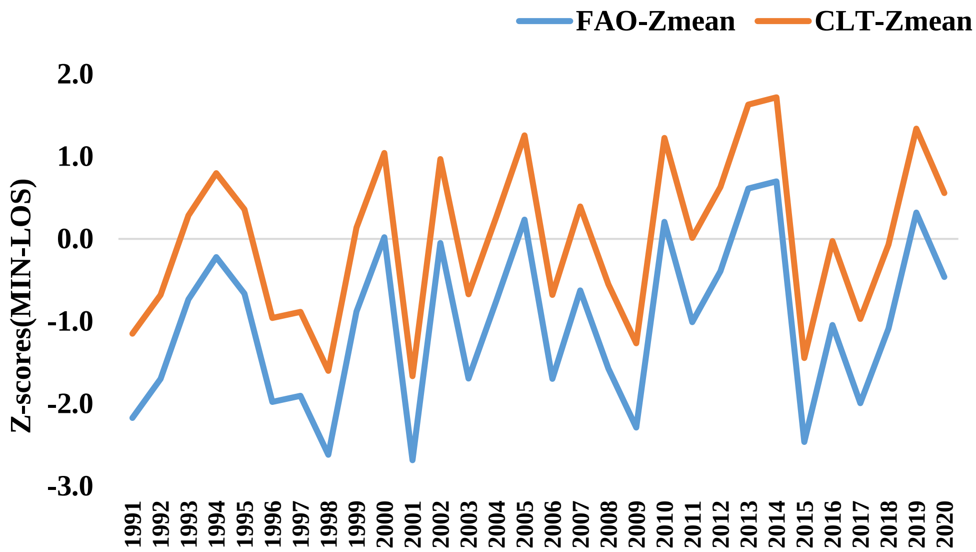

Figure 6.45: Standardized FAO-zmean and CLT-zmean MIN-LGP trends

From Figure 6.45, the long-term mean trends (MIN-LGP) indicate a decreasing trend for both the FAO-Zmean (-2.1) and CLT-Zmean (-0.4) datasets. The Pearson coefficient (1) indicated a strong positive correlation between the trends of the two datasets, suggesting a consistent decreasing pattern in the MIN-LGP. These results are consistent with the long-term mean decrease in length of growing period for the standardized FAO-Zmean dataset (-1.6), and apparently no change (0.0) in the CLT-Zmean dataset. The ANOVA test indicated a statistically significant difference (p-value of 1.71282E-05 at 0.05 alpha) in the standardized long-term means observed between the existing FAO and CLT thresholds for MIN-LGP.

The analysis of long-term trends and means has revealed that the existing MIN-LGP thresholds are no longer suitable for the current climatic conditions. This finding emphasizes the need for a revision of the threshold to ensure its alignment with the prevailing climate patterns in the region. The revision of the threshold holds significant importance as it will have practical implications for agro-economic decision-making and adaptation practices within the THAEZ. By updating the threshold to accurately reflect the present climatic realities, stakeholders, including farmers, policymakers, and investors, will have access to more reliable and relevant information for making informed choices

6.4.2 Decadal and long-term changes and variability in MAR and LGP

The analysis for potential inter-temporal variability was significant to further examine the patterns observed in the inter-decadal (1991-2000, 2001-2010, 2011-2020) in comparison with the long-term (1991-2020) means and trends in the standardized FAO-Zmean MAR and LGP datasets. Figure 6.46 resents the results for the inter-decadal and long-term differences in the means and trends for the FAO-zonal mean annual rainfall z-scores dataset.

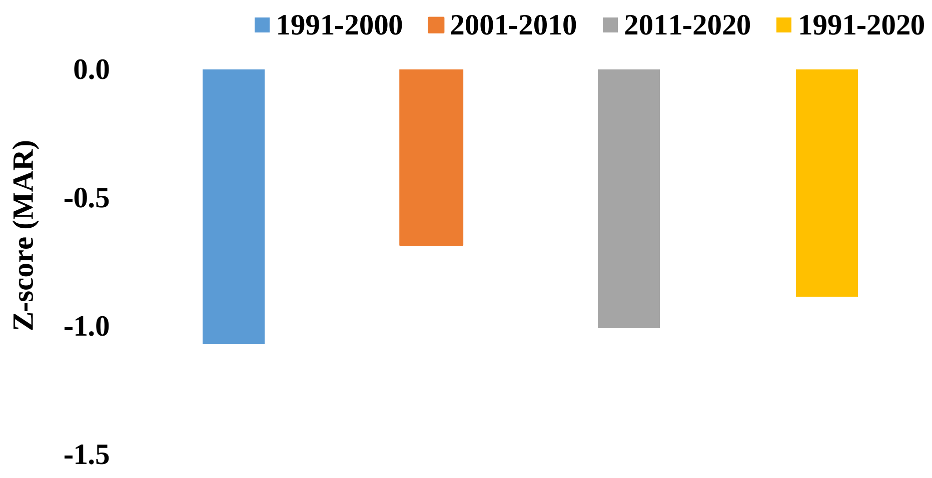

Figure 6.46: Inter-decadal and long-term trends in the FAO-zonal MAR

Based on the results in Figure 6.46, the decadal and long-term trends showed decreases in mean annual rainfall for the FAO-Zmean dataset. The trend coefficients for the three decades and long-term were: 1st decade, -0.6; 2nd, -0.7; 3rd, -1.7, and long term, -1.0. The Pearson coefficient (1) depicted a perfect positive correlation in the trends. Similarly, the standardized inter-decadal and long-term means for the FAO-Zmean dataset showed decreases (-1.1, -0.7, -1.0, and -0.9) for the 3-decadal and over the long-term. The ANOVA p-value (0.00002) at an alpha-value (0.05), indicated a significant difference between the means of the FAO-Zmean and CLT-Zmean datasets.

These findings proved clearly a significant change in the existing FAO zonal MAR threshold, not only in the long-term; but, also over the 3 decadal periods. Therefore, it is suggested that the existing FAO threshold for MAR is no longer representative. It has become obsolete, and requires a revision as a direct response to the impacts of climate change on MAR for the THAEZ.

Likewise, Figure 6.47 reveals the inter-decadal and long-term means and trends observed in the standardized FAO-zonal mean LGP (z-scores).

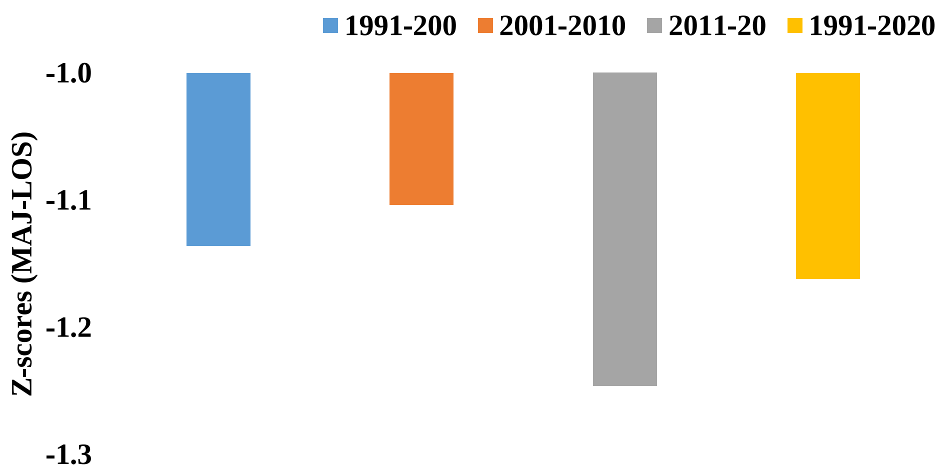

Figure 6.47: Decadal and long-term variability in the FAO-zonal MAJ-LGP

Figure 6.47 depicts a continuous decreasing trend in the 3-decadal and the long-term standardized MAJ-LGP anomalies. LINEST regression trend coefficients for the first decade (-0.7), second decade (-0.9), third decade (-1.6), and the long term (-1.1) indicated a continuous significant reduction in the FAO zonal threshold over all the periods. The Pearson coefficient (1) showed a perfect positive correlation in the trends over all four periods, suggesting a consistent shift in the length of the growing season in the THAEZ.

Furthermore, the ANOVA test for difference in the means of the inter-decadal and long-term standardized MAJ-LGP (1st -1.1; 2nd -1.2; 3rd -1.3; and long-term, - 1.2) showed a p-value of 0.001 at an alpha level of 0.05. These results suggest a statistically significant difference in both the inter-decadal and long-term standardized means. This result indicated a significant inter-decadal and long-term shift in the existing FAO MAJ-LGP threshold, given the current climatic and environmental conditions, and LULC dynamics in THAEZ.

Additionally, the analysis for changes in THAEZ included assessing temporal differences in the FAO-Zmean compared with CLT-Zmean MIN-LGP z-scores. The results of this analysis are depicted in Figure 6.49.

Figure 6.48 showed a decreasing trend in the inter-decadal and long-term standardized mean (MIN-LGP) anomalies. The observed trend (1st period: -0.8, 2nd period: -1.4, 3rd period: -0.7, and long term: -1.4) is statistically significant, with p-values less than 0.01 at an alpha value of 0.05. Pearson coefficient (1) indicated a perfect correlation, supporting the decreasing trends.

Figure 6.48: Decadal and long-term variability in FAO-zonal MIN-LGP

Furthermore, the standardized means for the three decades against the long-term showed (1st period: -1.9, 2nd period: -1.7, 3rd period: -1.3, and long term: -1.6). The single factor ANOVA test p-value of 5.31E-08 at a 0.05 alpha revealed significant differences in 4 temporal means.

These findings highlighted a statistically significant difference and noticeable deviation of the existing FAO threshold from the current climatic conditions in the THAEZ. Consequently, it is concluded that the existing FAO threshold is no longer suitable to represent the zone accurately. Thus, revising the FAO threshold is necessary to make informed decisions and design proactive adaptations based on the updated climatic conditions.

6.4.3 Multiple Pearson correlations for key agro-climatic parameters

Additionally, the analysis for changes in THAEZ included the test for correlations between the key agro-climatic (MAR, MAJ-LGP and MIN-LGP) and other relevant variables such as PET, RDAYS, TMEAN, SOS, and EOS. This analysis was done to better understand the associations and trends between and among the agro-climatic variables. The results for the multiple Pearson (R) correlation are shown in Figure 6.49.

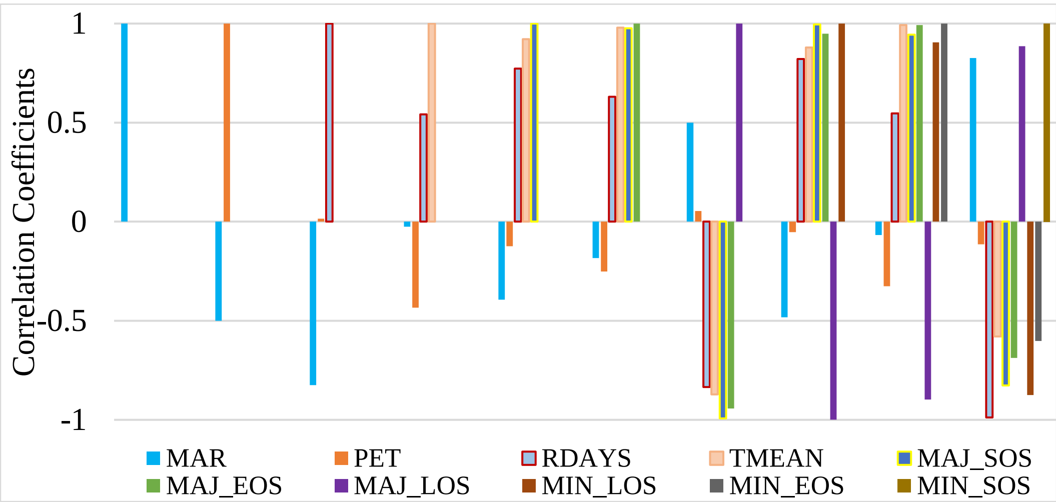

Figure 6.49: Multiple correlation for key agro-climatic parameters

From Figure 6.49, Pearson correlations show a positive relationship between MAR and MAJ-LGP as well as MIN-SOS. This indicates that higher MAR is associated with a longer MAJ-LGP and an earlier start of rainfall (MIN-SOS). Conversely, MAR exhibits a strong negative correlation with MAJ-SOS, MIN-LGP, Tmean, and RDAYS, suggesting that decreasing MAR aligns with earlier MAJ-SOS, increased Tmean, PET, and RDAYS, and vice versa.

Similarly, multiple correlations indicate that MAJ-LGP has a strong negative correlation with MAJ-SOS, MAJ-EOS, Tmean, and RDAYS. This implies that longer MAJ-LGP tends to occur with earlier MAJ-SOS and MAJ-EOS, lower Tmean, and fewer RDAYS. Additionally, MAJ-LGP demonstrates a moderate positive correlation with MAR, meaning higher MAR corresponds to longer MAJ-LGP, while lower MAR results in shorter MAJ-LGP.

For MIN-LGP, strong positive correlations with MIN-EOS, Tmean, and RDAYS suggest that longer MIN-LGP is associated with later MIN-EOS, higher Tmean, and more RDAYS. Conversely, MIN-LGP has a strong negative correlation with MAR and MIN-SOS, indicating that shorter MIN-LGP aligns with higher MAR and earlier MIN-SOS.

6.4.4 Summary of decadal and long-term FAO-zonal MAR and LGP

A coupled analysis for all the key agro-climatic analyses was done to examine the changes in the FAO zonal MAR, MAJ-LGP, and MIN-LGP mean thresholds set for the THAEZ. This analysis involved combining and comparing the long-term and decadal means and trends observed for the key agro-climatic parameters used to describe the THAEZ from the FAO agro-ecological classification of Ghana.

Figure 6.50 presents the final summary results.

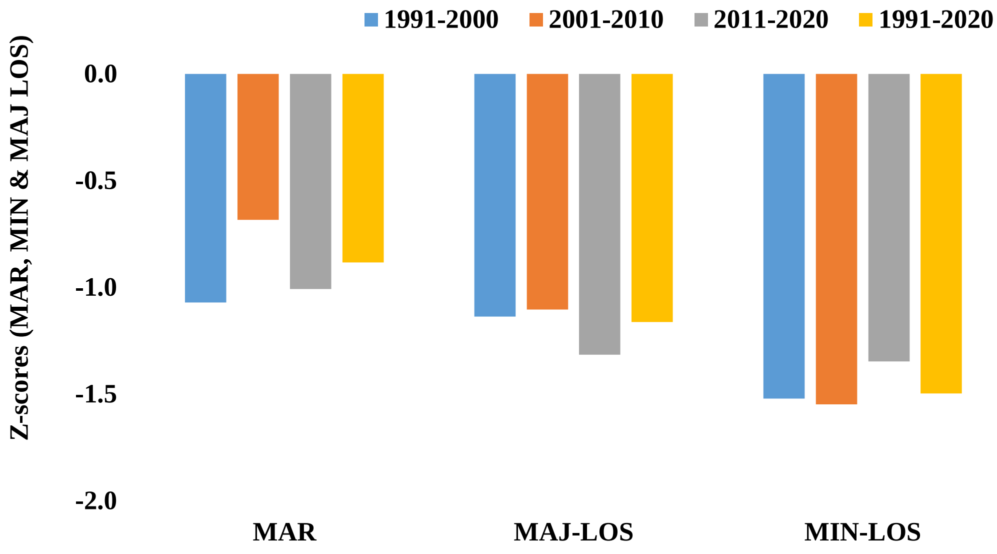

Figure 6.50: Summary decadal and long-term FAO-zonal MAR and LGP

From Figure 6.50, the standardized means show consistent decreasing trends for all FAO-Zmean MAR, MAJ-LGP, and MIN-LGP datasets across all four periods. The temporal mean decreases for MAR were -1.1 (1st period), -0.7 (2nd period), -1.0 (3rd period), and -0.9 (long-term). For MAJ-LGP, the decreases were -1.1 (1st period), -1.1 (2nd period), -1.2 (3rd period), and -1.2 (long-term). For MIN-LGP, the decreases were -1.9 (1st period), -1.7 (2nd period), -1.3 (3rd period), and -1.6 (long-term). A perfect positive Pearson correlation (1) was observed for the trends in all agro-climatic variables analyzed for THAEZ.

Similarly, the single-factor ANOVA test for differences in the standardized MIN-LGP and CLT-Zmean means at alpha (0.05) showed significant p-values for MAR (0.001), MAJ-LGP (0.03), and MIN-LGP (1.71E-05), indicating statistically significant differences in the long-term standardized means. This suggests significant shifts in the existing FAO thresholds, given the current climatic conditions in THAEZ.

The trends and differences in the standardized means between the FAO and CLT thresholds are consistent with observed mean differences: -325mm for MAR, -23 days for MAJ-LGP, and -48 days for MIN-LGP. The conclusion is clear: the existing FAO thresholds for MAR, MAJ-LGP, and MIN-LGP in THAEZ are outdated and no longer accurately represent the zone. Thus, revising these thresholds is necessary for informed agro-economic decisions and climate adaptation strategies in the zone

6.5 Evidence for Changes in the Transitional Agro-ecological Zone

Based on the FAO agro-ecological classification, Ghana's Transitional agro-ecological zone (TRAEZ) has been defined by a mean annual rainfall (MAR) of 1,300 mm, the major and minor rainfall seasons occurring from March to July and September to November respectively. The TRAEZ has a mean length of growing period (LOS/LGP) of 210 days within the major season and a 60-day for the minor season. A 30-year historical climate dataset was examined to establish new thresholds for the TRAEZ. The revised zonal thresholds for MAR showed 1,242 mm (±139), a 110-day (±33) for MAJ-LGP, and 67 days (±27) for MIN-LGP

6.5.1 Changes in FAO-zonal and CLT-zonal MAR and LGP thresholds

Again, to analyze climatological changes in the existing FAO-zonal mean thresholds for MAR and LGP, the 30-year standardized FAO-Zmean and CLT-Zmean datasets were used to identify long-term trends and means. Time series line graphs were created to visualize the trends for MAR and LGP Z-scores. Figure 6.51 presents the long-term trends and means for MAR from both FAO-Zmean and CLT-Zmean datasets. ANOVA was applied to test the significance of differences between the datasets, while Pearson's correlation assessed their relationship.

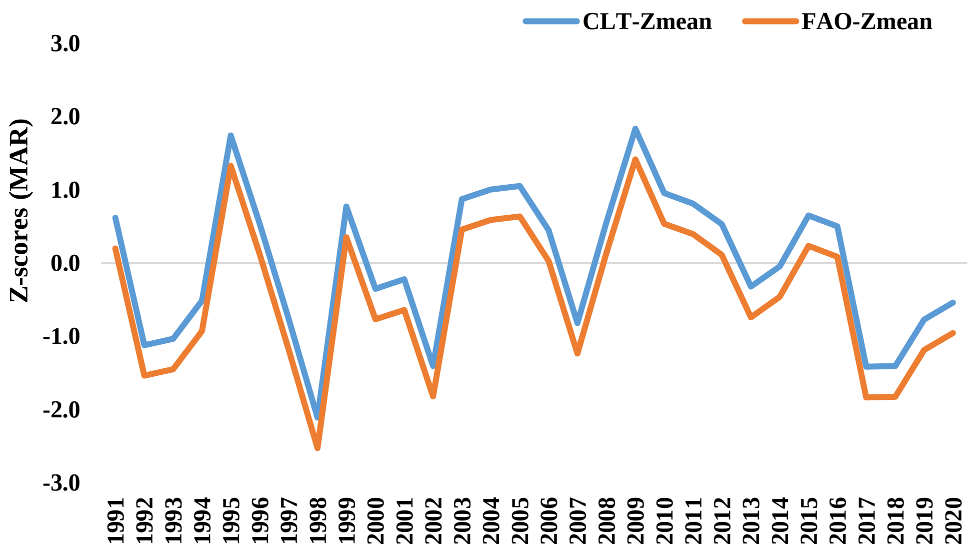

Figure 6.51: Standardized FAO-zmean and CLT-zmean MAR trends

The findings in Figure 6.50 indicate a long-term decreasing trend (-0.4) from FAO-Zmean dataset, while the CLT-Zmean dataset observed a slight increase (0.01) in mean annual rainfall z-scores. Similarly, the climatological long-term mean for FAO-Zmean was -0.4; the CLT-Zmean datasets revealed no obvious change (0.0) in MAR. These results align with the mean rainfall difference (-58 mm) observed between the existing FAO means threshold (1,300 mm) and the CLT threshold (1,242 mm) analyzed for the TRAEZ at present.

In support of the results, the Pearson coefficient revealed a strong positive correlation (+1) between the observed long-term means and trends in the FAO-Zmean and CLT-Zmean datasets. However, the ANOVA test indicated that there is statistically no significant difference in the means of the FAO-zonal mean and CLT zonal mean datasets, with a p-value of 0.11 at an alpha level of 0.05. Although the difference is not statistically significant, it is still important to update the existing FAO MAR threshold to align it with the current climatic conditions of the zone. This revision has the potential to positively impact the planning of agriculture and other activities in TRAEZ.

Similarly, Figure 6.52 present the results for the long-term trends and means from standardized FAO-Zmean and CLT-Zmean MAJ-LGP datasets.

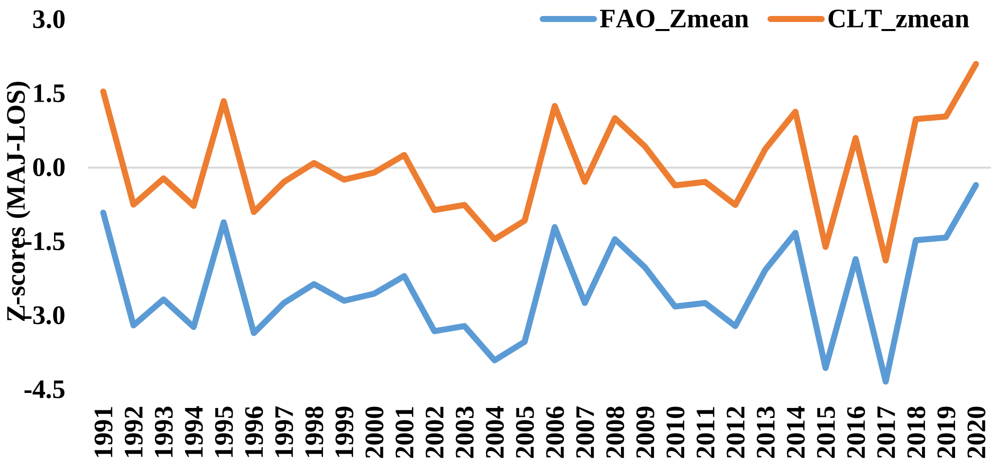

Figure 6.52: Standardized FAO-zmean and CLT-zmean MAJ-LGP trends

The findings from Figure 6.52 reveal a consistent long-term decreasing trend in both the FAO-Zmean (-3.3) and CLT-Zmean (-0.3) MAJ-LGP datasets. This result aligns with the climatological long-term decreases observed for the FAO-Zmean (-3.1) and CLT-Zmean (-0.01). The Pearson co-efficient shows strong positive correlation between the two zonal datasets, which further supports the trends and means observed. The ANOVA analysis showed a significant p-value of 3.52838E-17 at an alpha value of 0.05, indicating a significant difference in the climatological means observed between the FAO-Zmean and CLT-Zmean datasets. These results aligned with the observed difference of -80 mm between the existing FAO threshold (190 days) and the CLT threshold (110 days) for the TRAEZ

From these findings, it is evident that the existing FAO MAJ-LGP threshold has changed, and therefore needs to be revised to accurately reflect the current climatic and other environmental conditions. The revision is crucial for guiding sustainable agricultural practices, supporting economic investments, facilitating research, and aiding in planning socio-economic development.

Apart from the MAR and MAJ-LGP, the analysis for changes in the TRAEZ also involved examining the long-term trends and means differences in the FAO-Zmean and CLT-Zmean MIN-LGP datasets, shown in Figure 6.53.

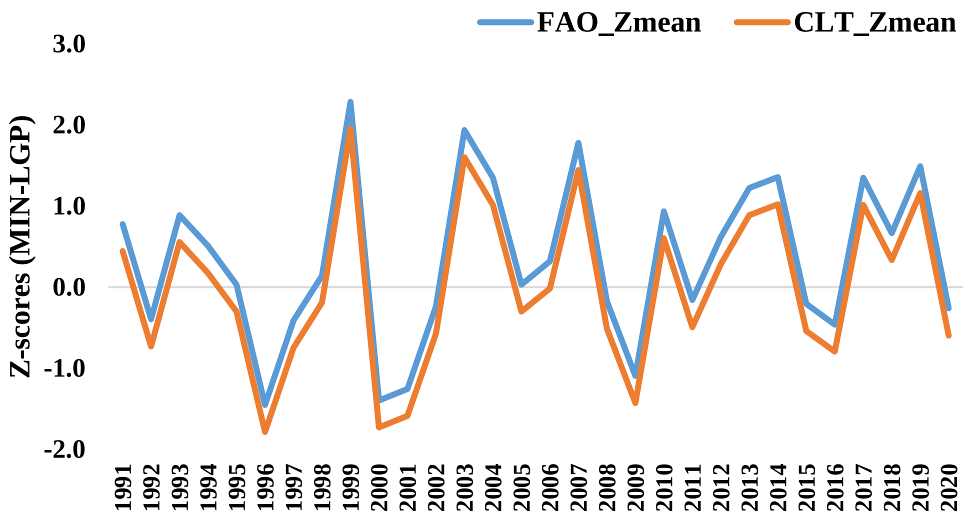

Figure 6.53: Standardized FAO-zmean and CLT-zmean MIN-LGP trends

From Figure 6.53, concerning the MIN-LGP analysis, the long-term results show a general increasing trend for both the FAO-Zmean (0.5) and CLT-Zmean (0.3). For the climatological long-term, there is a mean increase in MIN-LGP for the FAO-Zmean (0.3), and no apparently change for the CLT-Zmean (0.0) datasets in the past 30 years for both FAO and CLT standardized mean MIN-LGP anomalies. The Pearson coefficient indicates a perfect positive (+1) correlation, while an ANOVA p-value of 0.2 at an alpha of 0.05 showed no significant difference in the means and trends observed in two long-term zonal mean datasets.

6.5.2 Intra-zonal (FAO-Zmean vrs stations) variability in MAR and LGP

Another significant test done to better understand the agro-climatic changes in TRAEZ was the analysis of intra-zonal variability in FAO-zonal mean and the station's MAR, MAJ-LGP and MIN-LGP z-scores over 3 decadal and long-term. Figure 6.54 shows the results for MAR discrepancies analyzed for FAO-zonal mean and the representative stations for the TRAEZ.

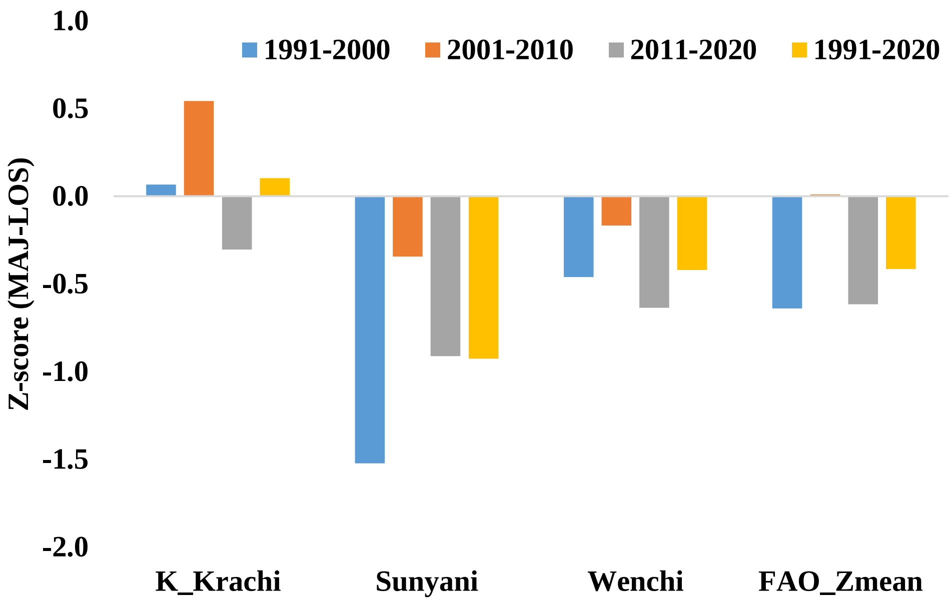

Figure 6.55: FAO-Zmean and Stations Decadal and Long-term MAJ-LGP

From Figure 6.54, the long-term trends reveal a general reduction in mean annual rainfall for TRAEZ, as indicated by FAO-Zmean z-scores (-0.4). The zonal trend associated with the MAR decreases at the Sunyani (-1.2) and Wenchi (-0.1) stations. However, the Kete Krachi station shows a rather slight increase (0.1) relative to the FAO-zonal mean. This results pattern is also consistent with the decreased climatological means observed for FAO-Zmean (-0.4), Sunyani (-0.9), and Wenchi (-0.4) datasets; while the Kete Krachi area still showed a slight increase (0.1) z-score. The Pearson multiple correlation matrix showed a strong correlation between the FAO-Zmean and Sunyani (0.9) and Wenchi (0.8) datasets, while a weak positive correlation (0.2) is observed for Kete Krachi. Moreover, the ANOVA p-value (0.021) at alpha (0.05), directly confirms clear significant differences in the MAR trends and means among different stations in comparison with the FAO-zonal z-scores dataset.

There is clearly a significant intra-zonal variability in the zone from the MAR analysis, with results indicating obvious changes in the existing FAO threshold induced by climate change. Based on these findings, reclassification is recommended to establish a representative MAR threshold that will accurately reflect the changing rainfall patterns in the zone. The revision would enable more informed decisions in agricultural production, in planning other economic activities, and in water resource management in the zone.

Additionally, the major season LGP z-scores were also analyzed over the long-term to identify any differences in the means, trends and correlations between the stations and FAO-zonal datasets. This analysis was done additionally to establish more adequate evidence for the intra-zonal variability in the TRAEZ. Therefore, Figure 6.55 presents the results for the FAO-Zmean and stations means and trends across all four analysis periods.

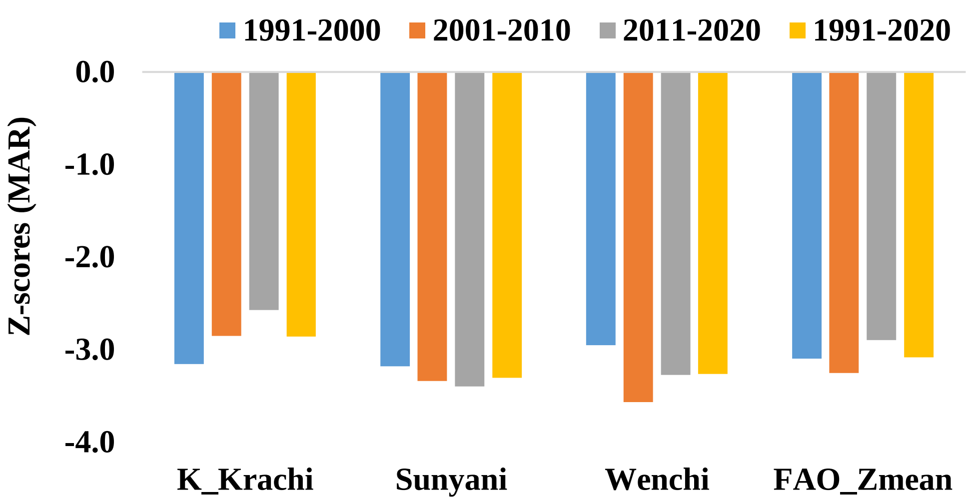

Figure 6.55: FAO-Zmean and Stations Decadal and Long-term MAJ-LGP

Clearly from the standardized z-scores anomalies, evident from Figure 6.55, a consistent significant decrease in the major season's length of the growing season or period is shown over both the long-term and within the three inter-decadal periods. Specifically, the long-term trends for observed FAO-Zmean, Kete Krachi, Sunyani, and Wenchi were -3.3, -3.1, -3.4, and -3.2, respectively. This is directly consistent with the climatological long-term means: -3.1 for the FAO-Zmean, -3.3 for Wenchi, -3.3 for Sunyani, and Kete Krachi (-2.9) z-scores. The Pearson correlation coefficient (1) shows a perfect positive correlation, confirming the consistent decreasing trend and means in the MAJ-LGP z-scores for all 4 groups over the four periods. The single-factor ANOVA with a p-value of 0.2 at an alpha of 0.05, indicated no significant difference in trend and means among the four groups' z-scores.

Based on these findings, it is evident that the existing FAO threshold for MAJ-LGP is no longer suitable and has become very obsolete to rely on any longer. A revision of this threshold is necessary to ensure sustainable planning of agricultural production and other economic activities that depend on these climatic variables in the zone.

Additionally, the minor season LGP z-scores were also analyzed for the same intra-zonal variability objective from the long-term means, trends and correlations observed between the stations and FAO-zonal z-scores datasets. Figure 6.56 showed the MIN-LGP analysis.

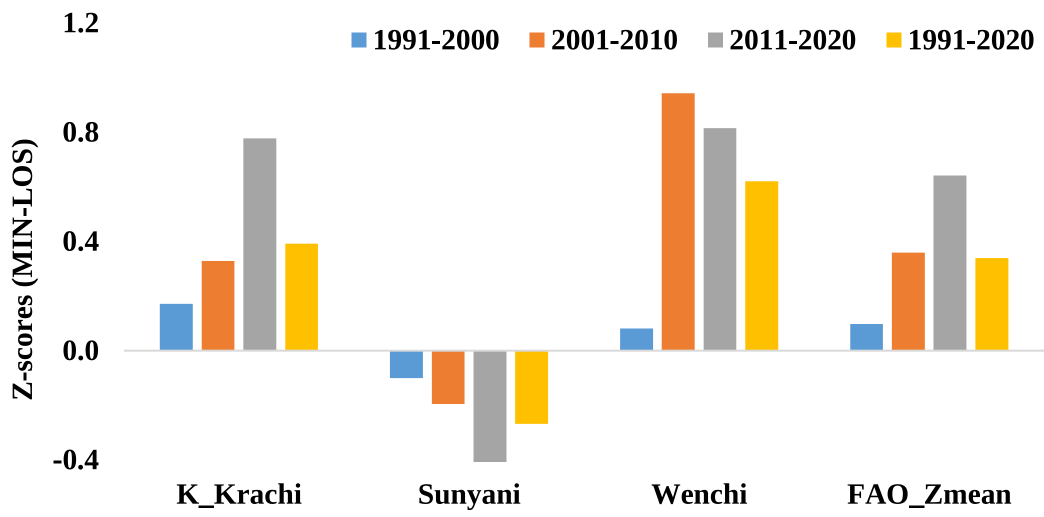

Figure 6.56: Decadal and Long-term standardized FAO-zonal and Stations MIN-LGP anomalies.

In Figure 6.56, there is obvious intra-zonal variability, indicated by consistent increases in the long-term and inter-decadal means from the FAO Zmean, Kete Krachi, and Wenchi MIN-LGP z-scores datasets. The values for each period were: FAO-Zmean (1st 0.1; 2nd 0.4; 3rd 0.6; long term. 0.3), Kete Krachi (1st 0.2; 2nd 0.3; 3rd 0.8; long term, 0.4), and Wenchi (1st 0.1; 2nd 0.9; 3rd 0.8; long term, 0.6). However, the Sunyani station exhibited continuous mean decreases across all four periods analyzed, with values of -0.1, -0.2, -0.4, and -0.3 z-scores. The multiple Pearson correlation matrix revealed strong positive correlations between FAO-Zmean and Wenchi (0.8) and Kete Krachi (0.9). But there is shown a strong negative correlation between Sunyani and FAO-Zmean (-0.96). Finally, the ANOVA test showed a p-value of 0.004 at an alpha level of 0.05, indicating a significant difference in the observed means and trends for MIN-LGP among the four groups over the four periods.

It is revealed from the findings that, a significant difference exists between the existing FAO MIN-LGP threshold compared with the CLT-Zmean based on the current climatic changes and land cover patterns. There are also notable differences in MIN-LGP within the Transitional agro-ecological zone, with Sunyani showing a significant variation (continuous decreases) from the stations and zonal means across all four periods. It is thus suggested that the existing FAO-zonal MIN-LGP threshold be revised as a practices adaptation strategy to mitigate the impacts of climate change, and to ensure sustainable planning of agriculture and economic activities in the area.

6.5.3 Decadal and long-term changes and variability in MAR and LGP

The analysis for inter-temporal variability was specifically performed to further describe the climatological long-term means and the trends (1991-2020) in comparison with the inter-decadal (1991-2000, 2001-2010, 2011-2020) means and trends observed for the FAO-Zmean MAR and LGP z-scores datasets. This seasonality analysis is key to better understanding inherent historical changes, shifts or variability occurring in the agro-climatic parameters over the long term. The results for the inter-decadal and long-term means and trends variability for the FAO-zonal mean annual rainfall, MAJ-LGP, and the MIN-LGP z-scores datasets are shown in 6.54, 6.55, and 6.56. The column bars display the results of this analysis.

Again, with reference to Figure 6.54, the findings show a consistent decrease in MAR observed for the FAO-zonal mean, the Sunyani, and Wenchi stations over all four periods analyzed. However, the MAR z-scores for Kete Krachi show initial increases for the 1st and 2nd decades; then, there was a shift unique (decrease) in the 3rd decade, and over the long-term show a slight increase. The 3rd and last decades show a significant decrease in rainfall for all the groups.

Apart from the unique decadal seasonal variations Kete Krachi, the rest of the stations and the zonal FAO-Zmean show no clear temporal variability in inter-decadal and long-term means and trends. The continuous decreases in MAR from FAO-zonal mean z-scores highlights significant changes in the existing FAO MAR threshold, and the need to update this threshold to reflect current climatic patterns or conditions in the TRAEZ. This revision will enable more accurate decision-making in agriculture and water resource management within the zone.

Similarly, the MAJ-LGP was analyzed for zonal temporal seasonality. From the earlier Figure 6.55, there is found a consistent reduction in the MAJ-LGP days over the long term and also within the 3 inter-decadal periods. The climatological long-term means showed (-3.1) for FAO-Zmean, (-3.3) for Wenchi, (-3.3) for Sunyani, and (-2.9) for Kete Krachi. The Pearson correlation coefficient (1) supported this trend with a perfect positive correlation. Here, again, the uninterrupted decreases in MAR from FAO-Zmean and stations z-scores highlights significant changes in the existing FAO MAR threshold, a clear manifestation of climatic changes in the TRAEZ.

Moreover, the temporal variability (zonal agro-climatic seasonality) was further examined by the MIN-LGP. From Figure 6.55, the results show an incessant increase in MIN-LGP for the zonal (FAO-Zmean), Wenchi, and Kete Krachi z-scores datasets, while Sunyani observe a rather continuous significant decrease over the four periods. From the seasonality analysis, the continual decreases in MIN-LGP from the FAO-Zmean z-scores clearly indicate significant changes in the existing FAO threshold set for the parameter. The impacts of climate change have altered the agro-climatic conditions of the zone with their direct impacts on agricultural production in the TRAEZ.

6.5.4 Multiple Pearson correlation for key agro-climatic parameters

Furthermore, the analysis for changes in TRAEZ included the test for correlations between the key agro-climatic (MAR, MAJ-LGP and MIN-LGP) and other relevant variables such as PET, RDAYS, TMEAN, SOS, and EOS. This analysis was done to better understand the associations and trends between and among the agro-climatic variables. The results for the multiple Pearson (R) correlation are shown in in Figure 6.57.

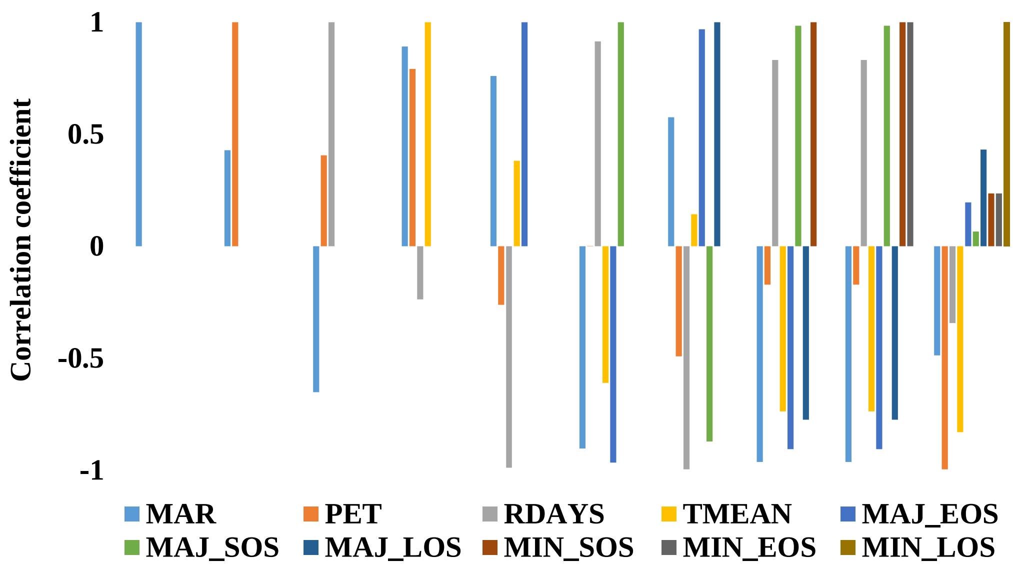

Figure 6.57 Multiple correlations for the key agro-climatic parameters

Figure 6.57's correlation matrix showed that MAR has a strong positive correlation with PET and RDAYS, and a weak correlation with SOS. However, it has a strong negative correlation with LGP and Tmean, and a weak correlation with EOS. The LGP has a positive correlation with Tmean but negative correlations with MAR, PET, RDAYS, SOS, and EOS. The decreasing trend observed in LGP and MAR over the last three decades, which is beyond the existing FAO thresholds, indicated a significant shift in the TRAEZs. This shift will have adverse effects on agriculture, economic investments, and research that rely on the existing thresholds for MAR, MAJ-LGP and MIN-LGP

6.5.5 Summary of inter-decadal and long-term FAO-zonal MAR and LGP

The final analysis was the presentation of coupled results for the standardized zonal FAO-Zmean MAR, MAJ-LGP, and MIN-LGP z-scores the four periods result for the TRAEZ. This comparative analysis was done by combining and comparing the means and trends in the long-term and inter-decadal. Figure 6.58 presents the summary results for TRAEZ.

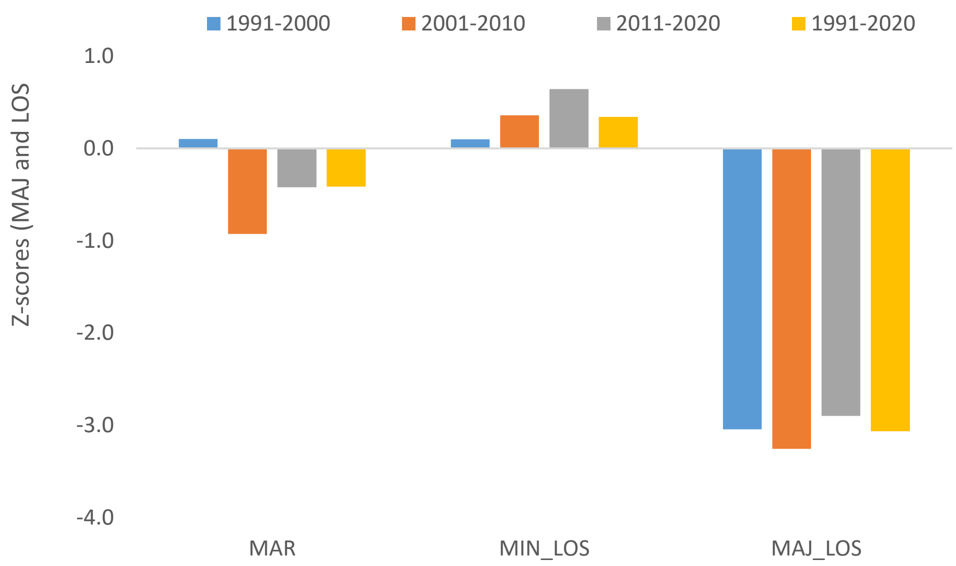

Figure 6.58: Summary decadal and long-term FAO-zonal MAR and LGP

In summary, the analysis in Figure 6.58 revealed key findings: Firstly, there is a consistent negative trend in the standardized FAO-Zmean rainfall (MAR) across the four periods, with a slight increase only in the first decade. Secondly, the standardized length of the minor growing period (MIN-LGP) exhibited a continuous positive trend, while the standardized length of the major growing period (MAJ-LGP) showed a significant decrease below the zonal standardized deviation. ANOVA tests confirmed significant differences between the Standardized FAO-Zmean and CLT-Zmean datasets for each parameter, highlighting the need to update the existing FAO thresholds for these agro-climatic variables. Additionally, intra-zonal discrepancies were observed, with the Sunyani station differing significantly from other defining stations. These findings underscore the necessity of revising the FAO thresholds for MAR, MIN-LGP, and MAJ-LGP to reflect the current climatic conditions, land use changes, and other environmental factors. Such revisions are vital for guiding sustainable agricultural practices, supporting economic investments, and aiding decision-making for socio-economic development

6.6 Evidence for changes in the Deciduous Forest Agro-ecological Zone

Similarly, the existing FAO agro-ecological classification of Ghana defined the DFAEZ to be characterized by a mean annual rainfall (MAR) of 1,500 mm, a major rainfall season that starts from March to July, and a minor season from September to November. In addition, the DFAEZ has a mean length of growing period (LGP/ LGP) of 155 days for the major season, and a 90-day LGP/LGP for the minor season. Similarly, a 30-year historical climate dataset was examined to establish current zonal thresholds for the DFAEZ. The analysis showed a new MAR (1,270mm, ± 122), MAJ-LGP (134mm, ± 29), and MIN-LGP (73, ± 17).

6.6.1 Changes in FAO-zonal and CLT-zonal MAR and LGP thresholds

To establish the climatological changes in the existing FAO-zonal mean thresholds for MAR and LGP, the 30 years standardized FAO-Zmean and CLT-Zmean datasets were analyzed for long-term trends and means. A-2 time series line graph was used to visualize the yearly and long-term trends in MAR and LGP Z-scores. Figure 6.59 shows the results of the long-term trends and means observed in the FAO-Zmean and CLT-Zmean z-scores for MAR.

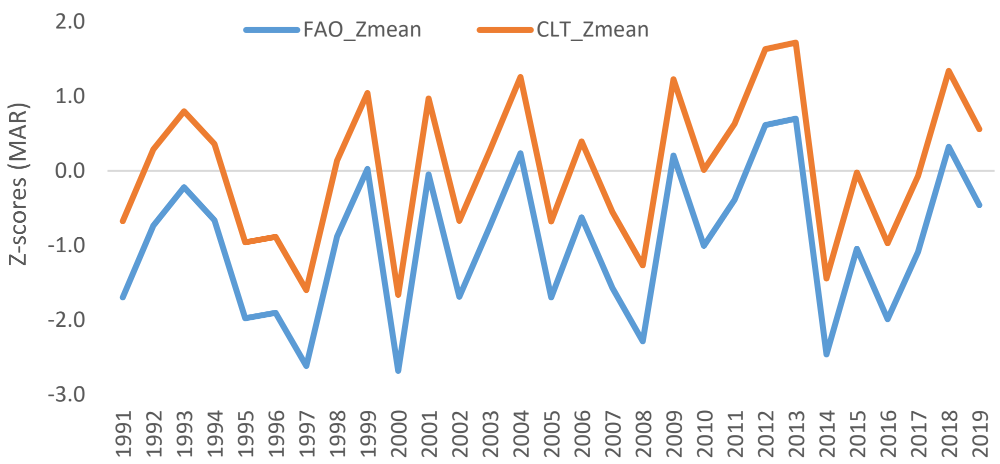

Figure 6.59: Standardized FAO-Zmean and CLT-Zmean MAR trends

From Figure 6.59, the long-term (30 years) means show a decreasing rainfall analyzed for the standardized FAO-Zmean (-1.8) and CLT-Zmean (-0.04) MAR z-scores. For the climatological mean, while the FAO-Zmean z-scores dataset reveal a significant decrease (-1.9), the CLT-Zmean show a slight (0.1) increase. The Pearson coefficient revealed a strong positive correlation (0.9) between the FAO-Zmean and CLT-Zmean datasets in their mean trends. The single factor ANOVA test p-value of 3.95169E-08 at 0.05 alpha, indicated statistically significant differences in the means and trends between the FAO-Zmean and CLT-Zmean MAR z-scores datasets. These findings align with the mean difference (-230 mm) observed between the existing FAO (1,500 mm) and the CLT (1,270 mm) zonal MAR amounts.

It can be inferred from this results that, at the current climatic conditions in the zone, the existing FAO threshold has become obsolete and unrepresentative of the DFAEZ. This reduction has possible negative impact agricultural production and other economic activities that plan with the current MAR information. With the current finding, a scientific basis is laid for developing sustainable climate change adaptations to enhance agricultural productivity and support.

Additionally, the two zonal MAJ-LGP z-scores was further analyzed to describe changes in the DFAEZ. This analysis involved examining the long-term trends and means in the FAO-Zmean and CLT-Zmean z-scores. The results for changes in the MAJ-LGP can be observed in Figure 6.60.

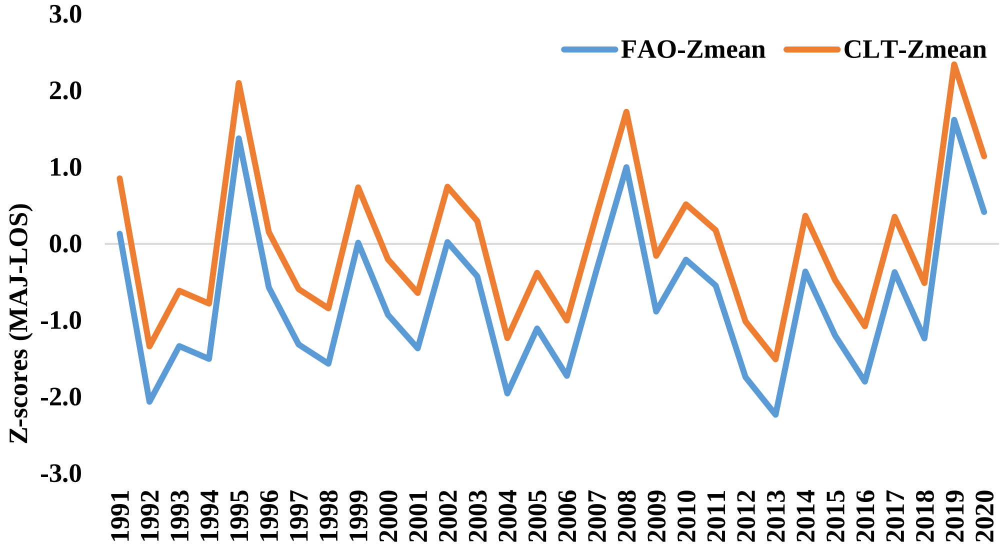

Figure 6.60: Standardized FAO-zmean and CLT-zmean MAJ-LGP trends

The results depicted in Figure 6.60 over the long-term show a decreasing trend of both the standardized FAO-Zmean (-0.9) and CLT-Zmean (-0.2) MAJ-LGP z-scores. This result aligns with the long-term decreasing MAJ-LGP means observed for both FAO-Zmean (-0.7) and CLT-Zmean (-0.01) datasets. The test for correlation using the Pearson correlation show a perfect positive correlation (1) between the two datasets, suggesting a uniform decreasing trend over the past 30 years. These findings are consistent with the observed negative difference (-21 days) between the existing FAO and CLT MAJ-LGP days analyzed. Finally, the p-value (0.0066) observed from the single-factor ANOVA test at a significant level of 0.05, indicates a significant difference in the means analyzed for the FAO-Zmean and CLT-Zmean MAJ-LGP datasets.

It is evident from the long-term climatological analysis for the MAJ-LGP z-scores dataset that, the existing MAJ-LGP threshold DFAEZ has become obsolete. It is therefore no longer suitable to inform decisions, and hence the need revise and accept the new thresholds to reflect current climatic and environmental conditions, as well as land use and land cover changes. A revised MAJ-LGP threshold will be valuable in informing agricultural policies and practices, promoting sustainable economic investments, redirecting academic research in the zone, and improving the general socio-economic development and standard of living of the people.

Similarly, Figure 6.61 also presented additional results to assess the evidence for the changes in the DFAEZ through the long-term trends and means analyzed from the standardized FAO-Zmean and CLT-Zmean MIN-LGP (z-scores) datasets for the zone.

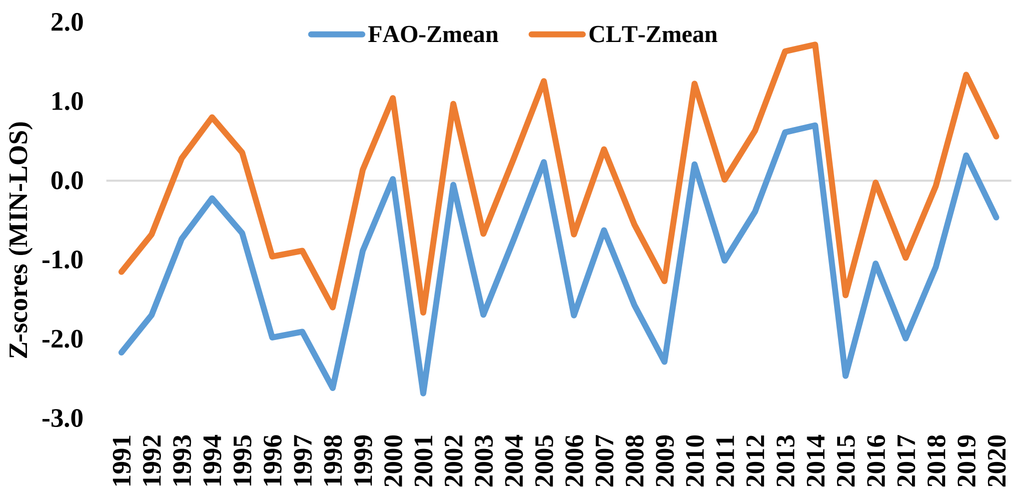

Figure 6.61: Standardized FAO-zmean and CLT-zmean MIN-LGP trends

From Figure 6.61, the findings indicate a long-term general decreasing trend in both the standardized FAO-Zmean (-1.5) and CLT-Zmean (-0.4) MIN-LGP z-scores datasets. Similarly, the long-term z-scores means also show for the FAO-Zmean (-1.0) and the CLT-Zmean (0.0). MIN-LGP days and no obvious change. The Pearson correlation showed a perfect positive association

(1) between the two datasets, indicating a uniform decreasing trend over the 30 years. This is consistent with the observed negative difference (-17 days) between the existing FAO and CLT means MIN-LGP days. In conclusion, thesingle factor ANOVA p-values 0.0002 at the 0.05 significant level also showed a significant difference in the means between the two FAO-Zmean and CLT-Zmean MIN-LGP thresholds.

Based on these findings, it can be concluded that the DFAEZ MIN-LGP threshold ha significantly decreased (-17 days) from the existing FAO threshold. Therefore, the existing FAO MIN-LGP threshold has become obsolete and needs to be revised to reflect current climatic conditions, land use and land cover changes, and other environmental factors. This suggestion is important for informing sustainable agriculture practices, economic investments, academic research, and related socio-economic developmental decision-making and planning.

6.6.2 Intra-zonal (FAO-Zmean vrs stations) variability in MAR and LGP

Another significant test done to better understand the agro-climatic changes in the DFAEZ is the analysis for intra-zonal variability or discrepancies observed from the long-term means and trends between the FAO-zonal mean and the stations MAR, MAJ-LGP and MIN-LGP z-scores. Figure 6.62 shows the results analyzed in terms of MAR for the FAO-Zmean and stations.

According to the results in Figure 6.62, the long-term z-scores means observed for Abetifi, Akim Oda, Akuse, Ho, Koforidua, Kumasi, Sehwhi Bekwai, and Takoradi and FAO-Zmean were -2.0, -1.0, -3.7, -2.0, -1.7, -1.1, -0.6, -3.2, and -1.9, respectively. Similarly, the stations showed a consistent decreasing mean trend of -1.8, -1.1, -3.4, -1.8, -1.2, -1.9, -0.7, -3.1, and -1.8, respectively in long-term

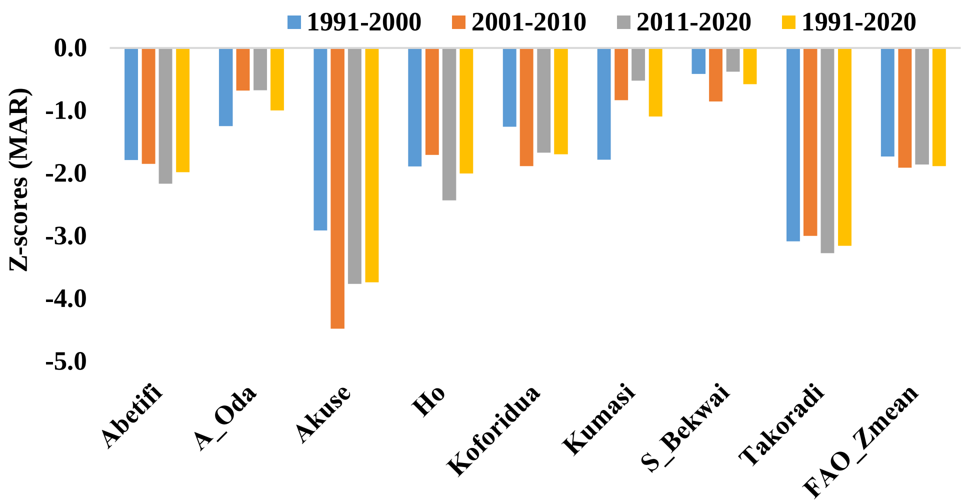

Figure 6.62: FAO-zonal and Stations Decadal and Long-term MAR trend

The multiple Pearson correlation matrix revealed positive correlations between the FAO-Zmean and six of the stations, indicating similar mean trends in mean annual rainfall. In relation to the FAO-Zmean, the Pearson co-efficient showed Abetifi (0.7), Akim Oda (0.6), Akuse (0.6), Ho (0.7), Koforidua (0.8), Kumasi (0.4), Sehwhi Bekwai (0.4), and Takoradi (0.7). These correlations indicate a consistent decreasing pattern for mean annual rainfall in the DFAEZ, as indicated by the FAO-Zmean dataset.

Furthermore, the p-value from the single factor ANOVA, test intra-zonal variability showed 4.42963E-15 at an alpha value of 0.05, indicated significant differences in the means, trend and correlations. Some stations are experiencing more rapid declines in mean annual rainfall compared to the FAO-Zmean, suggesting localized changes within the DFAEZ.

Additionally, the major season MAJ-LGP z-scores were also analyzed to further describe the intra-zonal variability, results shown in Figure 6.63.

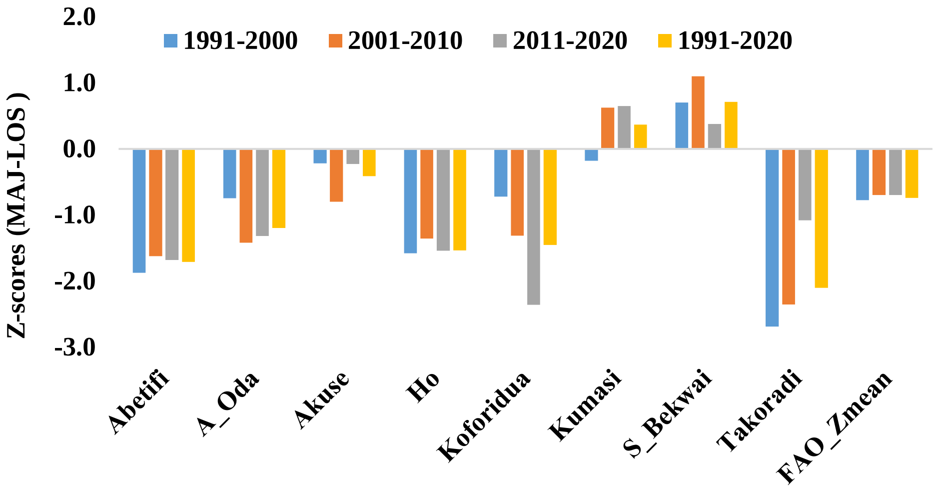

Figure 6.63: Standardized FAO-zonal and Stations MAJ-LGP anomalies

According to the results presented in Figure 6.63, there is a clear long-term and inter-decadal decreasing mean trend for MAJ-LGP observed for the FAO-Zmean and six stations (Abetifi, Akim Oda, Akuse, Ho, Koforidua, and Takoradi). This intra-zonal variability is shown by the climatological means: -1.7, -1.2, -0.4, -1.5, -1.5, -2.1, and -0.7, respectively FAO-Zmean, Abetifi, Akim Oda, Akuse,

Ho, Koforidua, and Takoradi. However, Sehwi Bekwai and Kumasi stations showed an opposite increase of 0.7 and 0.4, respectively. The Pearson correlation matrix showed positive correlations between the FAO-Zmean and Abetifi (0.3), Akim Oda (0.2), Akuse (0.5), Ho (0.7), Koforidua (0.4), Kumasi (-0.7), Sehwhi Bekwai (0.0), and Takoradi (0.6). Additionally, the single factor ANOVA p-value of 2.62E-13 at an alpha of 0.05. From results, while some stations observed significant decreasing trends and means over the climatological long-term, others showed increases above the existing FAO MAJ-LGP threshold for the DFAEZ.

The other agro-climatic parameters analyzed to describe the intra-zonal variability in the DFAEZ is MIN-LGP z-scores; Figure 6.64 display the results.

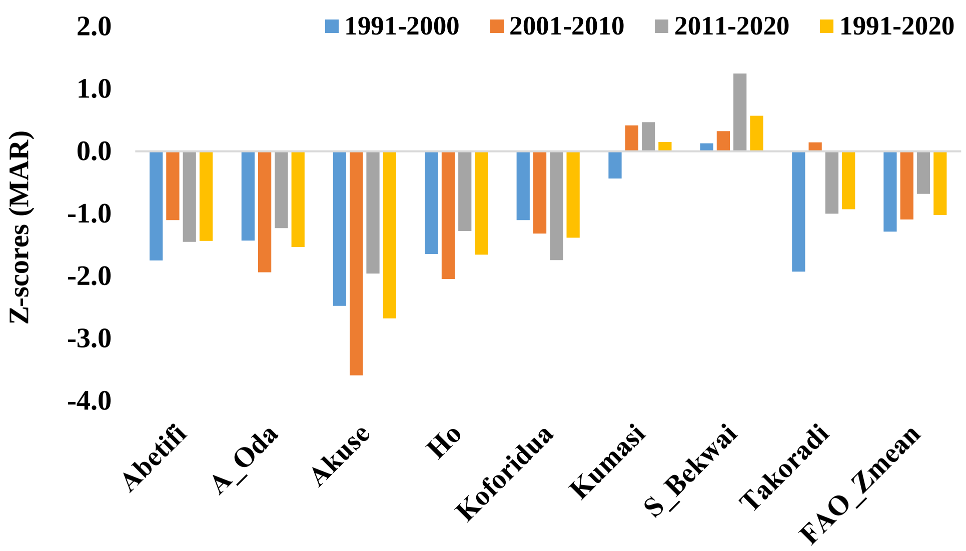

Figure 6.64: Decadal and Long-term FAO-zonal and Stations MIN-LGP trend

It is clear from Figure 6.64 that, while the long-term means analyzed for the standardized MIN-LGP z-scores show increases for Sehwi Bekwai (0.1) and Kumasi (0.6), the zonal FAO-Zmean and the other six stations revealed decreased means not only in the long-term, but also over inter-decadal regimes. Specifically, the long-term means for Abetifi, Akim Oda, Akuse, Ho, Koforidua, and Takoradi and FAO-Zmean were -1.4, -1.5, -2.7, -1.7, -1.4, -0.9, and -1.0, respectively, with corresponding decreasing mean trends of -1.7, -1.6, -3.4, -1.9, -0.9, -0.4, -0.1, -1.5, -1.5, and -0.4.

In relation to these results, the Pearson multiple correlation showed a positive correlation between FAO-Zmean and Abetifi (0.5), Akim Oda (0.4), Akuse (0.5), Ho (0.5), Koforidua (0.2), Kumasi (0.5), Sehwhi Bekwai (0.2), and Takoradi (0.7). The single factor ANOVA test yielded a p-value of 1.32155E-06 at an alpha value of 0.05, indicating a significant difference in the means and the means trends in the standardized FAO zonal means and station means z-scores (MIN-LGP) dataset over the long term. The ANOVA test revealed that, while some stations showed decreasing trends in means, others exhibited an increase significantly above and below the existing MIN-LGP threshold for the deciduous agro-ecological zone in Ghana. This result shows that, there is indeed clear local area or stations discrepancies due to the differential spatiotemporal impacts of climate change and changes in LULC across the entire DFAEZ. This is call for reclassification of the zones.

6.6.3 Inter-decadal and long-term variability in MAR and LGP

The analysis for latent inter-temporal variability was significant to further examine the patterns observed in the inter-decadal (1991-2000, 2001-2010, 2011-2020) in comparison with the long-term (1991-2020) means and trends in the standardized FAO-Zmean MAR and LGP datasets. The results for the inter-decadal and long-term differences in means and trends in the observed for the 30 yearly means from the FAO-zonal mean annual rainfall z-scores dataset are shown in Figure 6.62

Relative to Figure 6.62, over all the four periods (three inter-decadal periods and the long-term), the trends analyzed for the standardized FAO-Zmean and 8 stations MAR z-scores reveal a consistent significant decreasing trend in mean annual rainfall (MAR) within the Deciduous Forest agro-ecological zone. The FAO-Zmean consistently exhibited a decreasing trend in precipitation for all four time periods, with values ranging from -1.7 to -1.9. However, the individual stations showed varying patterns. For example, Abetifi exhibited a mixed pattern with a positive anomaly in the 1st inter-decadal period (1.8) and negative anomalies in the 2nd (-1.8), 3rd (-2.2), and long-term (2.0) periods. Similarly, other stations like Akim Oda, Akuse, Ho, Koforidua, Kumasi, Sehwhi Bekwai, and Takoradi also displayed varying anomalies across the different time periods.

The multiple Pearson correlation matrix indicated varied negative, weak, and strong positive correlations between the FAO-Zmean and the representative stations. The results for the FAO-Zmean correlation are: Abetifi (0.4), Akuse (0.9), Koforidua (1.0), Kumasi (0.4), Sehwhi Bekwai (0.7), and Takoradi (0.8). However, a negative correlation was observed between the FAO-Zmean and Akim Oda (-0.8). The additional ANOVA test results with a p-value of 1.54516E-12 at an alpha level of 0.05 clearly show statistically significant variations in the inter-decadal and long-term means for both the FAO zonal and station datasets.

It is evident from the study that, there is now substantial variations in rainfall patterns across the zone shown by the continuous significant decreasing means observed for the 8 representative stations in the DFAEZ, over the three inter-decadal periods and the long-term averages. The FAO-Zmean decreases over all the four periods were very significant far below the first standardized deviation; however, the individual stations displayed varied trends. It is also clear that, at present some stations have shifted from the characteristics of the DFAEZ. Consequently, it is recommended that the existing FAO MAR mean threshold for the DFAEZ be revised by way of reclassification to better align the threshold with the current climatic, environmental, and land use conditions in the region and at individual stations. This revision will provide more accurate guidance for decision-making in agriculture, water resource management, and climate change adaptation within the DFAEZ

Similarly, the MAJ-LGP was also analyzed to further describe the temporal variability in the agro-climatic condition over the long-term and within the 3 seasonal decades. Still from Figure 6.63, the results show clear consistent decreasing MAJ-LGP mean trends for the 3 inter-decadal and long-term periods from the FAO-Zmean and 6 stations z-scores. Specifically, Abetifi z-scores show -1.9, -1.6, -1.7, and -1.7 for the 1st , 2nd, 3rd inter-decadal periods and long-term, respectively. Akim Oda displayed means of -0.7, -1.4, -1.3, and -1.2 for the same periods, while Akuse showed means of -0.2, -0.8, -0.2, and -0.4. Similarly, Ho, Koforidua, Takoradi, and the FAO-Zmean demonstrated decreasing means over the inter-decadal and long-term periods. However, Kumasi and Sehwi Bekwai also show increasing mean trends over the same periods, with Kumasi displaying means of -0.2, 0.6, 0.6, and 0.4, and Sehwi Bekwai displaying z-scores of 0.7, 1.1, 0.4, and 0.7 for 1st, 2nd, 3rd and long-term.

The Pearson correlation matrix observed between the inter-decadal and long-term means and trends revealed positive correlation between the long-term means and the 1st decade (0.81), 2nd decade (0.86), and 3rd decade (0.92) means. The clear no significant temporal variations in the four periods are supported by the ANOVA test P-value of 0.994 at 0.05 alpha. But within the stations, the ANOVA test p-value of 9.03171E-11 at an alpha value of 0.05, indicate significant inter-temporal differences in the inter-decadal and long-term means.

Generally, the consistent significant decreasing mean trends observed over the long-term and within three decades show that the existing FAO MAJ-LGP mean threshold has changed significantly for the DFAEZ. There is also a clear significant inter-temporal variability analyzed from the stations MAJ-LGP z-scores. Based on these findings, it is concluded that the existing FAO MAJ-LGP threshold should be revised to reflect current climatic and environmental conditions and the LULC changes in DFAEZ.

Moreover, the analysis for temporal variability in the DFAEZ was also performed by examining the means and mean trends observed in the FAO-Zmean and stations MIN-LGP z-score over the 3 inter-decadal and long-term periods. In reference to the Figure 6.64, the results reveal a consistent decreasing means for FAO-Zmean (1st -1.3; 2nd -1.1; 3rd -0.7; and long term, -1.0. similarly, six of the stations show continuous significant decreases in the long-term and within the 3 inter-decadal means for Abetifi (1st -1.7; 2nd -1.1; 3rd -1.5;and long-term: -1.4), Akim Oda (1st -1.4; 2nd -1.9; 3rd -1.2; and long term -1.5), Akuse (1st -2.5; 2nd -3.6; 3rd -2.0; and long term, -2.7), Ho (1st. -1.6; 2nd -2.0; 3rd -1.3; and long term, -1.7), Koforidua (1st -1.1; 2nd -1.3; 3rd -1.7; and long term -1.4), and Takoradi (1st -2.7; 2nd -2.4; 3rd -1.1; and long term, -2.1). However, the long-term and inter-decadal means observed for Kumasi indicate continuous increases, apart from 1st decade (1st -0.4; 2nd 0.4; 3rd 0.5; and long term: 0.1), finally Sehwhi Bekwai results (1st 0.1; 2nd 0.3; 3rd 1.2; and long term, 0.6) show a consistent increasing mean trend.

The Pearson correlation matrix observed between the inter-decadal and long-term means for the stations and the FAO-z-scores positive correlation between the long-term means and the 1st decade (0.91), 2nd decade (0.92), and 3rd decade (0.94). The ANOVA test P-value of 0.814 at 0.05 alpha clearly indicate no significant temporal variations in the four period. However, within the stations, the ANOVA test p-value of 9.03171E-11 at an alpha value of 0.05, indicate significant inter-temporal differences in MIN-LGP days over the inter-decadal and long-term periods.

It can be inferred from the results so far that, the existing FAO MIN-LGP threshold set for the DFAEZ has changed significantly over the past 3 decades. There is also a clear significant inter-temporal variability analyzed from the stations MIN-LGP z-scores. The Abetifi, Akim Oda, Koforidua, Ho, and Takoradi stations showed a significant decrease in means far below the existing FAO threshold, while Kumasi and Sehwi Bekwai observed continuous increases over the four periods.

Therefore, it is recommended that the existing FAO MIN-LGP threshold be revised to reflect current climatic and environmental conditions and land use and land cover changes, possibly accounting for the zone's variability.

6.6.4 Multiple Pearson correlation for key agro-climatic parameters

Furthermore, the analysis for changes in DFAEZ included the test for correlations between the key agro-climatic (MAR, MAJ-LGP and MIN-LGP) and other relevant variables such as PET, RDAYS, TMEAN, SOS, and EOS. This analysis was done to better understand the associations and trends between and among the agro-climatic variables. The results for the multiple Pearson (R) correlation matrix are showed in in Figure 6.65.

The Pearson multiple correlation in Figure 6.64 revealed the standardized FAO-Zmean MAR has strong negative correlations with PET, RDAYS, Tmean, MAJ-LGP, MIN-SOS, MIN-EOS, and MIN-LGP while showed strong positive correlations with MAJ-SOS and MAJ-EOS.

Similarly, the standardized FAO MIN-LGP dataset displayed positive correlations with PET, RDAYS, Tmean, MAJ-LGP, MIN-SOS, and MIN-EOS, but negative correlations with MAR, MAJ-SOS, and MAJ-EOS.

From Figure 6.65, the standardized FAO MAJ-LGP dataset exhibited negative correlations with MAR, MAJ-SOS, and MAJ-EOS while displaying positive correlations with PET, RDAYS, and Tmean

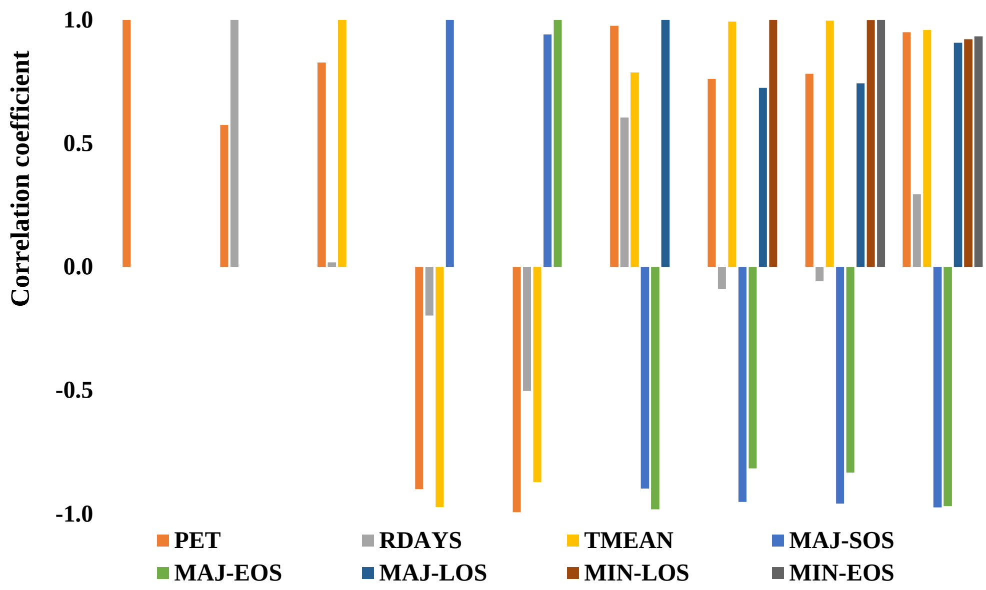

Figure 6.65: Multiple correlations for the key agro-climatic parameters

From Figure 6.65, These significant decreasing trends and means in the zonal MAR, MAJ-LGP, and MIN-LGP below the existing FAO thresholds indicated that the agro-climatic conditions have changed, and will continue to have significant implications on agricultural production, agro-economic investment planning, and academic research that utilizes the existing zonal thresholds.

6.5.5 Summary of inter-decadal and long-term FAO-zonal MAR and LGP

Additionally, the evidence for changes in the DFAEZ was summarized by presenting together the results for the standardized FAO-zonal means for the key agro-climatic parameters (MAR, MAJ-LGP, and MIN-LGP) over the four periods. This was done by comparing the long-term and inter-decadal means and trends observed for key parameters that used to define the DFAEZ in the existing FAO agro-ecological classification of Ghana.

The Figure 6.66 presents the summarized results for DFAEZ.

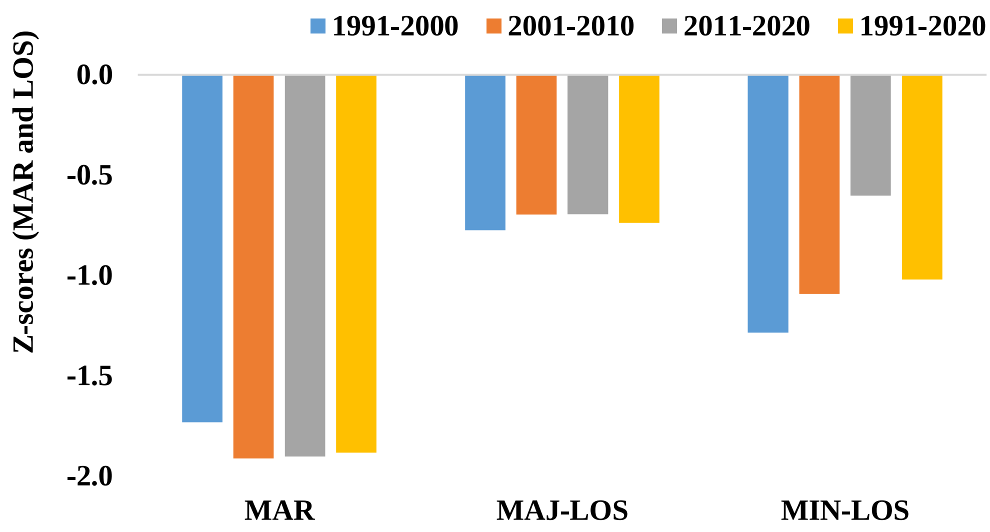

Figure 6.66: Summarized decadal and long-term standardized FAO-zonal MAR and LGP anomalies

The summary results of MAR, MAJ-LGP, and MIN-LGP showed significant continuous decreasing means and trends observed for the standardized FAO-Zmean over the four time periods in the DFAEZ. These results are consistent with the calculated mean difference for MAR (-230), MAJ-LGP (-21 days), and MIN-LGP (-17 days) observed between the existing FAO and CLT thresholds. The calculated ANOVA p-values for MAR (3.95169E-08), MAJ-LGP (0.006), and MIN-LGP (0.0002); long-term trends for MAR (FAO-Zmean, -1.9; CLT-Zmean 0.1), MAJ-LGP (FAO-Zmean -0.7; CLT-Zmean 0.0), and MIN-LGP (FAO-Zmean -1.0; CLT-Zmean 0.0); and the Pearson correlations for MAR (0.9), MAJ-LGP (1), and MIN-LGP (1) observed between the standardized FAO-Zmean and CLT-Zmean support these findings.

`In addition, the observed significant differences in the behaviour of the eight stations to the FAO-Zmean indicated clear intra-zonal discrepancies. Notably, the Sehwi Bekwai and Kumasi stations have shifted and behave significantly differently from the existing FAO thresholds set for the zone. In conclusion, the existing FAO MAR, MAJ-LGP, and MIN-LGP thresholds are obsolete and need to be revised to reflect the current climatic conditions, land use and land cover changes, and other environmental factors. This revision is crucial for informing sustainable agriculture practices, economic investments, academic research, and related socio-economic developmental decision-making and planning.

6.7 Evidence for Changes in the Coastal Savanna Agro-ecological Zone

The FAO classification identified the Coastal Savanna Agro-ecological Zone (CSAEZ) in Ghana as having a mean annual rainfall of 800 mm, with the major rainy season occurring from March to July and the minor season from September to November. The zone has a mean length of growing period (LGP/LGP) of 105 days during the major season and 50 days during the minor season. Analysis of 30-year historical climate datasets revealed the current long-term (CLT) zonal mean thresholds for the zone, which are MAR of 840 mm (±146), MAJ-LGP of 77 mm (±14), and MIN-LGP of 28 mm (±17).

6.7.1 Changes in FAO-zonal and CLT-zonal MAR and LGP thresholds

To establish the climatological changes in the existing FAO-zonal mean thresholds for MAR and LGP, the 30-year standardized FAO-Zmean and CLT-Zmean datasets were analyzed for long-term trends and means. ANOVA and Pearson correlation tests were applied to assess the significance of the differences and relationships between the datasets. A two-time series line graph was used to visualize the yearly and long-term trends in MAR and LGP Z-scores. Figure 6.67 displays the results of the long-term trends observed in the FAO-Zmean and CLT-Zmean z-scores for the MAR datasets.

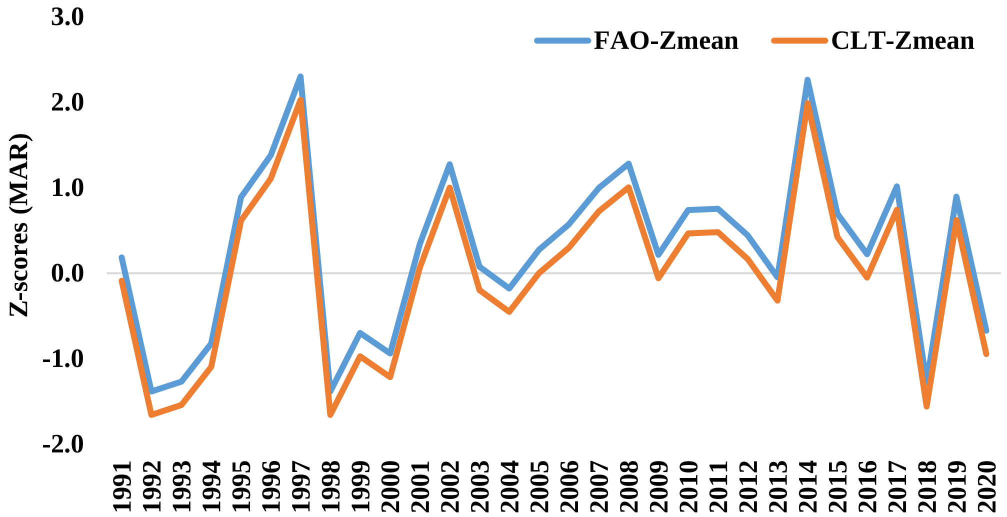

Figure 6.67: Standardized FAO-zmean and CLT-zmean MAR trends.

From Figure 6.67, the long-term mean trends analysis reveals a decreasing MAR for both the standardized FAO-Zmean (-0.1) and CLT-Zmean (-1.1) z-scores datasets. The climatological means show increasing MAR with observed z-scores of 0.3 for FAO-Zmean and 0.5 for CLT-Zmean. The Pearson correlation show a weak positive correlation between the standardized FAO-Zmean and CLT-Zmean datasets. The single factor ANOVA p-values (0.3) at 0.05 alpha indicated no statistically significant difference in the means and trends observed between the two standardized zonal MAR thresholds. This climatological mean increase is consistent with the mean difference of +40 mm between the existing FAO (800 mm) and CLT (840 mm) MAR thresholds.

It is evident from the results that, in relation to the existing CSAEZ, MAR has increased by 40 mm above the existing FAO threshold; thus, making the FAO MAR threshold not representative of the zone at present climatic conditions of the CSAEZ. These results can be attributed to the impact of climate variability. The increase in MAR has important implications for revising the AEZ, redefining research directions and planning policies towards improving agricultural development and designing proactive climate change adaptations.

Additionally, the zonal MAJ-LGP z-scores was further analyzed to describe the agro-climatic changes in the DFAEZ. The analysis involved examining the long-term trends and the climatological means observed in the FAO-Zmean and CLT-Zmean z-scores. The results for the changes in the MAJ-LGP can be shown in Figure 6.68.

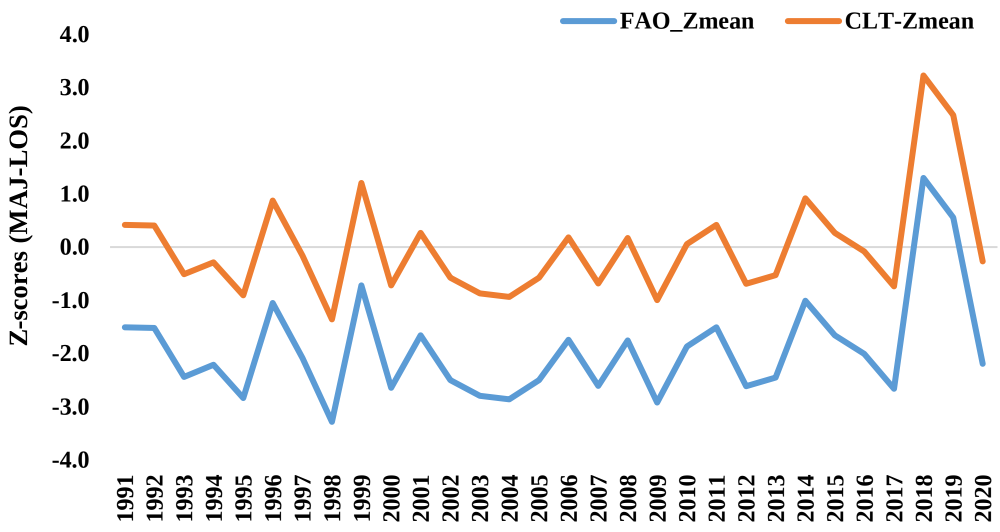

Figure 6.68: Standardized FAO-zmean and CLT-zmean MAJ-LGP trends.

The results from Figure 6.68 show a climatological decreasing means MAJ-LGP observed for the FAO-Zmean (-2.4) and the CLT-Zmean at (-0.5). Pearson correlation show a perfect positive correlation between the two zonal MAR threshold and datasets. The ANOVA test for confirms clearly that FAO-Zmean and CLT-Zmean datasets are significantly different in means, with a p-value of 0.0003 at an alpha of 0.05. The decrease in the long-term means is consistent with the observed negative difference (-28 days) observed between the existing FAO and CLT MAJ-LGP days analyzed for the CSAEZ.

It is evident from the climatological long-term mean results that, the existing MAJ-LGP threshold for CSAEZ has changed and become obsolete. It is therefore no longer suitable to inform decisions; hence, there is the need to revise and adopt the new threshold that reflect the current changes in climatic and environmental conditions, as well as the changes land use and land cover.

Another significant test for changes in CSAEZ was the analysis for difference in the long-term means for the FAO-Zmean and CLT-Zmean MIN-LGP z-scores. The Figure 6.69 the results.

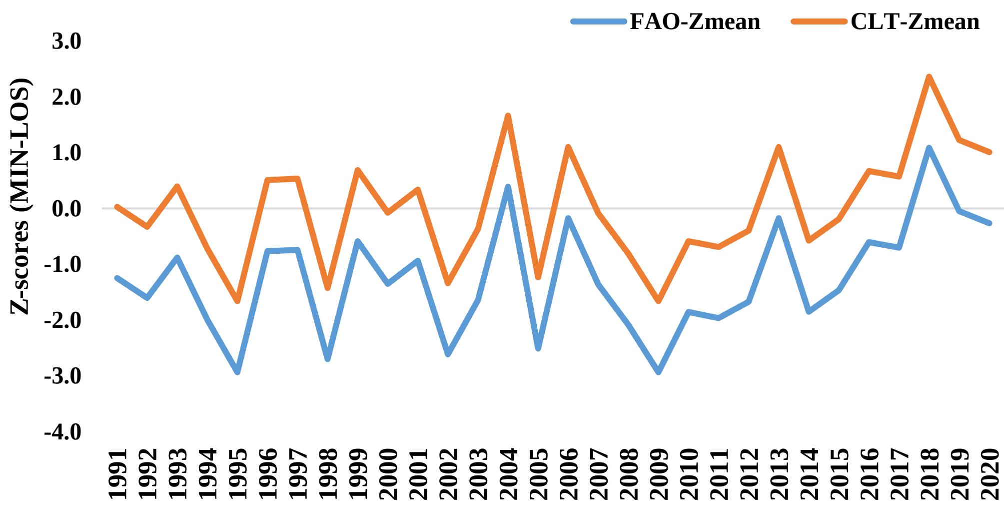

Figure 6.69: Standardized FAO-zmean and CLT-zmean MIN-LGP trends

Over the long-term, the results in Figure 6.69 show a discernible decreasing trend MIN-LGP for both the standardized FAO-Zmean (-1.8) and CLT-Zmean (-0.5) MIN-LGP z-scores. The climatological means thus indicate a significant decrease (-1.3) for the FAO-Zmean z-scores datasets; however, the CLT-Z mean (0.00) show no clear change. The Pearson correlation between the long-term means and trends in the two groups (FAO-Zmean and CLT-Zmean z-scores) show a perfect positive correlation (+1). The ANOVA p-value of 7.06621E-06 at an alpha value of 0.05 indicated a statistically significant difference between the means and trends observed in the two zonal MIN-LGP datasets. The decrease in the long-term means is consistent with the observed mean difference (-28 days) observed between the existing FAO and CLT MAJ-LGP days analyzed for the CSAEZ.

From these results, it is evident that the current FAO MIN-LGP threshold has changed, become outdated, and needs to be revised to reflect the current climatic conditions and changes in land use and land cover characteristics of CSAEZ. The observed change in MIN-LGP can be attributed to the impact of climate change and LULC changes in the zone. The urgent need for revision of the MIN-LGP threshold is essential for informing sustainable agricultural practices, economic investments, academic research, and related socio-economic developmental decision-making and planning.

6.7.2 Intra-zonal (FAO-Zmean vrs stations) variability in MAR and LGP

The analysis of long-term means and trends for the FAO-Zmean and CLT-Zmean z-scores in the CSAEZ revealed significant intra-zonal variability. Correlation and ANOVA tests were conducted to compare the standardized MAR, MAJ-LGP, and MIN-LGP z-scores between the FAO-zonal mean and individual station datasets. These tests highlighted discrepancies between stations and the FAO-zonal mean. Figure 6.70 shows the results for intra-zonal variability in MAR within the CSAEZ based on the FAO-Zmean and station z-scores.

From the results in Figure 6.70, the inter-decadal and long-term mean analysis reveal for Accra, Ada and the FAO-Zmean MAR an initial decrease, then an increase (shift) that continues through the 3rd decade and the long-term.

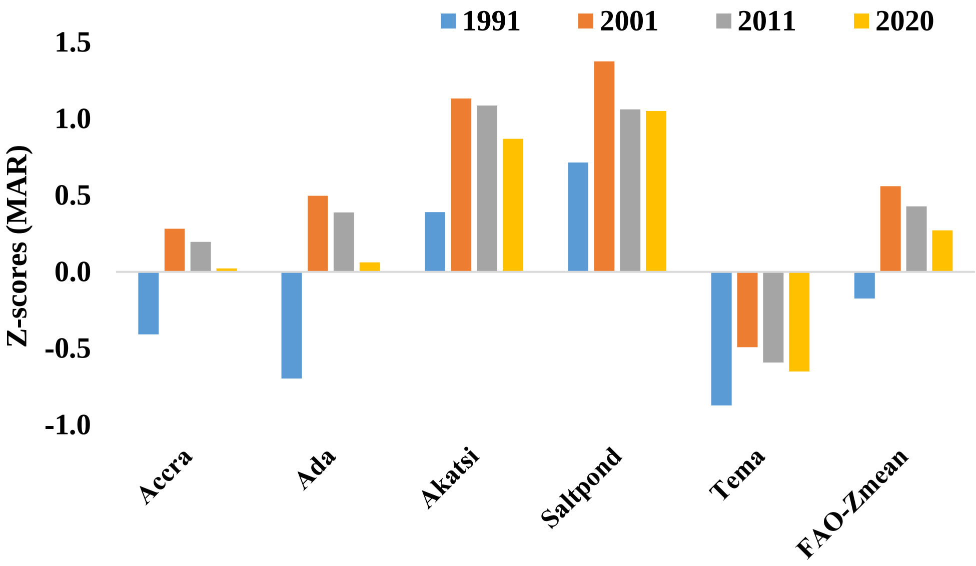

Figure 6.70: Decadal and Long-term FAO-zonal and Stations MAR trend

Differently, however, while Akatsi and Saltpond reveal continuous significant increases, the Tema station z-scores saw a consistent decreasing MAR over the four periods. The climatological means results show a general increase for the FAO-Zmean (0.3), Accra (0.02) and Ada (0.1), Akatsi (0.9) and Saltpond (1.1), while Tema exhibits a decrease (-0.7) relative to existing FAO zonal mean threshold representing the standardized mean (0). Additionally, the LINEST regression test reveals a long-term decreasing mean trend: Accra (-0.8), Ada (-0.5), Tema (-0.8), and the FAO-Zmean (-0.1); however, Akatsi (0.4) and Saltpond (0.8) stations show an increasing trend.

The Pearson multiple correlation matrix reveal a perfect positive correlation between the FAO-Zmean and Accra, Ada, Akatsi, Saltpond stations, but a strong negative correlation with Tema over the long-term. Finally, the single factor ANOVA test (p-value = 0.0001 with 0.05 alpha) showed a significant difference in the means, trends and correlations between the standardized FAO-Zmean and the stations MAR z-scores. It is thus evident from the means and mean trends that there is significant intra-zonal variability between the FAO-Zmean and the stations, with Tema showing a continuous decrease, and Saltpond and Akatsi exhibiting significant increases. The results highlight the need for reclassification of the FAO MAR thresholds, and to do a more detailed investigation of the factors underlying these discrepancies.

The MAJ-LGP z-scores was also analyzed to further describe the intra-zonal variability in the CSAEZ as evidence of changes in the zone. Figure 6.71 display the results

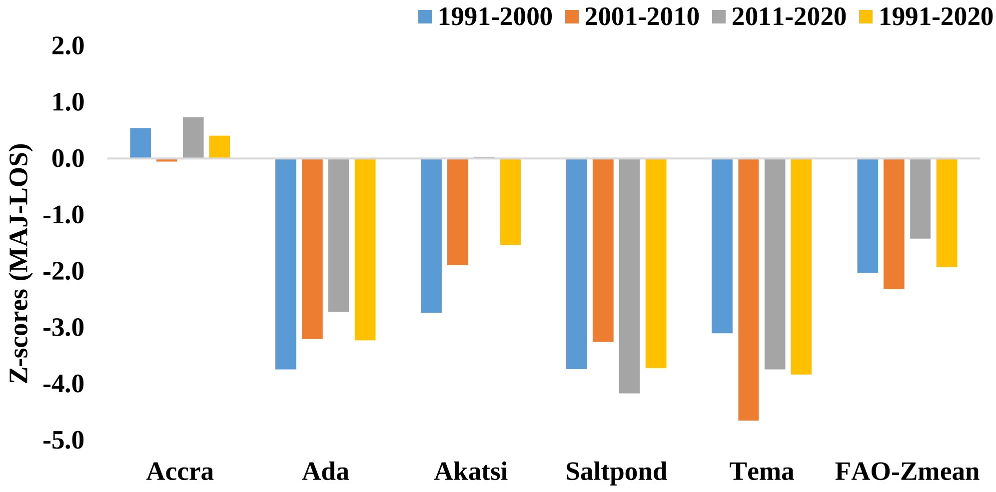

Figure 6.71: Decadal and Long-term standardized FAO-zonal and Stations MAJ-LGP anomalies

Apart from Accra, the results presented in Figure 6.71 indicate a consistent significant decreasing MAJ-LGP days observed over both long-term and inter-decadal time periods from the standardized FAO-Zmean and four station mean z-scores. The long-term mean z-scores for Accra, Ada, Akatsi, Saltpond, Tema stations, and the FAO-Zmean reveal 0.4, -3.2, -1.5, -3.7, -3.8, and -1.9, respectively, with a decreasing trend of -0.1, -3.8, -3.5, -3.1, -3.2, -2.4. The Pearson multiple correlation matrix showed positive correlations between the FAO-Zmean and Ada, Akatsi, Saltpond, and Tema standardized means, indicating a uniform decreasing mean trend in both the FAO-Zmean and the four stations over the last 30 years. Relative to the FAO-Zmean, the Accra showed a negative correlation.

Finally, the ANOVA test for intra-zonal discrepancies reveal p-value of 3.1784E-11 at significant level of 0.05, indicate there are significant differences in the means and mean trend observed in the FAO-Zmean and the stations means over the long-term. Apart from the clear opposite behaviour of Accra, the rate of decrease is more significant in some stations compared to the FAO-Zmean. Consequently, the clear continuous long-term decrease in MAJ-LGP z-scores for the FAO-Zmean, Ada, Akatsi, Saltpond, and Tema show the existing FAO MAJ-LGP has changed, become unrepresentative of the zone. This supports a revision of this threshold to keep the zone tandem with current climatic and LULC pattern.

The final agro-climatic variable analyzed for intra-zonal variability for the CSAEZ is the minor season length of the growing season. This test also involved the analysis for any significant differences in the climatological mean, mean trends and correlation between the standardized FAO zonal and stations z-scores observed for the coastal savanna agro-ecological zone**.** The Figure 6.72 present the results of this analysis.

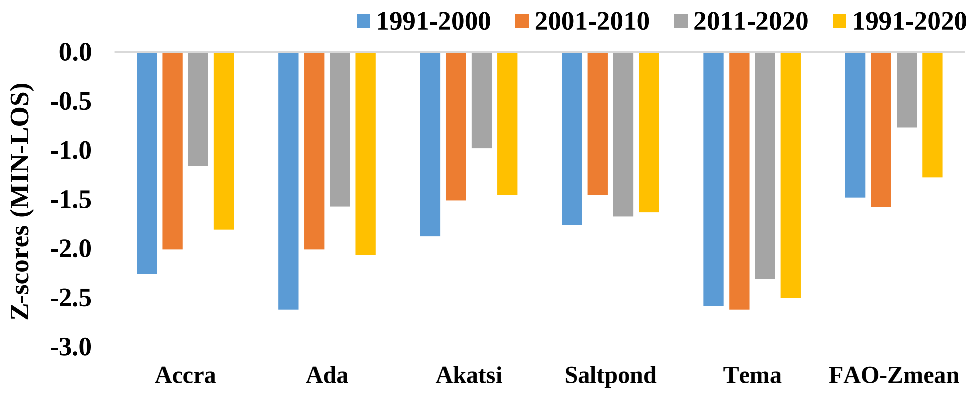

Figure 6.72: Decadal and Long-term FAO-zonal and Stations MIN-LGP anomalies

The findings in Figure 6.72 show a general discernible uniform decreasing mean trend in the MIN-LGP z-scores over the long term and inter-decadal time periods for all the six groups. The climatological (long-term) z-scores means reveal for Accra, Ada, Akatsi, Saltpond, Tema and FAO-Zmean1.8, -2.1, -1.5, -1.6, -2.5, and -1.3, respectively; with a decreasing trend of -2.6, -2.9, -2.1, -1.7, -2.7, -1.8. The Pearson correlation matrix showed a positive correlation between the FAO-Zmean and all the representative stations as 0.6, 0.7, 0.5, 0.6, and 0.3 for Accra, Ada, Akatsi, Saltpond, and Tema respectively. The ANOVA test p-values of 0.007 with alpha value of 0.05 indicated a significant difference in the long-term means and mean trends observed in the standardized FAO-Zmean and stations MIN-LGP z-scores for the CSAEZ.

From the continuous long-term decrease in the FAO-Zmean, Ada, Akatsi, Saltpond, and Tema MAJ-LGP z-scores, far below the first standardized deviation indicate that the existing FAO MIN-LGP threshold has significantly changed, become obsolete and needs a revision. There is clear intra-zonal discrepancies (stations deviations), where the climatological means and mean trends for Saltpond and Tema showed significant differences from the other stations and the zonal means. A revision of the existing FAO MIN-LGP zonal threshold is vital and has positive implications for planning agriculture and other economic activities sustainably in the area.

6.7.3 Inter-decadal and long-term variability in MAR and LGP

Furthermore, following the analysis of intra-zonal variability was the test for inter-temporal variability in the key agro-climatic parameters, and to understand not only the long-term changes, but also the decadal patterns in means. This analysis was done to compare the long-term means and mean trends analyzed for the key agro-climatic parameters (MAR, MAJ-LGP, and MIN-LGP Z-scores) for the FAO-Zmean and the stations. Figure 6.69 further presents the results for the inter-decadal and long-term MAR changes, variability and shift from the FAO-zonal and stations z-scores datasets.

It is evident from Figure 6.70 that, the FAO-Zmean and two representative stations (Accra and Ada) observed a long-term increase in MAR; within was a clear obvious shifting pattern from a decrease to a continuous increasing mean trend over the 2^{nd} and 3^{rd} decades. Quite differently, however, the climatological long-term and inter-decadal mean z-scores show a continuous increasing MAR observed for Akatsi and Saltpond, while Tema stations showed a continuous decrease over all the four periods. The ANOVA p-value of 1.59463E-07 with an alpha of 0.05 showed a general significant difference in the means and mean trends for the six groups over the four periods.

The results indicate clear decadal variability and intra-zonal discrepancies within CSAEZ. In conclusion, within the long-term climatological regime, there is clear inter-decadal variability. The inherent temporal decadal variability in MAR from the FAO-Zmean and stations Z-scores datasets imply regular revision of the CSAEZ by the use modern GIS and remote sensing techniques to keep the zone in tandem with current climatic and other environmental conditions and land use and land cover patterns.

Similarly, the test for temporal variability in the agro-climatic parameters of the CSAEZ included the analysis of standardized FAO-Zmean and stations MAJ-LGP z-scores for the over long-term and inter-decadal periods. The results in Figure 6.71 further reveal the evidence of inter-decadal and long-term temporal variability observed in the MAJ-LGP z-scores means and mean trends for Accra, Ada, Akatsi, Saltpond, Tema stations, and FAO-Zmean.

From Figure 6.71, the results show a continuous decreasing long-term means and a clear mean variability within the inter-decadal periods for the FAO-Zmean, Ada, Akatsi, Saltpond, and Tema stations. Accra showed a long-term increase in MAJ-LGP days; but within this period, it showed an initial shift from increase in the 1st decade to a decrease, and then further increase pattern in the 3rd decade. The Pearson correlation coefficient between the long-term and the three periods (1st, 2nd and 3rd decades) showed strong positive (0.9) correlation. The ANOVA test for temporal variability from the FAO zonal and station z-scores datasets showed a p-value of 6.55E-08 at an alpha of 0.05, indicating a significant mean decrease far below the existing FAO MAJ-LGP threshold. This result indicates not only a significant long-term change in the FAO threshold, but within each of the decades. A regular revision of the zonal MAJ-LGP threshold is crucial for planning agricultural production and a series of economic activities sustainably in the area.

Another relevant parameter analyzed for temporal variability within the CSAEZ is the FAO zonal and station MIN-LGP z-scores. The results in Figure 6.72 further present proof of inter-decadal and long-term variability in the MIN-LGP z-scores. From Figure 6.72 a discernible significant decreasing MIN-LGP z-scores over the long-term and within the three inter-decadal periods the FAO-Zmean and stations datasets. These decreasing z-scores occurring far below the 1st standardized deviation for all the stations and the FAO-Mean over all the periods clearly indicate that the existing FAO MIN-LGP threshold has changed and become redundant to represent the CSAEZ.

The Pearson correlation test between the long-term and the three inter-decadal z-scores showed a strong positive association with the 1st decade (0.6), 2nd decade (0.7) and 3rd decade (0.8). This is consistent with the observed decreasing mean trends for all the groups over all the periods. Additionally, the ANOVA p-value of 0.279 at alpha of 0.05, reveals no inter-decadal change within the long-term means, indicating a continuous decrease in the MIN-LGP z-scores for the FAO-Zmean and stations.

The study concludes that the existing FAO MIN-LGP threshold had become obsolete analyzed from the FAO-Zmean z-scores over the long-term and within each of the three decades. A regular decadal revision of the zonal MIN-LGP is suggested given the application of GIS and RS techniques in modern AEZ methodology. Additionally, intertwine with the temporal variability is the presence of intra-zonal discrepancies (stations variability), with stations means and mean trends significantly different from other stations and the FAO-zonal means. A revision of the existing FAO MIN-LGP zonal threshold AEZs is vital, and has the potential to guide the sustainable planning of agriculture and other economic activities CSAEZ, given the current climatic, environmental and land use land cover patterns.

6.7.4 Multiple Pearson correlation for key agro-climatic parameters

Furthermore, the analysis for changes in CSAEZ included the test for correlations between the key agro-climatic (MAR, MAJ-LGP and MIN-LGP) and the other relevant variables such as PET, RDAYS, TMEAN, SOS, and EOS. This analysis was done to better understand the associations and trends between and among the agro-climatic variables. The results for the multiple Pearson (R) correlation matrix is showed in in Figure 6.73.

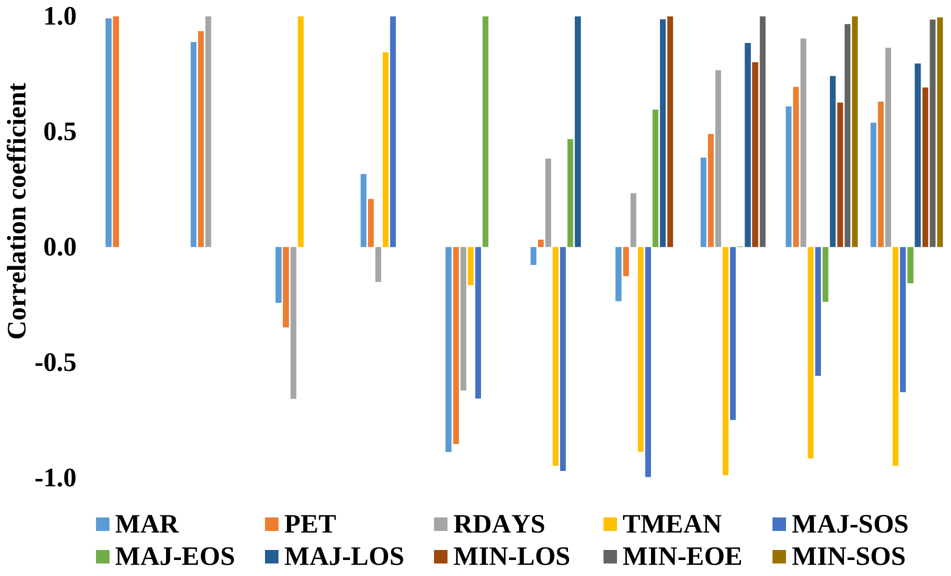

Figure 6.73: Multiple correlations for the key agro-climatic parameters

The results of the Pearson correlation matrix presented in Figure 6.73 show that MAR has a strong positive correlation with PET, RDAYS, MAJ-SOS, MIN-SOS, and MIN-EOS, but a weak negative correlation with MAJ-LGP. On the other hand, MAJ-LGP had positive correlations with PET, RDAYS, and MAJ-EOS, but negative correlations with MAR, Tmean, and MAJ-SOS. Meanwhile, MIN-LGP had negative correlations with MAR and Tmean, but positive correlations with RDAYS, RH, MIN-SOS, MIN-EOS, MAJ-EOS, and MAJ-LGP.

These results suggest that the agro-climatic conditions have changed significantly and that any research using the existing FAO thresholds for MAR, MAJ-LGP, and MIN-LGP needs to be reconsidered. Furthermore, the significant decreasing means observed in the standardized MIN-LGP and MAJ-LGP, which fell far below the existing FAO thresholds, indicated that these changes are projected to have significant adverse effects on agricultural production and agro-economic investment.

6.7.5 Summary of inter-decadal and long-term FAO-zonal MAR and LGP

Finally, there is a summary presentation of the results analyzed for all the key FAO MAR, MAJ-LGP and MIN-LGP over the 3 inter-decadal and long-term periods. The Figure 6.74 showed these results.

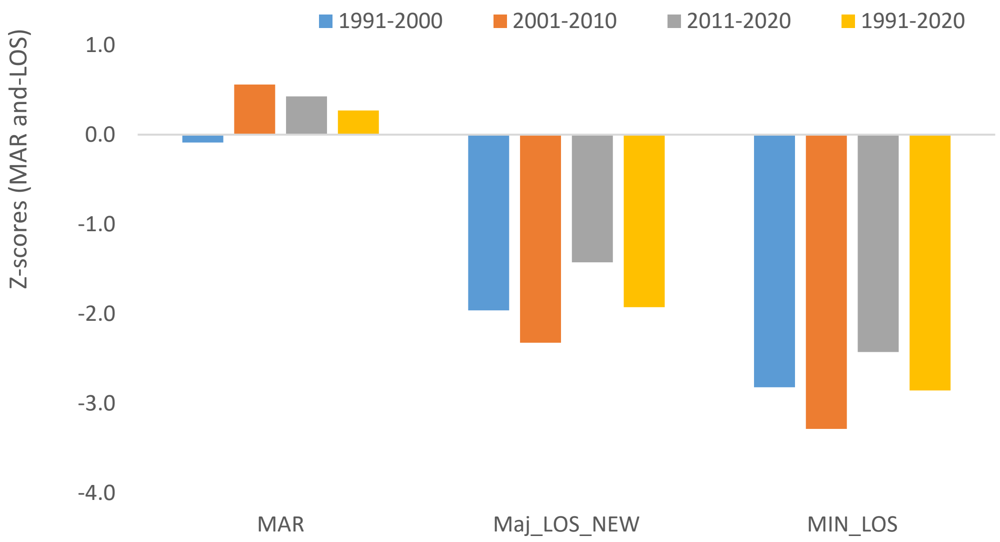

Figure 6.74: Decadal and long-term FAO-zonal MAR and LGP trend

The standardized FAO-Zmean MAR anomalies showed a continuous increase in means for the last three time periods, with a calculated MAR difference of 40 mm above the existing FAO threshold. However, the ANOVA showed no significant difference in the FAO and CLT zonal means. The Pearson correlation showed perfect positive correlation, but the LINEST regression slope indicated a decreasing trend in the observed FAO and CLT zonal means. The results further show a continuous significant decrease in means and trend for the FAO-Zmean over the four periods based on the observed standardized zonal means and trend in the MIN-LGP.

The calculated ANOVA showed a significant difference in the means observed between the FAO-Zmean and CLT-Zmean, as well as between the standardized FAO zonal and stations means for MAR, MAJ-LGP, and MIN-

LGP over the four periods. The LINEST regression showed decreasing trends, and the Pearson correlations also indicated positive correlation in the means and trends. Intra-zonal discrepancies were observed, with Saltpond, Tema, Ada, and Tema stations behaving significantly differently from the standardized FAO zonal means datasets.

Based on these results, it can be concluded that the existing FAO MAR, MIN-LGP, and MAJ-LGP thresholds have changed, become obsolete, and unrepresentative. The zonal thresholds need to be revised so that the zone can reflect current climatic conditions, land use and land cover changes, and other environmental factors occurring in Ghana and in the local zones. The suggestion for revision is crucial for guiding sustainable agriculture and economic investment planning, redefining research focus, and developmental decisions.

6.8: Inter-zonal spatio-temporal MAR and LGP trends in Ghana

Finally, the study presented a combined temporal and spatial analysis of MAR (Figure 6.75a-b) and LGP (Figure 6.76a,b,c) for all six FAO AEZs. This provided a holistic comparison of inter-zoanl agro-climatic dynamics Ghana

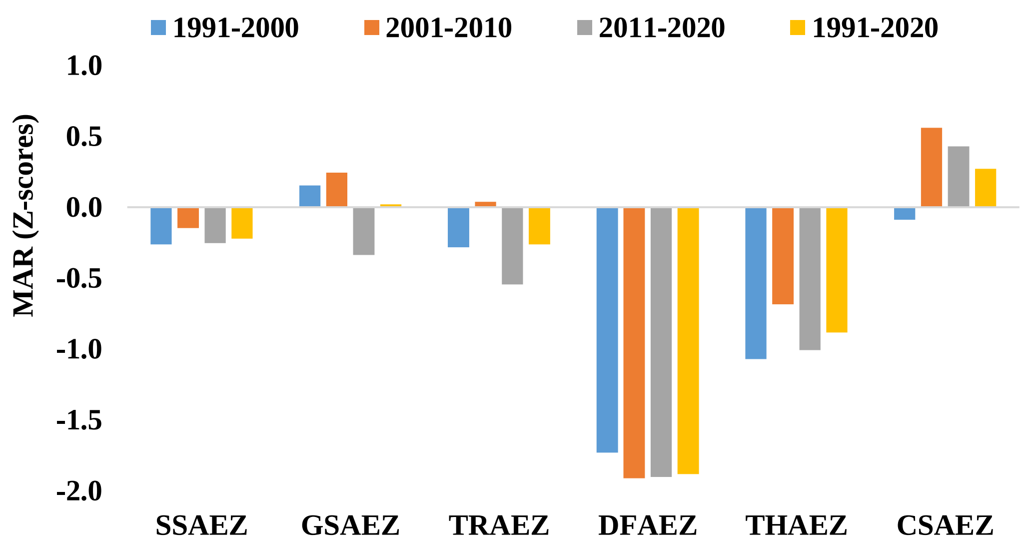

Figure 6.75(a): Inter-zonal temporal MAR trend across all AEZs

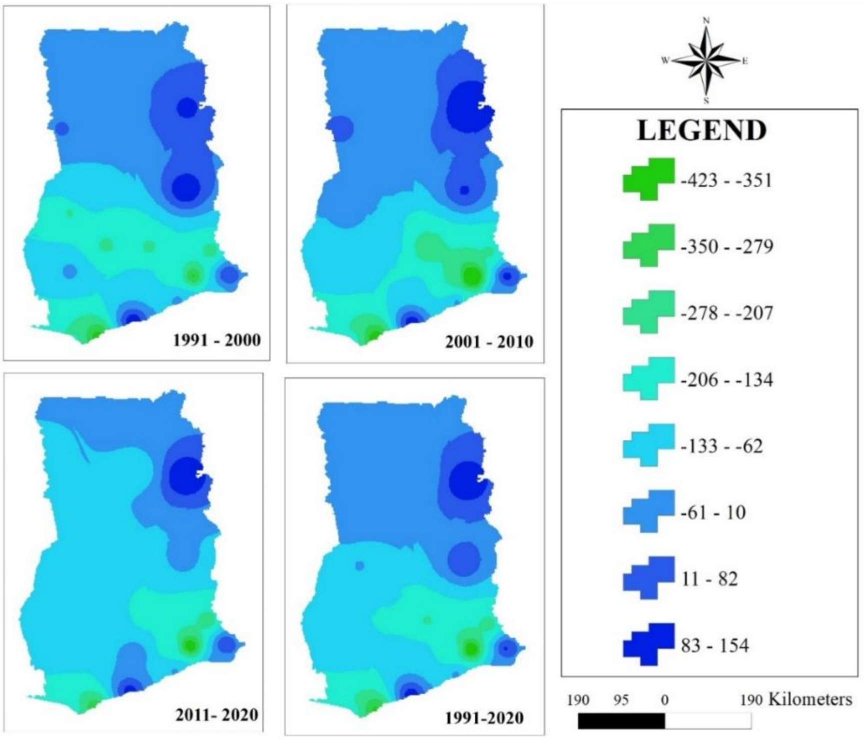

Figure 6.75(b): A -3 Decadal & Long-term MAR trend across

In summary, from Figures 6.75 (a & b), it is evident that nearly all six AEZs in Ghana have witnessed notable reductions in their established FAO MAR threshold, from all four periods (1991-2000, 2001-2010, 2011-2020) analyzed. Notably, the correlations between the multi-temporal spatial maps and graph reveal widespread decreases in rainfall, particularly in the forest dominated AEZs (THAEZ and DFAEZs) and transitional zones. However, some scattered spots in the CSAEZ and the northeastern flanks of GSAEZs reveal intra-zonal variations, marked by localized increases in MAR amidst the general declining trend.

The spatial and temporal coherence of the results underscores evolving rainfall patterns across Ghana's AEZs, highlighting the interplay between regional climatic drivers and localized factors influencing rainfall dynamics.

Similarly, the study also showed a generalized inter-zonal temporal and

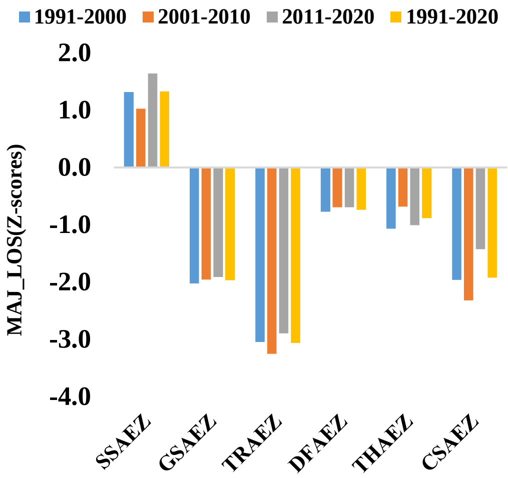

Figure 6.76a: Inter-zonal MAJ-LGP trends

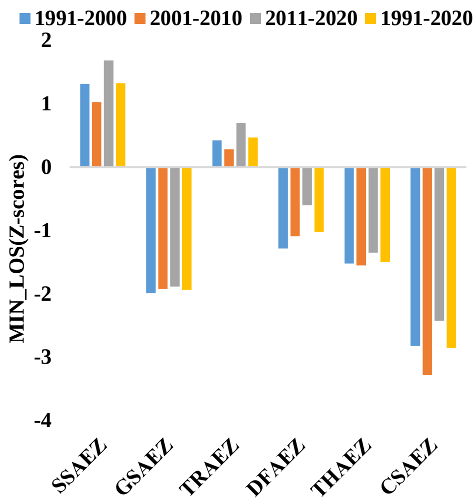

Figure 6.76b: Inter-zonal MIN-LGP trends

It is evident from Figure 6.76 (a-b) that, across all six FAO AEZs, except for the SSAEZ and TRAEZ (MIN-LGP), there is significant decrease in the historical FAO established LGP thresholds. From Figure 6.76 (a) SSAEZ now experiences an increase in growing periods, while the TRAEZ show continuous increase from the minor season LGP.

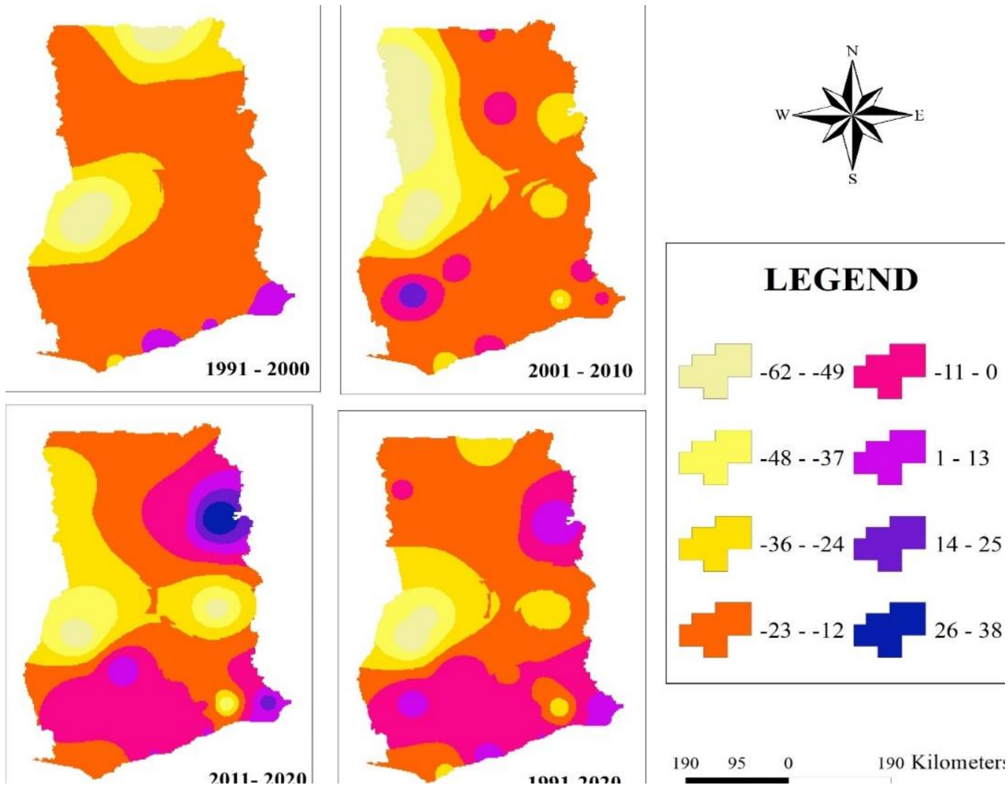

Figure 6.76 (b): A -3 Decadal & Long-term LGP trend across Ghana

Moreover, observed from the multi-temporal spatial maps (Figure 6.76 (b), except for few scattered spots where significant local increases in LGP, around Coastal and Guinea savanna AEZs, significant parts of Ghana now experience serious alterations in LGP thresholds. These results reveal the potential challenges for a continuous reliance on the old FAO AEZs in planning agriculture, research, extension services and economic investments.

Finally, detailed ANOVA results tested for the study hypotheses, in relation to Objective one, for objective conclusions made for any significant differences or shifts in old FAO MAR and LGP thresholds for the past three decades, have been presented in Table 7.10.

Table 7.10: Summary of ANOVA tests for significant changes (alpha P-value of 0.05)

FAO AEZs	FAO-Zmean	CLT-Zmean	LT-Zmean Changes	Temporal Shifts	Intra-zonal variations
SSAEZ					
MAR	1,000 mm	966 mm ((± 153)	(0.397)	0.005	-
LOS-MIN	155-days	183 days (± 21)	4.95283E-06	0.0003	-
LOS-MAJ	155-days	183 days (± 21)	4.95283E-06	0.0003	-
GSAEZ					
MAR	1100 mm	1103 mm (± 153)	0.94	0.0001	9.27797E-05
LOS-MIN	190 days	135 days (± 21)	1.13E-09	0.614	0.04
LOS -MAJ	190 days	135 days (± 21)	1.13E-09	0.614	0.04
TRAEZ					
MAR	1,300 mm	1242 mm (± 139)	0.11	0.01,	0.022
LOS-MIN	60 days	(67 days, ± 27).	0.079	0.013	0.335
LOS -MAJ	190 days	110 days (± 33)	3.52838E-1	0.043	0.577
DFAEZ					
MAR	1,500 mm	1,270 mm (± 122)	3.95169E-08	1.54516E-12	4.42963E-15
LOS-MIN	90 days	73 days (± 17)	0.0002	0.003	1.32155E-06
LOS -MAJ	155 days	134days (± 29)	0.006	9.03171E-11	2.52E-13
THAEZ					
MAR	2,200 mm	1,876 mm (± 367)	0.001	0.00002	2.68E-22
LOS-MIN	100-days	73 days (± 17)	1.71282E-05	5.31E-08	-
LOS-MAJ	155 days	134 days, ± 37)	0.033	0.001	-
CSAEZ					
MAR	800 mm	840 mm (± 146)	0.3	1.59463E-07	0.0001
LOS-MIN	50 days	28 days (± 17)	7.07E-06	0.007	0.001
LOS -MAJ	105 days	77 days (± 14)	5.03E-10	7.55E-08	3.18E-11

Results (2023)

6.9. Discussions

This study provides critical insights into the substantial changes in the agro-climatic thresholds of Ghana's FAO-classified AEZs, emphasizing the direct impacts of climate change and the indirect effects of evolving ULC changes. With the pivotal role that agro-climatic thresholds play in guiding extension services, government policies, and farmers' decisions, this research contributes essential knowledge for strategic planning in Ghana's agrarian economy. By analyzing 30 years of standardized Mean Annual Rainfall and Length of Growing Period datasets (1991–2020), using both the FAO-Zmean and CLT-Zmean frameworks, the study performed rigorous statistical tests, including hypothesis testing, trend analysis, correlation analysis, and ANOVA. The findings revealed statistically significant temporal changes ($p > 0.05$) in MAR and LGP thresholds across six AEZs, as well as intra-zonal discrepancies that suggest potential spatial shifts in zonal characteristics and their agricultural suitability.

6.9.1 Changes in the Existing FAO-Zonal MAR and LGP Thresholds

This study reveals significant reductions in Mean Annual Rainfall and length of growing period thresholds across Ghana's AEZ, highlighting the ongoing impacts of climate change and land-use changes. Specifically, MAR has decreased across the majority of AEZs: THAEZ dropped from 2,200 mm to 1,872 mm, DFAEZ from 1,500 mm to 1,266 mm, TRAEZ from 1,300 mm to 1,242 mm, and SSAEZ from 1,000 mm to 966 mm. These findings align with earlier studies by Amekudzi et al. (2015), Baidu et al. (2017), Klutse et al, (2018; 2020), Nkrumah et al (2020) (Yamba et al. (2023), which documented a decreasing trend in rainfall and erratic rainfall patterns in Ghana and southern

West Africa. GSAEZ and CSAEZ were exceptions, with slight increases in rainfall. These positive deviations from the general trend may reflect localized factors, such as coastal moisture influx and topographic variations, as suggested by Owusu and Waylen (2009). However, these increases are not enough to offset the broader climatic challenges observed in other zones.

Similarly, the LGP thresholds also showed significant reductions. GSAEZ decreased from 190 days to 135 days, THAEZ from 155 days to 134 days, DFAEZ from 155 days to 134 days, and TRAEZ from 210 days to 110 days. These reductions align with the trends of delayed seasonal onset (SOS) and earlier end of season (EOS) observed in earlier studies, including Gbangou et al. (2020), Owusu and Wayne (2013), Amekudzi et al. (2015) and IPCC (2014), who attributed the shifts to climate variability, particularly erratic rainfall. Conversely, the SSAEZ showed a notable increase in LGP (155 days to 183 days), which could indicate a shift toward earlier SOS and increased rainfall days, aligning with the observations.

The correlation between these shifts and the impacts of evolving LULC is evident. As Amekudzi et al. (2015), Asante & Amuakwa-Mensah (2015) Asare-Nuamaha and Botchay (2019); Fokuo et al. (2022) noted, these changes are exacerbated by anthropogenic factors, including deforestation and urbanization, which disrupt local microclimates and further alter agro-climatic conditions. Studies such as Baidu et al. (2017), CIAT (2014) and Nyadzi et al (2021) have also highlighted how land degradation and land-use changes amplify the impacts of climatic shifts, affecting existing AEZs in Ghana.

A revision of the FAO thresholds is vital for stakeholders to be able to design more zonal-specific policies that consider the complexities of local microclimates and climate variability, ensuring the long-term sustainability of Ghana's agriculture in the face of climate change. This approach is vital to ensuring that agricultural planning and climate resilience strategies remain responsive and effective.

6.9.2. Observed Seasonality in Rainfall and LGP

The study identified distinct spatio-temporal seasonality in MAR and LGP across Ghana's AEZs. The SSAEZ and GSAEZ displayed a unimodal rainfall regime, with synchronized Start of Season (SOS) and End of Season (EOS), leading to consistent LGP patterns. In contrast, the THAEZ, DFAEZ, TRAEZ, and CSAEZ showed bimodal rainfall patterns, indicating a more complex seasonal structure, which diverges from the unimodal trends seen in other regions (Yamba et al., 2023; Amekudzi et al., 2015). This change aligns with the Inter-Tropical Convergence Zone (ITCZ) and West African Monsoon (WAM) dynamics, which influence rainfall patterns and growing seasons.

Spatially, MAR decreases from the southwest to the northeast, with the lowest rainfall recorded in the CSAEZ (800 mm), a trend influenced by the ITCZ's movement and its impact on the WAM (Acheampong, 1982; Amekudzi et al., 2015). The LGP also mirrors this pattern, with reductions in the south and increases in the north, especially in the SSAEZ. These trends are shaped by factors like topography, vegetation, and sea surface temperatures (Manzanas et al., 2014), all contributing to Ghana's agro-climatic diversity.

Studies by Baidu et al. (2017) and Gbangou et al. (2020) confirm that local factors, such as deforestation and urbanization, exacerbate the impacts of climate change, disrupting microclimates and rainfall patterns. The results suggest that climate variability and local environmental changes must be addressed in agricultural planning. As noted by Mugandani et al. (2012), updating agro-climatic classifications to incorporate high-resolution data and local factors is essential for effective climate adaptation and sustainable agricultural practices (Yamba et al., 2023; Quiroz et al., 2001).

6.9.3. Understanding Intra-Zonal Variations

This study uncovered significant intra-zonal variations in Mean Annual Rainfall (MAR) and Length of Growing Period (LGP) across Ghana's AEZs, challenging the presumed homogeneity of the existing FAO classification. Multi-correlation and ANOVA analyses (p-values < 0.05) between standardized FAO-Zmean z-scores and station-level z-scores revealed substantial deviations from the FAO thresholds. For instance, in the GSAEZ, the Yendi station records higher rainfall, whereas Tamale and Wa show considerably lower rainfall than the FAO threshold. In the DFAEZ, Akuse and Takoradi exhibit significant rainfall decreases, while Sehwi Bekwai, Kumasi, and Akim Oda align more closely with the thresholds. Similarly, in the CSAEZ, Saltpond and Akatsi receive significantly more rainfall, while Tema records far lower rainfall, and Accra and Ada remain relatively consistent with the FAO benchmarks. Conversely, the SSAEZ shows minor deviations, suggesting a more homogeneous rainfall pattern. For LGP, notable deviations were also evident. In the DFAEZ, Sehwi Bekwai and Kumasi recorded increased growing seasons, diverging significantly from the FAO thresholds, while Takoradi showed a marked decrease. Across the GSAEZ and TRAEZ, all representative stations exhibited significant LGP reductions, falling far below the thresholds defined for these zones.

These current findings are consistent with earlier work of Yamba et al

(2023) and Gbangou et al. (2020), Amekudzi et al. (2015), Owusu and Wayne (2013) who reported shorter growing periods and decreasing rainfall regime caused by delayed seasonal onsets and early cessations. Additionally, observed variability in topography, vegetation cover, and land-use changes, including deforestation and urbanization within same zone disrupt local microclimates, leading to these deviations (Bisht et al., 2019; Baidu et al., 2017). Within zones, specific microclimates influence differential climatic trends, as noted by Asante and Amuakwa-Mensah (2015), Amekudzi et al. (2015), and Baidu et al. (2017), underscoring the complexity of intra-zonal climatic variability. Similarly, reliant on aggregated zonal data, the FAO classification system, fails to account for these local variations, rendering its thresholds inadequate for capturing current climatic realities (Quiroz et al., 2001; Chikodzi et al., 2013). Furthermore, these disparities may also stem from the lack of sophistication in old agro-ecological zonation methods, data inadequacy and poor data resolution (Bisht et al., 2019; Chikodzi et al., 2013; Patel et al., 2005; Quiroz et al., 2001; van Wart et al., 2023).).

Revising the thresholds using high-resolution data and advanced zonation methods would address these intra-zonal differences, creating a more accurate representation of Ghana’s diverse climatic conditions. Such revisions would improve agricultural planning, support climate adaptation, and ensure policies are tailored to the specific needs of each region (Araya et al., 2010; Mugandani et al., 2012; Yamba et al., 2023).

6.9 Chapter Summary

The chapter analyzed changes in key agro-ecological parameters across Ghana's six FAO AEZs by comparing FAO-zonal thresholds with recalculated long-term means. Tests for trends, correlations, and ANOVA revealed significant changes in MAR, MAJ-LGP, and MIN-LGP across all zones, driven by climate and LULC changes. These findings underscore the need to reclassify Ghana's AEZs to reflect current climatic and environmental conditions, supporting food security, biodiversity conservation, and sustainable development. Implementing these recommendations, Ghana can ensure food security, biodiversity conservation, and environmental well-being.

CHAPTER SEVEN

SPATIO-TEMPORAL CHANGES IN LULC OF GHANA

7.1 Introduction

The main objective of this study was to reclassify the FAO six AEZs or classification of Ghana's to align with current climatic and LULC patterns. Based on studies such as Fischer et al. (2009), IIASA and FAO (2012), Paladini (2017), Mugandani et al. (2012), and Musher et al. (2016), analyzing spatio-temporal changes in LULC is a reliable method and/ or a good proxy for understanding shifting AEZs, including Ghana's. Accordingly, the Chapter Seven examined evolving historical LULC dynamics of Ghana using a multi-temporal post LULC classifications for 2001, 2010, and 2019 to assess their potential impacts on shifting the country's AEZs. By adapting the FAO (1996) and Anderson (1976) classification schemes, the geographical landscape of Ghana was reclassified into six LULC classes: forest land, rangeland, wetland, and agricultural land, built-up, and barren land. Changes in these classes potentially alter agro-climatic conditions (MAR and LGP), affect land productivity and crop suitability patterns, disrupt agricultural production, and existing agro-economic investment structure within the zones. Significantly, this chapter analyzes the evolving LULC dynamics of Ghana across all six AEZs, examining their links to climate change and degradable anthropogenic land uses, and thus examines their implications in shifting spatial patterns and zonal boundaries of old FAO AEZs. Specifically, the chapter outlines the spatio-temporal dynamics, temporal trends (spatial extends and area percent), spatial (digital) and statistical LULC change detections. Moreover, the findings are discussed in relation to current studies, and finally a chapter summary.

7.2 LULC Classification and Accuracy Assessment

The LULC classification results provide a robust basis for analyzing land-use and land-cover dynamics in Ghana. As shown in Table 5.6 (methodology section), the reclassified maps achieved high accuracy: 84.85% (2001), 83.72% (2010), and 84.00% (2019), with corresponding kappa coefficients of 81.93%, 80.82%, and 80.81%. These values fall within the "very good" range of classification accuracy (Anderson, 1979; Fielding & Bell, 1997Monserud & Leamans, 1992; Moriasi et al. (2007), underscoring the reliability of the classification. The high accuracy validates the spatial maps and ensures the credibility of the subsequent analyses, effectively capturing LULC changes and trends across the three historical periods.

7.3 Spatio-temporal Dynamics in the Historical LULC maps of Ghana

This study analyzed how Ghana's LULC patterns have evolved over the past two decades (2001–2010 and 2010–2019) and their implications for shifting the old FAO AEZs, as depicted in the three (3) multi-temporal reclassified LULC maps (2001, 2010, and 2019) presented in Figure 7.77

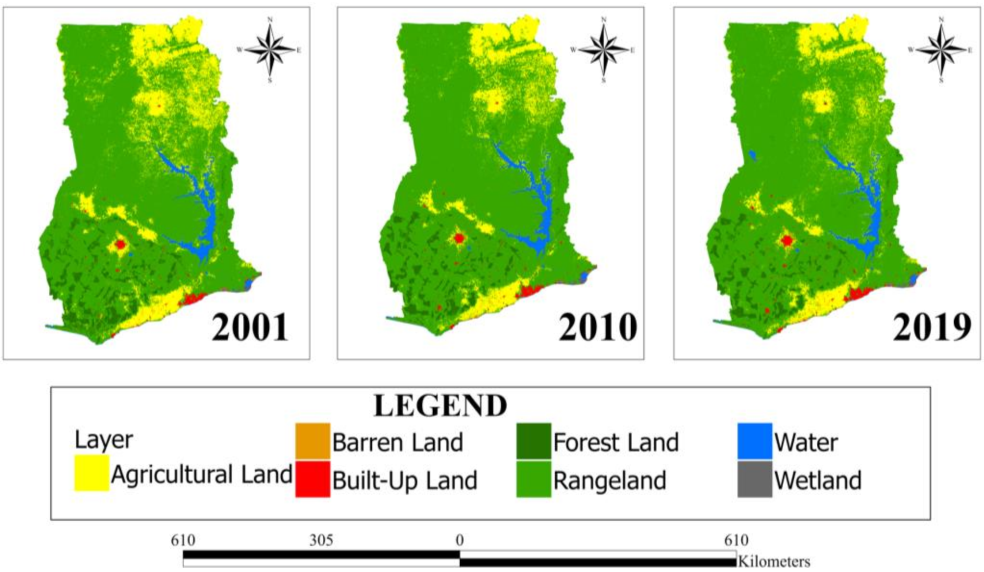

Figure 7.77: A 3-Multi-temporal LULC maps of Ghana

From Figure 7.77, a critical analysis of the three historical LULC maps (2001, 2010, and 2019) reveals significant changes in Ghana's land use patterns. Forest and agricultural lands have shown a marked decline across all periods, while rangeland, barren land, built-up areas, and wetlands have experienced notable expansion. These shifts suggest transformations in Ghana's old AEZs, with forest-dominant zones shrinking and savanna-dominant zones expanding. Such changes have far-reaching implications for land use structures, food security, and biodiversity, underscoring the urgent need for AEZ reclassification and sustainable land management strategies.

7.4 Analysis of spatial extent and percentage distribution of LULC classes

Using the three multi-temporal historical LULC maps of Ghana (2001, 2010, and 2019; Figure 7.77), additional quantifications were calculated to assess the spatial extents and percentage coverage of the six LULC classes over the periods. Table 7.11 presents the results, showing area distributions (km^2) and proportional percentages, while Figures 7.7878a-b illustrate trends. Major classes (forest, rangeland, and agricultural land) are detailed in Figure 7.78a, while minor classes (wetland, built-up, and barren land) are shown in Figure 7.78b.

Table 7.11: **Historical LULC classes, Spatial extent, Percentage area**

Periods	**2001**		**2010**		**2019**	
LULC	**Area (km^2)**	**%**	**Area (km^2)**	**%**	**Area (km^2)**	**%**
Forest	11,778.25	5.03	10,252.25	4.38	9,225.25	3.94
Ranged	178,003.8	76.01	188,270.3	80.42	190,801.3	81.55
Wetland	265.5	0.11	745	0.32	421.5	0.18
Agricult	41,830.5	17.86	32,250.5	13.78	30,496.75	13.03
Built-Up	2,234.25	0.95	2,521.5	1.08	2,925.75	1.25
Barren	73.75	0.03	81.25	0.03	93.75	0.04

Results, 2023

Based on Figure 7.77 and Table 7.11, rangeland dominates Ghana's LULC across all periods, covering 76.01% (178,003.8 km²) in 2001 and increasing to 81.55% (190,801.3 km²) in 2019. In contrast, barren land remains the smallest class throughout, covering only 0.03% (73.75 km²) in 2001 and slightly increasing to 0.04% (93.75 km²) by 2019. Over the analysis period, forest and agricultural lands show consistent declines, with forest land decreasing from 5.03% (11,778.25 km²) in 2001 to 3.94% (9,225.25 km²) in 2019, and agricultural land reducing from 17.86% (41,830.5 km²) to 13.03% (30,496.75 km²). Built-up areas, though a minor LULC class, increased from 0.95% (2,234.25 km²) in 2001 to 1.25% (2,925.75 km²) in 2019. Wetlands, while fluctuating, peaked at 0.32% (745 km²) in 2010 before declining to 0.18% (421.5 km²) in 2019. These trends reveal a clear dominance of rangeland, steady declines in forest and agricultural lands, and marginal increases in built-up and barren land areas over the historical period, reflecting shifts in Ghana's LULC.

Similarly, Figures 7.78a-b graphically illustrate Ghana's LULC spatial extents and trends. Figure 7.76a shows major LULC classes, while Figure 7.78b depicts minor ones, linking to the quantified changes

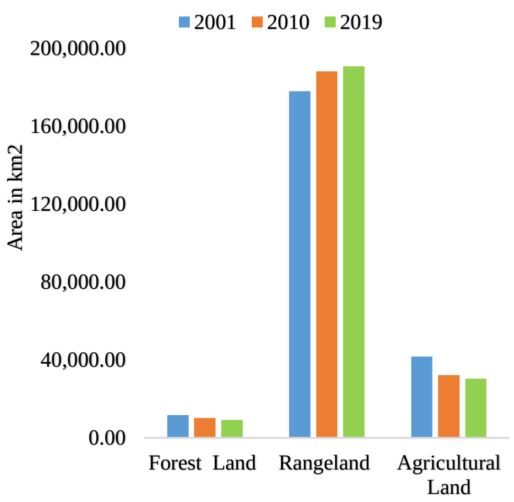

Figure 7.78(a): Trends in major LULC

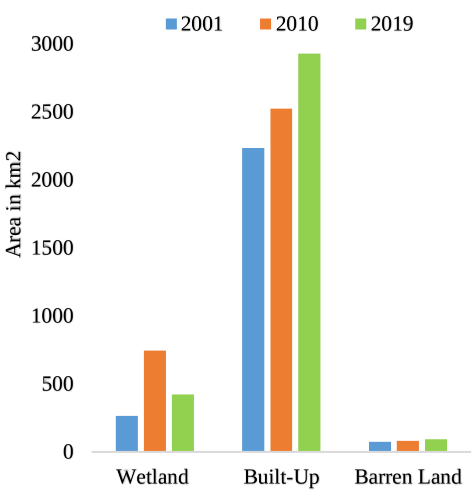

Figure 7.78(b): Trends in minor LULC

7.5 Analysis of spatio-temporal change detections in the LULC Ghana

Moreover, to understand the historical evolution of LULC in Ghana, a detailed spatio-temporal change detection, still using the three multi-temporal LULC maps from 2001, 2010, and 2019, was conducted. Our analysis produced two seasonal spatial LULC change maps (2001–2010) and (2010–2019), as depicted in Figure 7.79 (a-b).

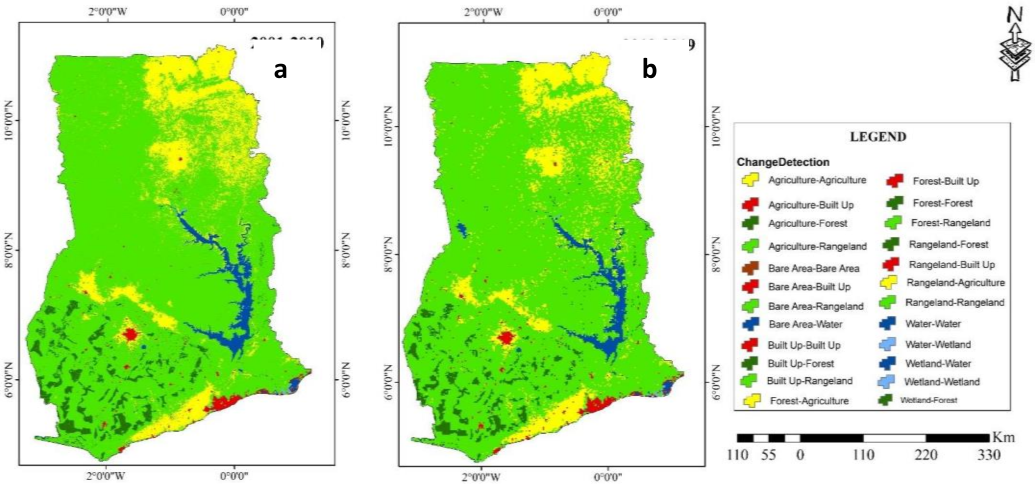

Figure 7.79(a-b): Decadal Spatio-Temporal LULC Change Maps of Ghana

From Figure 7.79 (a-b), the spatial change maps reveal significant shifts in Ghana's LULC over the past two decades (2001–2019), affecting AEZs, crop suitability, and agro-climatic conditions. Between 2001 and 2010, agricultural lands were converted into rangelands, especially in the northern and southern regions, due to land abandonment or increasing grazing demand. Forest areas declined, transitioning into agricultural and built-up zones driven by rapid urbanization and deforestation. From 2010 to 2019, rangeland expansion continued, further encroaching on agricultural lands, while urban growth and deforestation persisted. Over the entire period (2001–2019, agricultural and forest lands saw notable reductions, largely replaced by rangelands and urban areas, reflecting LULC shifts influenced by climatic and anthropogenic factors.

7.6 Quantifications on the spatio-temporal LULC change maps

Similarly, the study complemented the spatial change detection (maps) with additional statistical matrices, including net area gains or losses (G/L) in area (km²) and rates of change (%) for each LULC classes for 2001-2010, 2010-2019 and (2001-2019) and extent of areas changed versus unchanged LULC. Table 7.12 provides the quantification, while Figures7.8 (a-b) and Figure 7.79 offer the graphical appreciations of the results.

Table 7.12: Net Area Changes and Rates of LULC Dynamics (2001–2019)

Periods	**1st (2001-2010)**		**2nd (2010-2019)**		**Overall (2001- 2019)**	
LULC	**Net G/L (km²)**	**Rate (%)**	**Net G/L (km²)**	**Rate (%)**	**NetG/ L(km²)**	**Rate (%)**
Forest	-1,526.0	-13.0	-1,027.0	-10.0	-2,553.0	-21.7
Rangelan.	10,266.5	5.8	2,531.0	1.3	12,797.50	7.2
Wetland	479.50	180.6	-323.5	-43.4	156.00	58.8
Agricult.	-9,580.0	-22.9	-1,753.8	-5.4	-11,333.8	-27.1
Built-Up	287.25	12.9	404.25	16.0	691.5	30.9
Barren	7.50	10.2	12.5	15.4	20.0	27.1

Results, 2023

Table 7.12 highlights significant changes in Ghana's LULC from 2001 to 2019, with notable net gains and losses (G/L) in area and varying rates of change. Forests experienced a consistent decline, losing 1,526 km² (-13%) between 2001 and 2010 and an additional 1,027 km² (-10%) from 2010 to 2019, culminating in a total loss of 2,553 km² (-21.7%). Agricultural lands faced the steepest decline, with a total reduction of 11,333.8 km² (-27.1%), concentrated primarily in the first decade (-9,580 km², -22.9%). Conversely, rangelands expanded significantly, gaining 10,266.5 km² (+5.8%) in the first decade and 2,531 km² (+1.3%) in the second, totaling 12,797.5 km² (+7.2%). Built-up areas also grew steadily, increasing by 287.25 km² (+12.9%) from 2001 to 2010 and

404.25 km² (+16%) from 2010 to 2019, for an overall gain of 691.5 km² (+30.9%). Wetlands displayed mixed trends, expanding by 479.5 km² (+180.6%) in the first decade but shrinking by 323.5 km² (-43.4%) in the second, resulting in a modest net gain of 156 km² (+58.8%). Barren land, though a minor class, consistently expanded, with a total gain of 20 km² (+27.1%) over the entire period.

Similarly, Figures 7.80(a-b) and Figure 7.80 collectively illustrate graphical representations of the net gains and losses and the rates of change in the LULC dynamics Ghana's. From 7.80a and 7.80b, visually show declines in forest and agricultural lands and expansions in rangelands, built-up areas, and barren lands.

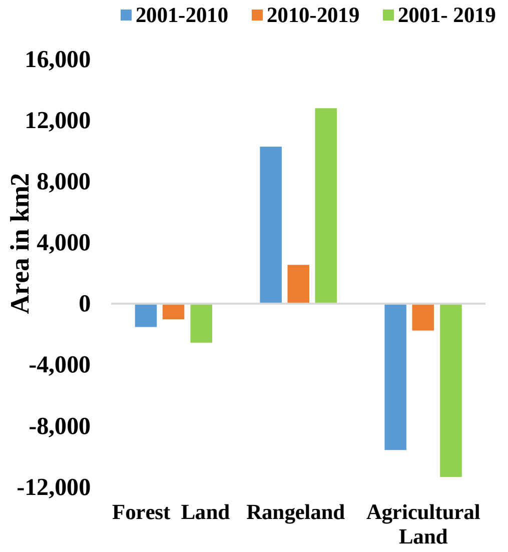

Figure 7.80 (a): Gain/Los in Maj. LULC

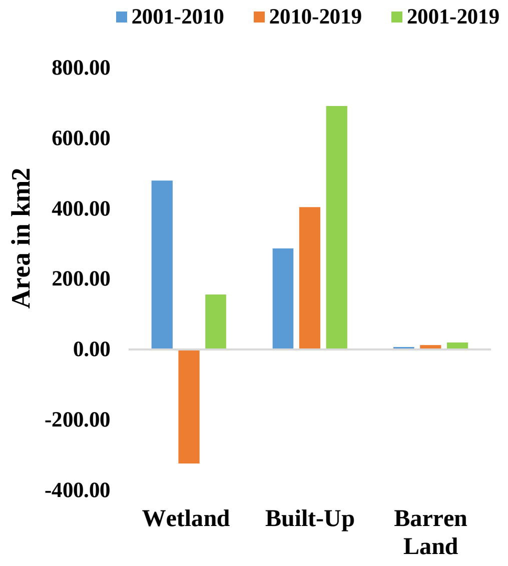

Figure 7.80 (b): Gain/Los in Min. LULC

Figure 7.80 (a-b), highlighting rate of change anomalies, reveal positive trends for rangeland, built-up, and barren land above the zero line, and negative trends below for forest and agricultural lands.

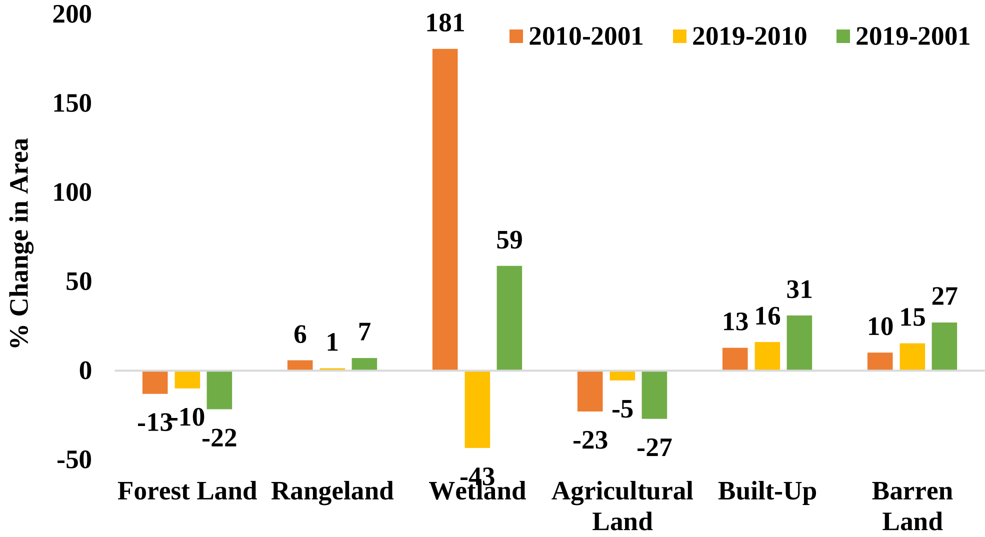

Figure 7.81: Trends in the rate of change in LULC anomalies (2001-2019)

Overall, these dynamics underscore the evolving LULC patterns in Ghana, highlighting the importance of sustainable land management practices to address the observed shifts and their implications for environmental and AEZs sustainability.

7.7 Discussions

This study analyzed historical LULC change across Ghana as a proxy for assessing shifting AEZs, by highlighting the potential impacts of shifting LULC on the agro-climatic characteristics, spatial distributions, boundaries shifts, land use productivity and crop suitability of existing zones. The LULC dynamics was analyzed across 2001-2010, 2010-2011 and 2001-2019 periods.

7.7.1 Spatio-Temporal Trends in LULCC Dynamics

Over the past two decades, Ghana's land use and land cover have undergone significant transformations, marked by substantial declines in forest and agricultural lands and expansions in rangeland, built-up areas, and barren lands. Forest cover declined by 13%, 10%, and 27% across three periods (2001–2010, 2010–2019, and 2001–2019), while agricultural land decreased by 23%, 5%, and 27% during the same intervals. Conversely, rangeland expanded by 5.8%, 1.3%, and 7.2%, built-up areas increased by 13%, 16%, and 31%, and barren lands grew by 10%, 15%, and 27%. These trends align with findings by Addo-Fordjour and Ankomah (2017), Darko et al. (2021), Nyadzi et al. (2021), and Tappen et al. (2016), highlighting the increasing conversion of Ghana's forest and agricultural areas into rangelands and built-up zones.

The persistent expansion of built-up and barren lands, alongside the decline in forest and agricultural lands, reflects the direct impact of human activities such as deforestation, illegal mining, urbanization, population growth, and unsustainable farming practices (Fokuo et al., 2022; Gbedzi et al., 2022; Koranteng et al., 2020; World Bank, 2010). These anthropogenic pressures are compounded by climate variability and change, manifested through erratic rainfall patterns, rising temperatures, increased droughts, and elevated evapotranspiration rates (Asante & Amuakwa-Mensah, 2015; CIAT, 2014; IPCC, 2019; Osei et al., 2019). Such dynamics are reshaping Ghana's LULC, with profound implications for agro-climatic systems and land productivity

7.7.2 Impact on shifting Agro-climatic Parameters of Ghana's AEZs

The evolving LULC dynamics in Ghana reveal profound transformations with significant implications for agro-climatic conditions and the integrity of AEZs (CIAT, 2014; Issahaku et al., 2016; Owusu & Waylen, 2013; Yamba et al., 2023). Declines in forest and agricultural lands, coupled with the expansion of rangeland and bare lands, have disrupted vegetation cover, altered local microclimates, and affected temperature regulation and rainfall distribution (Amekudzi et al., 2015; Gbangou et al., 2020; Nyadzi et al., 2016). These shifts, primarily driven by deforestation, agricultural intensification, and climate variability (Fokuo et al., 2022; Koranteng et al., 2020), are further exacerbated by economic pressures and land-use demands, significantly destabilizing Ghana's AEZs (Asante & Amuakwa-Mensah, 2015; Asare-Nuamah & Botchway, 2019; Stanturf et al., 201; Tappen et al., 2016).

Thresholds of key agro-climatic parameters, including mean annual rainfall and length of growing period have been notably disrupted. In Ghana, forest-dominated AEZs (DFAEZ, THAEZ, and TRAEZ) have experienced declining MAR, while savanna zones show erratic rainfall patterns, reducing crop suitability and productivity (Amekudzi et al., 2015; Issahaku et al. 2016; Nyadzi et al., 2021; Yamba et al., 2023). Furthermore, significant reductions in LGP across almost all AEZs pose additional challenges to traditional farming systems and land suitability (Gbangou et al., 2020; Owusu & Waylen, 2013).

7.7.3 Chapter Summary

This chapter analyzed the evolving LULC dynamics in Ghana, highlighting significant changes that have disrupted the stability of AEZs. Declines in forest and agricultural lands were observed alongside expansions in rangeland, built-up, and barren areas. These transformations have altered vegetation cover and agro-climatic conditions, reduced crop suitability and shrinking forest-related zones while expanding savanna areas. The impacts of decreasing rainfall and shorter growing periods further challenge traditional farming systems. These findings emphasize the urgent need to reclassify Ghana's AEZs to align with current LULC and climatic realities.

CHAPTER EIGHT

CHANGES IN GHANA'S AEZS: EVIDENCE FROM THE NEW AEZS CLASSIFICATION MAP OF GHANA

8.1 Introduction

Chapter Eight presents the newly updated agro-ecological zones (AEZs) classification for Ghana. The reclassified AEZs were delineated using an ArcGIS-based multi-criteria Analytical Hierarchical Process (AHP) decision-making model, meticulously applying the new dynamic AEZ methodology developed specifically for this study. This chapter begins with an overview of the methodological procedures employed to delineate the new AEZs, followed by a comprehensive description of their current spatial distribution, extents, agro-climatic, and agro-edaphic characteristics. A key focus is a comparison between the old FAO AEZs and the newly updated AEZs, conducted by superimposing the shapefile of the old FAO AEZs classification on the newly reclassified map. This comparison highlights inter-zonal and intra-zonal spatial variations, as well as shifts within and across zones. Additionally, the chapter examines the potential impacts of shifting climatic patterns and the rapid evolution of LULC dynamics on Ghana's old AEZs over the past three decades. The remaining sections of Chapter Eight include a detailed thematic discussion of the results in relation to existing studies and conclude, and a summary of Chapter Eight.

8.2 Methodology for the classification of New AEZs for Ghana

The updated agro-ecological zones (AEZ) map for Ghana (Figure 8.80 a-b) was developed using the GIS Multi-Criteria Analytical Hierarchy Process (MC-AHP) decision-making model, as outlined in Figure 5.29 of the methodology chapter. This approach effectively integrates diverse datasets of varying ranges, sources, scales, and formats, essential for robust AEZ classification. These datasets included the 2021 post-LULC map, DEM (elevation, slope, and topography), soil unit map, and agro-climatic parameters such as mean annual rainfall, length of growing period, mean temperature, evapotranspiration, humidity, and rainy days. To ensure high data quality, these inputs were refined and smoothed using RClimDex, LOCF, and spatial interpolation techniques.

The process began with rasterization, employing GIS-based spatial interpolation techniques (Spline and Inverse Distance Weighting) to convert scattered agro-climatic point datasets into continuous raster layers. These raster datasets were then reclassified into relevant classes aligned with AEZ criteria and normalized using the GIS resampling tool. Standardization to a uniform scale (0–1) was applied, ensuring consistency for effective comparison and integration. Weights were assigned to all parameters using Saaty's Pairwise Comparison method, which evaluates their relative importance based on expert input and statistical analysis. The GIS MC-AHP model aggregated these weighted factors to delineate homogenous AEZs within the GIS environment.

The resulting composite AEZ maps (Figure 8.80 a-b) represent land resource mapping units characterized by homogenous climate, topography, elevation, soil properties, and land cover. These zones provide valuable insights into the potentials and constraints for land use and agriculture across Ghana, supporting sustainable land management and planning

8.3 Newly Reclassified Agro-ecological Zones classification map of Ghana

Given the primary objective of the study, reclassification of Ghana's AEZs, the study rightly produced an updated AEZs map that aligns with the current climatic and evolving LULC patterns in Ghana. Figure 8.80a shows the initial AEZs output from the GIS MC-AHP analysis, while Figure 8.80b shows the final AEZs generated by applying GIS-based boundary and pixel smoothing methods. Together, these maps represent the newly classified AEZs for Ghana.

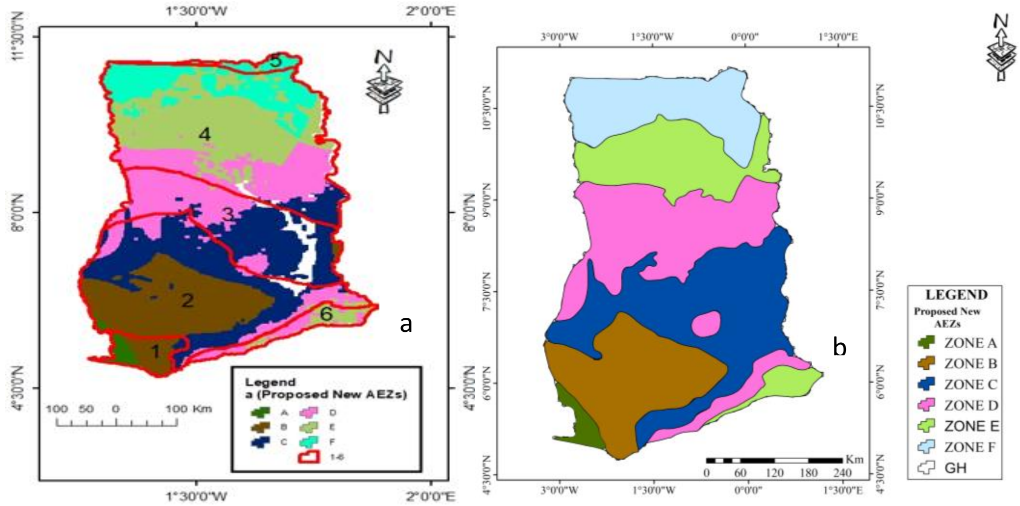

Figure 8.82 (a-b): Proposed New AEZs classification for Ghana

As clearly evident from Figures 8.82 (a-b), the newly reclassified AEZs map and/ or AEZ classification delineated Ghana into six zones (Zones A-F). Based on the superimposed six boundary (BI-B6) shapefile of old FAO AEZ classification in 8.82 (a), the New Zone A in 8.82 (b) correlate spatially with the old THAEZ (B1); the Zone B aligns with old DFAEZ (B2); the Zone C aligns with old TAEZ (B3); Zone D with old GSAEZ (B4); Zone E associate with the old CSAEZ (B6), and Zone F correlates with the old SSAEZ (B-5).

The subsequent sections present a detailed description of the current spatial patterns and distributions, as well as the unique agro-climatic thresholds and agro-edaphic characteristics of the newly classified zones (Zones A-F).

8.3.1 Inter-zonal description of the New Zone AEZs of Ghana

From 8.82 (a-b), the newly delineated Zone A, representing old THAEZ of B1, now occupies a very small farthest southwestern part of Ghana. Based on agro-climatic analysis for the current climatological window (1991-2020), Zone A share a mean annual rainfall threshold of 1,875 mm, with a bimodal rainfall regime: the major season occurring from May 12th to July 30th, and minor season from September 3rd to October 29th. The length of the growing period is 112 days for the major season and 54 days for the minor season. Additionally, Zone A experiences a mean temperature of 27.5 °C, mean annual potential evapotranspiration of 1,341 mm, 92 rainy days, and relative humidity of 84%, all of which significantly influence agricultural activities.

By agro-edaphic, Zone A is predominantly characterized by forest land cover, wetlands, and agricultural land use. Its general slope ranges from 1-8% to 8-30%, indicating level to gently undulating, and rolling to hilly terrain, with an average height below 100 meters. The dominant soil types are ferrasols, acrisols, and gleysols, which are suitable for agricultural production with proper management practices. The agro-climatic and agro-edaphic features underscore the zone's potential for sustainable agricultural development and natural resource management.

8.3.2 Description of the New Zone-B AEZ of Ghana

Similarly, from the new AEZ map (Figure 8.80a-b), new Zone B corresponds to the old DFAEZ in the old FAO classification. This new zone spans the central areas of the old DFAEZ and extends to the northeastern and southeastern boundaries of the old THAEZ. Based on agro-climatic analysis for the climatological window (1991-2020), the new Zone B exhibits a mean annual rainfall of 1,266 mm, with a bimodal rainfall regime occurring from April 14th to August 13th (major season) and from September 15th to November 10th (minor season). The major season growing period (MAJ-LGP) is 134 days, while the minor season growing period (MIN-LGP) is 73 days. Other agro-climatic zonal thresholds include a mean annual temperature of 28.5 °C, potential evapotranspiration of 1,395 mm, 113 rainy days, and relative humidity of 81%.

Agro-edaphically, Zone B is characterized by forest land, scrub land, and agricultural land. The average slope ranges from 1-8% to 8-30%, representing level to gently undulating, and rolling to hilly terrain. The average elevation is generally below 100 meters, with scattered highlands or peaks. Dominant soil types include acrisols, ferrasols, cambisols, and fluvisols, all of which support agricultural production with appropriate management practices. These agro-climatic and agro-edaphic conditions highlight the zone's importance for effective land use planning and land cover management in Ghana.

8.3.3 Description of the New Zone-C AEZ of Ghana

As shown in Figure 8.80 (a-b), the new AEZ classification reveals Zone C as correlating with old TRAEZ (B3) from the FAO AEZ classification. This zone extends from the southeastern part of the old TRAEZ to encompass the northern and southeastern edges of the old DFAEZ. Based on the climatic and LULC patterns over the 1991-2020 period, the Zone C exhibits new unique agro-climatic thresholds composed of a mean annual rainfall of 1,242 mm with a bimodal rainfall regime occurring from April 24th to July 25th and from September 6th to November 15th. The major season growing period is 110 days, while the minor season growing period is 72 days. Additional agro-climatic characteristics include a mean annual temperature of 29.4 °C, potential evapotranspiration of 1,466 mm, 84 rainy days, and a relative humidity of 73%.

Regarding agro-edaphic characteristics, the Zone C is dominated mainly by agricultural lands, savanna woodland, and forest-scrub areas. The terrain has slopes ranging from 1-8% (level-gentle), 8-30% (undulating to rolling-hilly), and areas exceeding 35% (steeply dissected mountains). While the average elevation is predominantly below 100 meters, there are isolated highland and mountainous areas exceeding this height. The zone's soil units include alisols, luvisols, lixisols, and leptosols (found in hilly areas). All except leptosols are highly suitable for agricultural use. These coupled agro-climatic and agro-edaphic characteristics provide critical insights into agricultural land use potential and natural resource conservation within Zone C.

8.3.4 Description of the New Zone-D AEZ of Ghana

Figure 8.80 (a-b), highlights Zone D AEZ as spatially correlating representing the old GSAEZ (B4). The Zone D now occupies the southern part of the old GSAEZ, the northwestern and some western edges of the old TRAEZ, and nearly the entire old CSAEZ. Based on the current climatology (1991-2020), Zone D has a mean annual rainfall of 1,103 mm threshold, with a unimodal rainfall pattern occurring from June 20th to November 2nd. The length of the growing period (both major and minor) is 134 days, revealing a single rainfall regime for the zone. Other zonal agro-climatic thresholds include a mean annual temperature of 28.9 °C, potential evapotranspiration of 1,178 mm, 73 rainy days, and relative humidity of 70%.

Regarding agro-edaphic conditions, Zone D is predominantly covered by rangeland, agricultural land, and wetland. The slope varies from 1-8% to 8-30%, ranging from level-gentle to undulating and rolling-hilly terrains. Elevation within the zone is mixed, with areas below and above 100 meters. These characteristics provide essential insights for agricultural planning, land use management, and natural resource assessments in Zone D.

8.3.5 Description of the New Zone-E AEZ of Ghana

From the proposed new AEZs map of Ghana, new AEZ E corresponds to the old SSAEZ (B5). Spatially, the Zone E extends from its original boundary (B5) to occupy a lager northern part of the old GSAEZ. Based on the 30 year (1991-2020) climatological period, agro-climatic analysis showed the Zone E to exhibits a mean annual rainfall of 966 mm, with a uni-modal rainfall regime from April 22nd to October 22nd. The LGP is 183 days for both major and minor seasons. Other related agro-climatic thresholds include a mean annual temperature of 29.7 °C, annual mean potential evapotranspiration of 2,003 mm, 63 rainy days, and relative humidity of 56%.

For Zone E, analysis for agro-edaphic characteristics show dominance for rangeland and agricultural land use, savanna-woodland, and wetland. The slope varies between 1-8% and 8-30%, representing level-gentle to rolling-hilly terrains. The average elevation is below 100 meters, with scattered areas in the northwest and northeast exceeding this height. The zone features soil types such as leptosols, plinthosols, gleysols, vertisols, and lixisols, which require intensive management for agricultural productivity. These characteristics are significant for land use planning, LULC monitoring, resource management, and conservation.

8.3.6 Description of the New Zone-F AEZ of Ghana

The sixth AEZ delineated in the proposed new AEZs map is Zone F. This zone aligns significantly with the CSAEZ (B6) of the old FAO AEZs. Zone F now occupies a small south-eastern part of its old boundary, and show a significant northerly migration into the north of current old GSAEZ. Based on the updated agro-climatic analysis (1991-2020), Zone F is uniquely characterized by a mean annual rainfall threshold of 840 mm, with a bimodal rainfall pattern. The major season occurs from May 16th to July 15th, while the minor season spans from August 23rd to November 22nd. The LGPs are 77 days for the major season and 28 days for the minor season. Other zonal agro-climatic thresholds include a mean annual temperature of 29.7°C, annual mean potential evapotranspiration of 1,464 mm, 56 rainy days, and a relative humidity (RH) of 81%.

Zone F's agro-edaphic characteristics are defined by the dominance of rangeland, agricultural land, and wetland. The terrain features slopes ranging from 1-8% to 8-30%, reflecting level-gentle to rolling-hilly landscapes. The elevation varies, with some areas below 100 meters and others exceeding this height. The zone includes soil types such as lixisols, acrisols, plinthosols, and leptosols. These characteristics underscore the importance of Zone F for agricultural planning, sustainable land use management, and the monitoring of land cover and natural resources.

8.4 Spatial comparison of old FAO AEZs and Reclassifies new AEZs

In this study, the newly delineated AEZs map (Figure 8.83a) was critically analysed in comparison with the old FAO AEZs map (Figure 8.83b). This comparative analysis facilitated the evidential evaluation of the significant inter-zonal shifting spatial extents, evolving patterns and boundary modifications, as direct impacts of evolving climatic conditions and LULC dynamics on Ghana’s AEZs over time. Figure 8.83(a) show the newly reclassified AEZs, while Figure 8.83(b) represents old FAO classification.

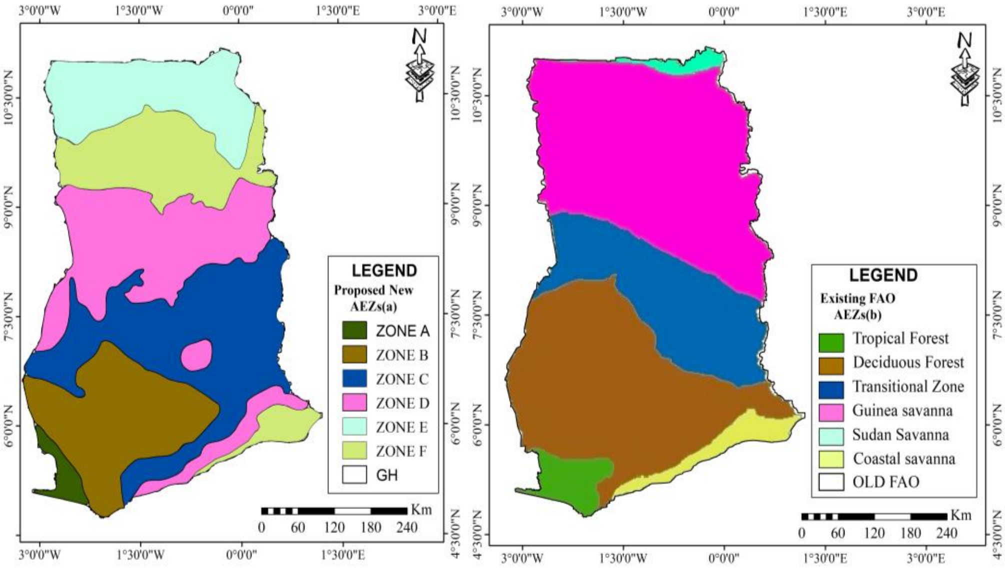

Figure 8.83a-b: New AEZs (a) and Old FAO AEZs (b) of Ghana compared

A critical visual analysis of Figure 8.83a (New AEZs) from Figure 8.83b (old FAO) show both classifications share six AEZs**.** Similarly, the reclassified new AEZs (A-F) spatially correlate with the existing AEZs (THAEZ – SSAEZ), as indicated identified and described earlier. However, new AEZs map (Figure 8.83a) shows significant spatial reconfigurations compared to the old FAO AEZs map (Figure 8.83b). Zone A, corresponding to the old THAEZ, now occupies a much smaller area in the far southwestern part of Ghana, indicating a substantial reduction in its spatial extent. As quantified in Table 8.12, Zone A has decreased from 8,430.67 km² (3.5%) of its land area in FAO classification to 3,828.5 km² (1.6%), reflecting a contraction of 4,602.17 km² or 54.6%.

Similarly, Zone B (old DFAEZ) demonstrates a notable reduction, primarily in its central and northeastern parts. Its area has decreased from 79,088.43 km² (33.1%) to 41,342.53 km² (17.2%), representing a contraction of 37,745.9 km² or 47.7%. Conversely, Zone C (old TRAEZ) has expanded southward, now covering portions of the northern DFAEZ and southeastern GSAEZ. This expansion increased its area from 45,232.43 km² (18.9%) to 63,906.73 km² (26.5%), a gain of 18,674.3 km² or 41.3%.

Zone D (old GSAEZ) has contracted significantly, particularly in its southern and central regions, reducing from 94,967.82 km² (39.7%) to 59,605.82 km² (24.7%), a decrease of 35,362 km² or 37.2%. In contrast, Zone E (old SSAEZ) exhibits the most dramatic expansion, extending into areas previously dominated by the old GSAEZ. Its area has grown from 3,356.78 km² (1.4%) to 38,081.62 km² (15.8%), an increase of 34,724.84 km² or 1,034.5%. Zone F (old CSAEZ) has also expanded substantially, especially into the northern parts of the former GSAEZ, increasing its area from 7,930.75 km² (3.3%) to 34,147.72 km² (14.2%), a gain of 26,216.97 km² or 330.6%.

Table 8.13 shows the quantification of the net gain/loss in spatial extent.

Table 8.13 Spatial extents (area) and change in Ghana's AEZs

AEZs	Old-Area (km^2)	Area (%)	New-area (km^2)	Area (%)	Area Gain/ Loss(km^2)	Spatial change (%)
THAEZ/A	8,430.67	3.5	3,828.5	1.6	-4602.17	-54.6
DFAEZ/B	79,088.43	33.1	41,342.53	17.2	-37745.9	-47.7
TRAEZ/C	45,232.43	18.9	63,906.73	26.5	18674.3	41.3
GSAEZ/D	94,967.82	39.7	59,605.82	24.7	-35362	-37.2
SSAEZ/E	3,356.78	1.4	38,081.62	15.8	34724.84	1034.5
CSAEZ/F	7,930.75	3.3	34,147.72	14.2	26216.97	330.6

Results, 2023

These spatial (Figure 8.81a-b) and quantifications (Table 8.13) significant shifts in the FAO classifications, highlighting the dynamic nature of Ghana's agro-ecological landscape, reflecting the combined impacts of climatic changes and evolving LULC patterns.

8.5 Inter-zonal shifting boundaries and intra-zonal spatial variability.

Similarly, the study analyzed both inter-zonal and intra-zonal shifts in the old FAO AEZs of Ghana. The inter-zonal analysis focused on detailed zone by zone analysis spatial extents (expansion and contraction) differential spatial patterns and migration, highlighting significant changes in old FAO AEZs. The related intra-zonal analysis explored the significant variations within same individual zones based on inherent migrations and encroachment of zones, reflecting the growing heterogeneity in agro-climatic and land use characteris.

Together, these analyses provided further insights into the dynamic nature of Ghana's AEZs in response to climate change and land use changes. Here, by clearly superimposing the shape-file of the old FAO AEZs (six-red boundaries, 1-6) on the new AEZs map in Figure 8.82, the study revealing glaring evidence of significant inter-zonal alterations and intra-zonal heterogeneity in the existing old AEZs. Inter-zonal analysis is followed and intra-zonal analysis.

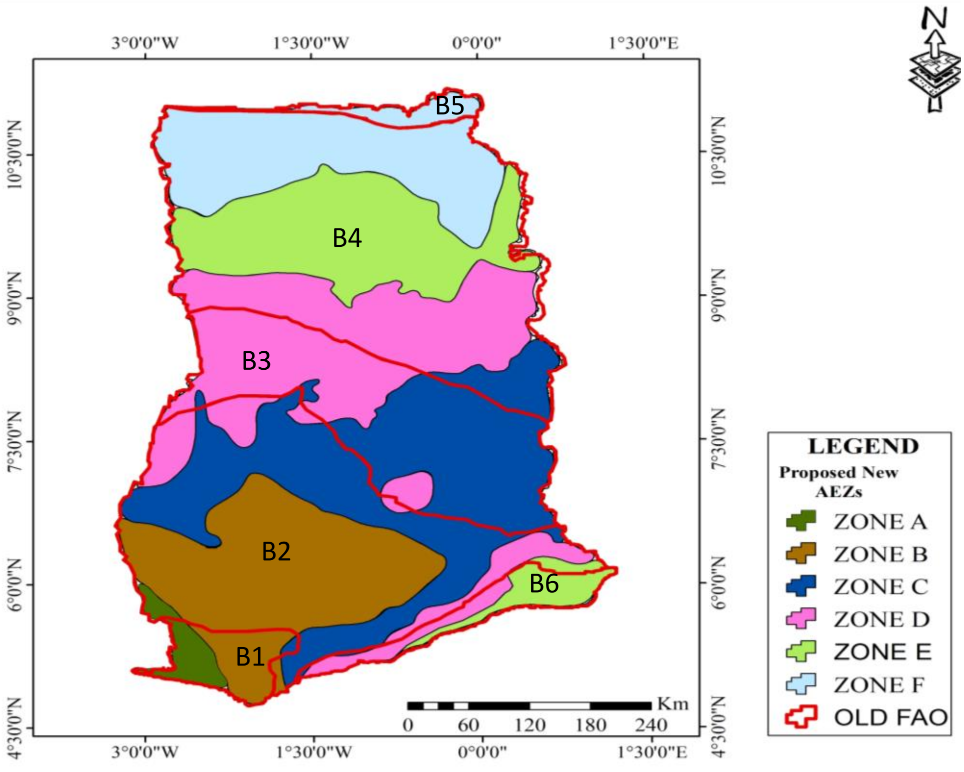

Figure 8.84: New AEZs with superimposed Old AEZs (Results, 2023)

8.5.1 Inter-zonal shifting patterns and spatial boundaries

Clearly, from Figure 8.84, Zone A, representing the old FAO THAEZ (B1) reveals old THAEZ now significantly reduced in size, having shifted toward the far southwestern border of its former extent. The observed contraction of Zone A, from B1 where its spatial extent has decreased, is now significantly encroached by Zone B (DFAEZ). This transformation is consistent with earlier declining forest cover, reduction in rainfall, and shortened growing periods, indicating the impacts of climate change and LULC changes on the THAEZ.

Similarly, the current extent of Zone B (B2), reveals old DFAEZ having reduced in spatial extent considerably, now occupying relatedly a small central part of its original boundary and extending to the northeastern and southeastern borders of the old THAEZ. Observed from boundary B2 in Figure 8.84, the western and southeastern flanks of the old DFAEZ are now occupied by characteristics of the Transitional and Coastal Savannah AEZs. These shifts align again with earlier results of declining forest cover and altered agro-climatic thresholds such as reduced rainfall and shorter growing seasons, resulting in the significant boundary changes for Zone B.

Moreover, the Zone C, corresponding to the old TRAEZ, shows a clear expansion and southward shift, now occupying portions of the DFAEZ and the northeastern edge of the old GSAEZ. The enlargement of Zone C, evident in boundary B3, is attributed to rangeland expansion and changing agro-climatic conditions, including shifts in rainfall distribution and growing periods. This expansion reflects the direct impacts of climatic changes and LULC dynamics on the Transition AEZ.

Furthermore, the Zone D, old GSAEZ now exhibits a scattered spatial pattern, occupying fragmented areas across the northeastern TRAEZ, the southeastern DFAEZ, and the old Coastal AEZ. The central parts of the old GSAEZ are now dominated by characteristics of Zones E (SSAE) and F (CSAEZ). These inter-zonal shifts, shown in boundary B4, highlight the significant encroachment of the SSAEZ into the northern borders and the CSAEZ into the southern borders of the GSAEZ, driven by forest depletion and expanding rangeland.

Again, Zone E (old SSAEZ), as observed from Figure 8.82, has expanded significantly, now encroaching into the northern boundaries of the old Guinea Savannah AEZ. This expansion, depicted in boundary B-5, reflects the replacement of Guinea Savannah woodland with Sudan Savannah characteristics, influenced by prolonged growing periods and reduced rainfall. These changes highlight the increasing dominance of savanna conditions in the northern regions.

Finally, the Zone F (old CSAEZ) now occupies a larger central and northern portions of the old GSAEZ, while retaining its southeastern boundary. This northward shift, observed in boundary B-6, suggests a significant transformation in the agro-climatic and land cover characteristics of Zone F, aligning it more closely with GSAEZ conditions.

From the new AEZs map, a dynamic inter-zonal shifts and spatial reconfigurations in Ghana exist, driven by climatic changes and land use dynamics. Zones A and B show reductions and contractions, while Zones C, E, and F demonstrate significant expansions and migrations. These boundary shifts emphasize the need for updated agro-ecological classifications to reflect current conditions, supporting sustainable agricultural planning and land management in Ghana.

8.5.2 Intra-zonal spatial variability and discrepancies in Ghana's AEZs.

Based on Figure 8.84, the study examined intra-zonal spatial variability and discrepancies within the existing old FAO AEZs, revealing how inter-zonal shifts have influenced variability within individual zones. The analysis of the new AEZs map shows significant intra-zonal variability in the existing old AEZs, evident in their current sizes, areas, locations, and shifting spatial patterns. For instance, in boundary B-1, Zone A, representing the old THAEZ, has reduced in size and shifted southwestward to occupy a small southwestern edge of the original THAEZ. Meanwhile, the northern, eastern, and southeastern borders of the old THAEZ have transformed into deciduous forest agro-ecological conditions. This has resulted in a mix of THAEZ and DFAEZ agro-ecological characteristics within the same zone, challenging the principle of homogeneity fundamental to agro-ecological zoning.

Similarly, Zone B (DFAEZ) exhibits a noticeable southwestward shift and reduction in spatial extent. Currently, within boundary B2, Zone B has been encroached upon by transitional and Guinea Savanna agro-ecological characteristics at its northwestern, eastern, and southeastern flanks. This invasion of diverse agro-ecological traits compromises the homogeneity of the DFAEZ. These findings align with observed agro-climatic and LULC patterns.

The Zone C (old TRAEZ) shows a distinct south and southwestward shift, expanding to now include portions of the DFAEZ and the old Guinea Savanna AEZs, particularly affecting the northwestern parts of the TRAEZ. Within the current boundary (B3), the zone shares agro-climatic and LULC characteristics with the GSAEZ, further disrupting its homogeneity.

Similarly, Zone D (Guinea Savanna AEZ) demonstrates an extensive scattering pattern, leaving only fragmented patches in the northeastern part of the old GSAEZ. Within boundary B4, Zone D shares its northern borders with the SSAEZ and the central portion with CSAEZ features. A significant portion of the old GSAEZ has migrated into neighboring AEZs, further compromising its homogeneity.

Zone E (old SSAEZ) shows a substantial southward expansion into the farthest northern boundaries of the old Guinea Savanna AEZ. Within boundary B5, the SSAEZ remains largely unaffected by encroachment from other zones, although inter-zonal variability is evident.

Lastly, Zone F (CSAEZ) reveals a significant northward shift. Within boundary B6, large portions of the zone are now dominated by Guinea Savanna AEZ characteristics in terms of land use, land cover, and agro-climatic features. This encroachment undermines the spatial homogeneity that once defined the CSAEZ, emphasizing the need for the reclassified Zone F to better reflect current climatic and land use patterns in Ghana.

In summary, the observed inter-zonal shifts and intra-zonal changes across all six old FAO AEZs underscore significant spatial discrepancies in the wake of climate change and evolving land use patterns. These changes have direct implications for agricultural planning, crop suitability assessments, land use monitoring, and resource management within specific zones and across Ghana. Understanding these patterns is vital for achieving sustainable land use and resource conservation.

8.6: Impacts of Climate change and changes in LULC on FAO AEZs

Climate change and land use changes have significant impacts on agro-ecological conditions in Ghana. They affect the spatial distribution and characteristics of agro-ecological zones both between zones (inter-zonal) and within each zone (intra-zonal). Understanding the direct impacts these changes is crucial for sustainable land management and agricultural planning. This section thus explores how climate change and LULC have coupled to influence the current spatial patterns in the new AEZs in Ghana. Similarly, the implications of the spatial changes or shifts on agricultural production, food security, rural livelihoods, agro-economic investment planning and the monitoring and management of land cover and resources are analyzed.

The results of the direct impacts of climate change and land-use changes on the old national of AEZs are evident from Figure 8.80. A comparison of the new AEZs map (a) and the old FAO (b) reveal significant changes in current sizes, area, locations, and spatial shifting patterns. The inter-zonal spatial shifting patterns and intra-zonal variability in the new AEZs map are analyzed relative to the earlier results for significant changes in the key agro-climatic parameters and LULC changes across Ghana.

From boundary (B1), which represents the spatial extent of the old THAEZ, the discernible significant reduction in the size and southwestward shifting pattern of the zone relative to Zone A, are direct impacts of climate change and land use changes. This result is consistent with the earlier finding of significant changes in the key agro-climatic parameters such as mean annual rainfall and the major and minor length of the growing season analyzed for THAEZ. Similarly, the current decreasing trend in the forest cover of the zone has accounted for the reduction and transformation of a greater part of the THAEZ into deciduous forest agro-ecological conditions.

Likewise, in boundary (B2), the analysis of the current spatial overage of Zone B observed in the new AEZs map (a) as compared to the size of the old DFAEZ in the existing FAO AEZs map 8.81(b), reveals noticeable southwest shifting pattern and reduction in spatial extent. In relation to the impacts of climate change, the significant spatial shifting pattern and changes intra-zonal changes in size of DFAEZ aligns with the earlier significant changes observed in the zonal MAR, MAJ-LGP and MIN-LGP threshold set for DFAEZ. The reduction in the forest characteristics of the zone in replacement by rangeland cover account for the reduction in size and shifting pattern (spatial distribution) in the deciduous forest zone in Ghana. It is evident that climate change and land use changes have modified the agro-ecological characteristics of existing DFAEZ.

Additionally, the current size and shifting pattern in Zone C (from boundary C-1) in Figure 8.80 manifest clear direct impacts of climate change and land use changes in TRAEZ. The southwestward shifting pattern and expansion in Zone C indicates a substantial impact of climate change and land use changes. This result is explained by the decreasing mean annual rainfall, a clear cut LGP (MAJ-LGP and MIN-LGP), reduction in MAJ-LGP analyzed for the zone. Again, the current conversion of forest lands to related rangeland have influenced these reduced sizes and shifting boundary of Zone C.

Similarly, from the new AEZs map (a) in Figure 9.78, the results of the current inter-zonal spatial shifting pattern and intra-zonal changes in the Zone D (representing GSAEZ) are direct manifest of climate change and land use changes. Climate change has affected the zone through significant changes in the agro-climatic parameters such as MAR, LGP, Tmean, RDAYS and PE. The reduction in size and scattered spatial distribution of Zone D reflect the current significant modifications in rangeland and agricultural land, which are the notable characteristic LULC features of zone. There is now clear invasion of new agro-ecological conditions into the zone.

Moreover, considering the spatial pattern and distribution of current Zone E, the impacts of climate change and land use have led to the significant southward expansion and invasion of the SSAEZ into the farthest northerly borders of old Guinea Savanna AEZs. This result is consistent with the current increasing LGP and RDAYs and the decreasing MAR trends for the zone attributed to climate change. With respect to LULC, the zone has seen expansion in its rangeland characteristics, a significant feature of the zone. Climate change and LUC changes have altered the spatial distribution and characteristics of Zone E compared to its extent in boundary E.

Finally, the analysis of the current spatial pattern of Zone F from the old boundaries (B1 and B6) demonstrate discernible impacts of climate change and land use changes. The earlier results of significant changes in agro-climatic MAR and LGP analyzed for the zone have direct impacts on the reduction in size of Zone F boundary (B6) and its migration and expansion north ward into the central north of the old Guinea Savanna AEZ. The result of the current spatial distribution of Zone F is directly associated with the decreasing coastal woodland-forest cover in replacement by significant expansion in clear Guinea savanna rangeland. This shows clear alterations in the agro-ecological conditions of the CSAEZ from the spatial distribution and shifting boundaries observed in Figure 8.82.

It can be concluded that the impacts of climate change and land use changes have had substantial effects on the shifting patterns and spatial distribution of old agro-ecological zones in Ghana. These changes observed in the new AEZs show significant inter-zonal spatial shifting pattern and intra-zonal changes relative to the old FAO AEZs. The results support the changes analyzed for the key agro-climatic parameters and LULC pattern across the zones. The changes in the new AEZs have implications for planning agricultural production, determining crop suitability within specific AEZs, and for monitoring sustainable land use and land cover patterns in Ghana.

8.7 Discussions

Relative to existing literature, the observed reduction, expansion, migrations; the varied inter-zonal spatial shifting patterns and the intra-zonal heterogeneity in old AEZs, from the new map have been discussed. The current study found significant inter-zonal shifts and intra-zonal variations in all the old AEZs (boundaries, B1, 2, 3, 4, 5 and 6). Specifically, Zone A (old THAEZ) observed a reduction in size and a southwestward shift, transforming it into, and/ or sharing deciduous forest agro-ecological conditions along it north-eastern borders. Also, the DFAEZ has migrated into the THAEZ, allowing it northern flanks to be occupied by TRAEZ and GSAEZ agro-ecological conditions. Similarly, Zone C (old TRAEZ) clearly demonstrate a south and southwestward shifting pattern, expanding and encompassing parts of DFAEZ and old Guinea savanna AEZs. GSAEZ has invaded the boundaries of old TRAEZ, DFAEZ, and the CSAEZ. The SSAEZ show southward migration into old GSAEZ, while a greater characteristic of the CSAEZ have migrated into the central north of impacts of old GAEZS. These results have been attributed to direct impacts of climate change and land use and land cover changes over the past three decades in Ghana.

The current findings on the significant inter-zonal and intra-zonal changes and spatial distribution in the new AEZs map of Ghana align with many existing studies. From the works of Fischer *et al*. (2006), Lane and Jarvis (2007), Lin *et al*. (2013), Kurukulasuriya and Mendelsohn (2008), Mugandani *et al*. (2012), the global, sub-regional, and national AEZs have changed. The changes have been shown in terms of shifts in old spatial or geographical boundaries, crop suitability potentials and constraints, and changes in their productivity.

In Ghana, the recent work by Yamba *et al* (2023) revealed significant changes in the country's agro-climatic regions analyzed relative to a-4 class GMET climatic map. These authors reported of a significant expansion of the SSAEZ (agro-climatic regions) and derived a-five agro-climatic map based on climatic analysis for the period (1981-210). In a direct relation to the current study, the EPA (2010) and Stanturf *et al*. (2011) had suggested potential changes in Ghana's AEZs, indicating a merging up of the Transitional agro-ecological zones with the Guinea Savanna AEZ boundary and characteristic.

Also, CIAT (2014) noted a decreasing spatial extent in cocoa growing AEZs. From related studies, Mugandani *et al*. (2012) found significant shifting boundaries in the old AEZs of Zimbabwe, leading to a reclassification of the zones. Over Africa, the finding from studies by Mendelsohn and Kurukulasuriya (2008) concluded that the Africa continent AEZs are changing spatially, indicated by migration from high to low productive AEZs. Similarly, in China, Lin *et al* (2013) showed a shifting spatial pattern and geographical boundaries in the existing AEZs under future changing climate in China.

With respect to the direct impact of climate change and land use changes on AEZs (inter-zonal and intra-zonal), several studies confirm the current findings analyzed for the study. According to Kurukulasuriya and Mendelsohn (2008), Lin *et al*. (2013) Mugandani *et al*. (2012), and Musher *et al*. (2016), climate change and variability alter agro-climatic variables (temperature and rainfall), and in turn directly impact the other agro-edaphic or bio-physical variables such as soil, land use, land cover and vegetation characteristics of the AEZs (FAO, 2020; Fischer et al., 2006; IPCC, 2014). Through erratic rainfall patterns, global warming has increased drought and forest fires, leading to significant forest LGPs and the expansion of woody vegetation into grasslands (Flannigan, Stocks, Turetsky & Wotton, 2009; Westerling, 2016). The findings of EPA (2010), Amekudzi *et al* (2015), Asante and Amuakwa-Mensah, (2014); Asare-Nuamah and Botchway (2019); Codjoe and Owusu (2011), Stanturf *et al*. (2011) Gbangou *et al*. (2020), and recent study by Yamba *et al* (2023) report changes in climatic characteristics of AEZs.

Apart from the impact of climate change, the current study has concluded that the trends observed in the LULC of Ghana have coupled with climate change to alter the exiting national AEZs. This finding is consistent with many studies. CIAT (2014), Stanturf *et al*. (2011) and World Bank (2011) reported that Ghana's forest land is decreasing due to rapid land use-changes with a direct impact on the existing AEZs. These results are consistent with Tappen *et al* (2016), Mücher *et al* (2016), Fischer *et al* (2009) and World Bank (2011). According to Asare-Nuamah and Botchway (2019) Sleeter *et al*. (2018); UNEP (2006), Stanturf *et al*. (2011) and World Bank (2011), human activities, including agricultural practices such as slash and burn, shifting cultivation, continuous farming, and overgrazing have resulted in reduced vegetation, soil fertility LGPs, decreased groundwater, deforestation, and land degradation. Growing population has led to the conversion of forest and arable land into woodland, grassland, and residential areas. These anthropogenic factors contribute to changes in AEZs and land use patterns.

Based on the finding for significant changes observed in the agro-climatic parameters, land use and land cover, and the significant inter-zonal and intra-zonal changes and spatial distribution, the study concluded potential impacts on changes in AEZS on Ghanaian agriculture, AEZs crop suitability and productivity, and agro-economic investments structure. From their studies, Yamba *et al*. (2023) indicated possible difficulty in agricultural production with the ongoing changes in agro-climatic variables such LGP. Also, studies by FAO (2009; 18), Fischer (2009), IPCC (2013), Jayathilaka *et al*. (2012) and Lane and Jarvis (2007) have revealed significant changes in the suitability of arable areas hitherto suitable for specific crops. There have been perhaps observed changes in arable lands once suitable for staple food crops (e.g., maize, rice, cocoyam, sorghum etc) and cash crops (e.g., cocoa, coffee etc) in many areas of old AEZs.

The alteration in AEZs has disrupted existing economic investment patterns and in general agriculture structure with direct impacts on food security, food prices, and livelihood sustainability in agrarian economies (FAO; Fischer *et al*; UNDP, 2015; World Bank). In Ghana, farmers are facing difficulties in planning crop production and the choice of farm management due to the changing AEZs (Amekudzi *et al*., 2015; Asante and Amuakwa-Mensah, 2014; MoFA, 2016; UNDP, 2013; Owusu *et al*., 2008). From the reports of Asante and Amuakwa-Mensah, MoFA and UNDP and World Bank, the changes in AEZs have contributed to reduction in agricultural production, food security risk, increase vulnerability rural agricultural, and failures in agro-economic investments. Reports from MoFA, UNDP and the World Bank highlighted the socio-economic impacts of changes in AEZs, including food shortages, rising food prices, increased hunger, and worsening poverty in Ghana. The proposed new AEZs are viral adaptation strategy to ensure sustainable agriculture, enhance food security, boost the agro-economic livelihoods and reduce rural poverty in the face climate change and changes in LULC pattern (Mendelsohn and Kurukulasuriya, 2008 Mugandani *et al*., 2012; Lin et al., 2012; Yamba *et al*., 2023)

8.8: Chapter summary

The LULC dynamics revealed substantial agriculture and forest lands decrease, while rangeland and built-up increased, affecting Ghana’s AEZs.

CHAPTER NINE

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

9.1 Introduction

This chapter summarizes the entire study, and carefully provides a summary of the major findings derived from the analysis of the main and specific objectives of the study. Similarly, there is a presentation of conclusions carefully based on the major findings outlined. Furthermore, the chapter outlines clear action-based recommendations for consideration by government and policymakers, departments and agencies, researchers and research institutions, and farmers that can potentially address the inherent challenges and harness the opportunities emerging from the changes in agro-climatic and land use-land cover patterns, and AEZs dynamics in Ghana. Finally, the chapter presents key contributions to present knowledge in the field, and also suggests the additional areas for further study.

9.2 Summary of the Study

The main objective was to reclassify Ghana into new AEZs through the development of a more robust and dynamic AEZ model that employs the most relevant climatic and edaphic parameters, and applications of remote sensing (RS) and geographic information systems (GIS). The specific objectives of the study were to: (1) analyze the spatio-temporal changes in the key agro-climatic variables of Ghana's AEZs from 1991 to 2020, (2) analyze the spatio-temporal changes in LULC of Ghana for the periods 2001, 2010, and 2019, and finally (3) develop a new AEZs map of Ghana showing the current spatial distribution of the zones.

In this study, three research questions were set for achieving the main and specific objectives, which are: (1) what are the spatio-temporal changes in the key agro-climatic variables of Ghana's AEZs between 1991 and 2020? (2) what is the pattern for spatio-temporal changes in the LULC of Ghana the periods (2001, 2010, and 2019)? (3) what are the proposed new AEZs of Ghana, and how do they reveal inter-zonal and intra-zonal shifting spatial patterns from the existing FAO AEZs, and as a reflection of the impacts of climate change and LULC changes in Ghana?

This study was underpinned by the positivist philosophy, which allowed for the choice of analytical research design and the use of quantitative methods for collection, processing and analysis of data and results presentation. Consequently, the study analysed quantitative climatic datasets on daily rainfall, maximum temperature, minimum temperature, wind speed, solar radiation, sunshine hours, and relative humidity mainly from the 22 synoptic stations of the Ghana Meteorological agency. These were further analysed into the key agro-climatic parameters such as MAR, MAJ-LGP, MIN-LGP, PET, RDAYS, TMEAN, SOS and EOS. Similarly, satellite remotely sensed geospatial data on the key agro-edaphic parameters were also used. These included a 30-m DEM from ASTER, which was analysed for topography such as slope, elevation and aspect features. Another 30-m LULC from MODIS and a-10 m Sentinel 2 LULC satellite imageries were analyzed for the study.

In this study, the key agro-climatic parameters were analyzed for the evidence for direct impacts of climate change on the existing FAO AEZs, while the LULC imageries were also analyzed for the spatio-temporal changes in the agro-edaphic characteristics of the Ghana's AEZs. By combining all the other essential agro-edaphic and agro-climatic parameters, new agro-ecological zones were delineated, showing the current inter-zonal spatial distribution and intra-zonal changes.

The data processing and analysis were done by the application of several statistical tools and geospatial process-based analytical GIS techniques. The statistical analysis tools included InStat + computer programming, Microsoft excel Data analysis, Pivot Table and GIS spatial analysis tools. Similarly, the statistical tests conducted included standardization (Z-scores), trend analysis, correlation test, single factor ANOVA, hypothesis testing and the test of significance.

The last-observation-carried-forward (LOCF) and the RClimdex methods, as well as the statistical and GIS process-based interpolation (spline interpolation) were used as reliable data management techniques to address the inherent gaps and inconsistencies, and to ensure smoothing in the climatic datasets. Similarly, the quantitative statistical means, standard deviation, and percentages were analyzed. The results analyzed for the changes in the key agro-climatic parameters, the changes in LULC of Ghana, and the new AEZs delineated in tandem with current climatic and LULC were presented by tables, figures and spatial maps.

9.3 Major findings

Summary of the key findings analyzed from this study are presented as themes structured according to the three research questions set for the attainment of the main and specific objective. These themes include:

1. Spatio-temporal changes in the key agro-climatic variables of Ghana's AEZs
2. Spatio-temporal changes in the LULC patterns in Ghana
3. Inter-zonal and intra-zonal shifting spatial patterns in the new AEZs of Ghana

9.3.1 Spatio-temporal changes in agro-climatic variables of old AEZs

1. The study reveals significant variations in agro-climatic thresholds, particularly in terms of Mean Annual Rainfall (MAR) and Length of Growing Period (LGP), across all six AEZs. These variations point to potential shifts in the spatial distribution and boundaries of the AEZs, highlighting the impact of climate change and evolving land use patterns.
2. The observed changes in MAR and LGP have implications for crop suitability and land productivity within the AEZs. These changes

suggest potential risks for agricultural production, particularly in terms of crop planning and extension services, which may need to adapt to new agro-climatic realities.

3. The research identifies spatial shifts in agro-climatic conditions within the AEZs, suggesting that certain zones may no longer be suitable for the crops historically grown in those areas. This shift in the boundaries and agro-climatic conditions requires updated agricultural planning and adaptation strategies.
4. The significant decline in agro-climatic thresholds such as MAR and LGP across the zones points to challenges in maintaining agricultural viability in the affected AEZs. These changes may lead to reduced crop yields and, consequently, a threat to food security in certain areas of Ghana.
5. The findings challenge the assumed uniformity of the existing FAO

AEZs classification, indicating that the old classification does not accurately reflect current agro-climatic conditions. The decline in MAR and LGP across the zones further reinforces the need for periodic updates to AEZs to ensure alignment with the changing climate and land use patterns

9.3.2 Spatio-temporal changes in LULC patterns in Ghana

1. A key finding from the LULC analysis is the significant decline in forest and agricultural land across Ghana. Forest land showed a steady decrease, with 2,553 km² lost between 2001 and 2019. Similarly, agricultural land decreased by 11,333.75 km² over the same period. This reduction in forest and agricultural land has been primarily driven by urbanization, population growth, and agricultural intensification.

2. There was a substantial expansion in rangelands (12,797.5 km²), built-up areas (691.5 km²), and barren lands (20.0 km²). This shift suggests ongoing urbanization and land degradation, particularly in rural and peri-urban areas. The increased conversion of agricultural and forest lands into built-up areas and rangeland further exacerbates pressures on the environment and agricultural systems.
3. The observed changes in land use were accompanied by significant shifts in agro-climatic parameters such as MAR and LGP. The reduction in forested areas and agricultural lands, especially in the THAEZ and DFAEZ, has contributed to a decrease in MAR and a shortening of the growing season in some regions. These alterations in climate patterns are further exacerbated by the conversion of land for other uses, such as urban development and rangeland expansion.
4. The LULC changes have directly impacted the spatial distribution and boundaries of the AEZs in Ghana. For instance, the rapid encroachment of built-up areas and rangeland into previously forested and agricultural zones has altered the biophysical characteristics of these AEZs, shifting their suitability for traditional crops and affecting land productivity.
5. The significant increase in built-up areas and barren lands indicates an ongoing trend of urbanization and land degradation. The expansion of urban areas has been particularly pronounced, reflecting rapid population growth, economic activities, and infrastructure development. These urban expansions are contributing to the loss of fertile agricultural land and the degradation of ecosystems, which in turn has implications for agricultural production and food security.

6. Climate change has exacerbated the observed LULC dynamics. The increasing frequency of droughts, erratic rainfall patterns, and rising temperatures have influenced land use decisions, particularly in forest and agricultural areas. These climatic factors, combined with anthropogenic activities, have led to significant changes in the landscape, further influencing the suitability of land for different agricultural practices.

9.3.3 Inter-zonal and intra-zonal spatial patterns in Ghana's New AEZs of

1. The study reveals significant alterations in the spatial boundaries and geographical extents of Ghana's six AEZs, mainly attributed to the direct impacts of the ongoing climate change, rapidly evolving land use and land cover changes, and mythological challenges inherent in the old FAO classifications.
2. Clear inter-zonal shifting patterns and intra-zonal spatial variations have been observed across all six AEZs. These shifts are strongly aligned with significant changes in key agro-climatic parameters, such as MAR and LOS, as well as substantial alterations in LULC.
3. The findings highlight the dynamic nature of AEZs over time; the observed interactions among different zones and the obvious encroachments reveal heterogeneity, a serious challenge to AEZs homogeneity in Ghana.
4. The significant shrinking of Zones A, B, and D, and the expansion of Zone E suggest potential negative impacts on key agricultural regions for staple and cash crop production. Conversely, the expansion of

Zone F could have positive implications for food production. These shifts indicate that some AEZs may become less suitable for certain crops, thus posing challenges to food security and agriculture in Ghana.

5. The reclassification of Ghana's AEZs reveals the inadequacy of the old FAO classification due to outdated and insufficient agro-climatic and geospatial data. The proposed new AEZs offer a more accurate representation of current agro-climatic conditions and land use, helping to identify areas for crop suitability analysis and better agricultural planning.
6. The study shows that the continuing reliance on the outdated FAO AEZs presents significant challenges for sustainable agricultural development, particularly in crop production planning and agricultural extension services. The significant changes in agro-climatic conditions and land use patterns indicate a need for updated zoning to ensure sustainable agricultural practices.

9.4 Conclusions

Based on the main findings, the following intuitive conclusions can be made from the study:

9.4.1 Spatio-temporal changes in agro-climatic variables of old AEZs

1. The study concludes that the existing FAO AEZs classification is outdated and fails to capture the current and evolving agro-climatic conditions in Ghana. Regular updates to AEZs, using modern geospatial techniques and current climatic data, are essential for more accurate land use and agricultural planning.

2. With the significant decline in key agro-climatic parameters (MAR and LGP), the study emphasizes the importance of adopting climate-resilient agricultural practices. These practices will help ensure food security and maintain agricultural productivity in light of changing agro-climatic conditions.
3. The shifting boundaries and agro-climatic characteristics of AEZs highlight the direct impact of climate change on Ghana's agricultural landscape. These shifts necessitate a reassessment of agricultural strategies and policies to mitigate risks to crop production.
4. The study suggests that integrating updated agro-climatic thresholds into existing agro-ecological classifications will better reflect current and future agricultural conditions. This approach will help stakeholders adapt to dynamic agro-climatic changes and improve food security in Ghana

9.4.2 Spatio-temporal changes in LULC patterns changes in Ghana

1. There is a need for continuous monitoring of LULC changes using satellite imagery and other remote sensing technologies. This will help track the ongoing shifts in land use and provide timely data to inform agricultural and environmental policies.
2. To mitigate the adverse effects of urbanization and land degradation, sustainable land management practices should be promoted, such as agroforestry, soil conservation, and sustainable agricultural practices. These strategies will help restore degraded lands, increase soil fertility, and improve agricultural productivity.
3. Policies should be developed to promote climate-resilient agricultural

practices, particularly in areas affected by climate change and land degradation. These practices should focus on improving water management, soil fertility, and crop diversification to adapt to the changing agro-climatic conditions.

4. Agricultural extension services should integrate the findings of this study into their advisory services for farmers, focusing on adapting to the changing LULC and agro-climatic conditions. Providing farmers with climate-smart tools and knowledge will improve their resilience to the impacts of climate change.
5. Given the significant changes in land use, a reclassification of AEZs using updated LULC and climatic data is essential to better align agricultural policies with the current environmental conditions. This would help in identifying the most suitable land for agricultural use, supporting food security, and ensuring sustainable land management practices.

9.4.3 Inter-zonal and intra-zonal spatial patterns in New AEZs

1. The findings confirm that Ghana's AEZs are dynamic and are influenced by both climate change and land use changes. The reclassification of AEZs, based on up-to-date data, provides more accurate zones for assessing the impacts of these changes on agriculture.
2. The study concludes that the observed shifts in AEZs have potential implications for crop suitability, food security, and agricultural productivity. The shrinking of certain zones and the expansion of others necessitate the adoption of climate-resilient agricultural strategies.
3. The study highlights the limitations of the old FAO AEZs, which were

based on less sophisticated data and methodologies. These outdated classifications fail to reflect the current realities of climate change and land use changes.

4. The updated AEZs classification is crucial for better agricultural policy planning, land use management, and ensuring food security in Ghana. The new classification offers a more precise tool for addressing the challenges posed by climate change and changing land use.
5. The study stresses the need for periodic revisions of AEZs to incorporate current climatic data, land use patterns, and improved geospatial datasets to support effective agricultural policies and land management practices

9.5 Recommendations

9.5.1 Spatio-temporal changes in Agro-climatic parameters of old AEZs

1. Gmet, EPA, MoFA and research institutions should ensure periodic revisions of key agro-climatic thresholds of Ghana's AEZs, using up-to-date climate data and geospatial techniques to reflect changing climatic conditions, particularly changes in MAR and LGP .
2. Extension officers, MoFA and Gmet should train and encourage farmers to adopt climate-resilient crop varieties and farming techniques to enable them adapt to shifting agro-climatic conditions and maintain agricultural productivity.
3. Key institutions like MoFA, FAO, and GMet should integrate updated agro-climatic data (MAR and LGP) into national agricultural policies and planning to ensure alignment with current environmental conditions.
4. Agricultural extension services should provide farmers with accurate,

updated agro-climatic data to inform decisions on crop suitability and sustainable

9.5.2 Spatio-Temporal Analysis of LULC Dynamics in Ghana

1. There is a need for continuous monitoring of LULC changes using satellite imagery and other remote sensing technologies by EPA, MESTI and Forestry department. This will help track the ongoing shifts in land use and provide timely data to inform agricultural and environmental policies.
2. To mitigate the adverse effects of urbanization and land degradation, sustainable land management practices should be promoted, such as agroforestry, soil conservation, and sustainable agricultural practices by EPA, MESTI and town and country planning. These strategies will help restore degraded lands, increase soil fertility, and improve agricultural productivity.
3. Policies should be developed to promote climate-resilient agricultural practices, particularly in areas affected by climate change and land degradation. These practices should focus on improving water management, soil fertility, and crop diversification to adapt to the changing agro-climatic conditions.
4. Given the dynamic nature of land use and land and its impacts on agro-climatic and agro-ecological zones, regular reclassification of AEZs using updated LULC and climatic data is essential to better align agricultural policies with the current environmental conditions. This would help in identifying the most suitable land for agricultural use, supporting food security, and ensuring sustainable land management

practices. This requires the collaborations of EPA, MoFA, and MESTI.

5. Agricultural extension services should integrate the findings of this study into their advisory services for farmers, focusing on adapting to the changing LULC and agro-climatic conditions. Providing farmers with climate-smart tools and knowledge will improve their resilience to the impacts of climate change.

9.5.3 Reclassification of Ghana's AEZs

1. The newly reclassified AEZs should be integrated into existing and evolving national agricultural policies and land-use planning. This requires the efforts of MoFA, NDPC, MESTI, and local governments, and technical and financial assistance by FAO, UNDP and other development partners.

2. Ghana's agro-ecological zones should be revised, preferably within a decadal time scale to reflect ongoing climatic and land-use changes. These revisions should leverage advanced geospatial techniques, remote sensing tools, and updated agro-climatic data to ensure AEZ classifications remain relevant and scientifically robust. Institutions, including the MoFA, EPA, MESTI, GMet, CSIR and research universities should coordinate to ensure regular future AEZs revision

3. There is a need for enhanced capacity in data collection, monitoring, and analysis related to AEZs, especially through the use of modern GIS tools and satellite imagery by EPA, GMet, MoFA, researchers and research institutions. Regular monitoring will help assess the impacts of climate change and land use changes on the AEZs and ensure timely interventions.

4. Special support should be provided to farmers in regions experiencing shifts in AEZs. MoFA's extension services must train farmers on sustainable land management and adaptive techniques, including crop diversification and water management. UNDP and USAID should fund these initiatives, with NGOs and the media promote education for effective grassroots implementation. MESTI should integrate innovative practices to enhance resilience in vulnerable area.

5. There should be a strong collaboration among key government institutions such as the MoFA, GMet, EPA, MESTI, research institutions, and development partners like FAO and UNDP, focusing on capacity building, data sharing, and cohesive strategies to address agro-climatic and land-use challenges posed to AEZs, the national agrarian investment environment and decision-making framework.

6. It is recommended that local governments, in collaboration with MoFA, research institutions, and communities, periodically update agro-ecological zones to reflect current agro-climatic conditions, while promoting sustainable farming practices such as drought-resistant crops and water-efficient irrigation tailored to local needs.

7. It is also recommended that Ghana adopt a unique, standardized naming and labeling system for her agro-ecological zones that is distinct from existing related classifications, including vegetation zones, ecological zones, climatic zone to prevent existing confusions in literature and avoid wrong conception and unacceptable interchangeability of use of these different classifications. The newly reclassified AEZs, labeled A-F, with unique description for its classification methodology, agro-climatic and agro-edaphic characteristics, and having unambiguous

mappings of each zone's boundaries should be not be interchanged with any classifications. MoFA, GMet, EPA, FAO and NGOs, educational and research institutions should adopt and apply across all agricultural, educational and environmental policies documents, and in research, and communication efforts consistently applied in

9.6 Areas for further studies

Based on the significant changes in agro-climatic variables, the observed changes in LULC, and the consequent significant inter-zonal and intra-zonal shifting pattern in the new AEZs, the following areas are opened for further studies:

The study calls for in-depth research on specific crops' suitability and productivity in the shifted AEZs. This is essential to optimize agricultural practices, boost food security and reduce vulnerability of farmers.

Additionally, it is suggested for a further study to identify potential future scenarios for AEZs in Ghana, contributing to sound decision-making and sustainable land use planning.

Research into investigating the socio-economic implications of the shifting agro-ecological zones on local agrarian communities and livelihoods in Ghana is relevant.

There is also the need for exploration into the role of land management practices, such as afforestation and reforestation in mitigating climate change impacts on agro-ecological zones.

9.7 Contribution of the current study to knowledge

This study in Ghana has made significant contributions to our understanding of how climate and land use changes affect agro-ecological zones

(AEZs). The main achievement is the development of a dynamic GIS-RS process-based agro-ecological classification methodology. This methodology has allowed for the creation of a more accurate and up-to-date AEZ map based on current climate and land use patterns in Ghana. The research's innovative approach to AEZ mapping, data integration, and rigorous statistical analysis can serve as a blueprint for future AEZ studies in Ghana and beyond. By analyzing historical trends, this study provides updated information on the spatial variability and shifting patterns between zones, as well as changes within each zone. These insights shed light on how climate change and land use influence Ghana's AEZs. Ultimately, this research enriches our existing knowledge of AEZs and underscores the importance of proactive adaptive strategies to mitigate the adverse impacts of climate change and land use changes on Ghana's AEZ

9.8 Chapter summary

Chapter Nine presented the proposed new AEZs in comparison with the old FAO AEZs. The analysis of inter-zonal and intra-zonal spatial variability, along with the changes in climate and land use and land cover (LULC) has provided valuable insights into Ghana's agro-ecological conditions. There are significant inter-zonal spatial shifts between different AEZs, and intra-zonal boundaries changes within the same zone. The several findings from the reclassified maps are consistence with earlier agro-climatic and evolving LULC change detection results analyzed, highlighting the direct impacts of climate change and land use changes affecting Ghana's old FAO AEZs. Though the current study reveals six zones (A-F) like the old FAO classifications, there is now a marked spatial shifts and boundary modifications; similarly, the new agro-climatic and LULC analyses have shown significant differences in the agro-ecological characteristic. Current research focus, agricultural and economic investment planning, government policies on sustainable agriculture, climate change resilience and famers decisions should align with current AEZs reclassified for Ghana.

REFERENCES

Acheampong, P. K. (1982). Rainfall anomaly along the coast of Ghana–Its nature and causes. *Geografiska Annaler: Series A, Physical Geography, 64*(3-4), 199–211

Addo-Fordjour, P. & Ankomah, F (2017). Patterns and drivers of forest land cover changes in tropical semi-deciduous forests in Ghana. *Journal of Land Use Sci*ence, *12*(1), 71–86

Aquastat-Ghana (2005). FAO information system on water and agriculture. Retrieved from http://www.fao.org/nr/water/aquastat/ countriesregions/ GHA/index.stm

Adjei-Gyapong, T. & Asiamah, R. D. (2002). The interim Ghana soil classification system and its relation with the World Reference Base for Soil Resources. *Rapport sur les Ressources en Sols du Monde*. Soil Research Institute, Kwadaso-Kumasi.

Adnan, S., Ullah, K., Gao, S., Khosa, A. H., & Wang, Z. (2017). Shifting of agro-climatic zones, their drought vulnerability, and precipitation and temperature trends in Pakistan. *International Journal of Climatology*, *37*(2), 529–543.

Agroecosystem Health Project. (1996). *Agroecosystem health: An approach to assessing agricultural ecosystems at a landscape scale*. International Potato Center.

Alcamo, J., Dronin, N., Endejan, M., Golubev, G., & Kirilenko, A. (2007). A new assessment of climate change impacts on food production shortfalls and water availability in Russia. *Global Environmental Change, 17*(3-4), 429–444.

Allen, R.G., Pereira, L.S., Raes, D., & Smith, M. (1998). *Crop evapotranspiration guidelines for computing crop water requirements.* Food and Agriculture Organization of the United Nations, Rome.

Amekudzi, L. K., Yamba, E. I., Preko, K., Asare, E. O., Aryee, J., Baidu, M., *et al*. (2015). Variabilities in rainfall onset, cessation and length of rainy season for the various agro-ecological zones of Ghana. *Climate, 3*(2), 416–434.

Anand, S & Sen, A. (2000). Human development and economic sustainability. *World Development, 28*(11), 2029–2049.

Anderson, J. R., Hardy, E. E., Roach, J. T., & Witmer, R. E. (1976). *A land use and land cover classification system for use with remote sensor data.* USGS professional paper 964.

Aniah, P., Kaunza-Nu-Dem, M. K., & Ayembilla, J. A. (2019). Smallholder farmers' livelihood adaptation to climate variability and ecological changes in the savanna agro-ecological zone of Ghana. *Heliyon, 5*(4), e01492.

Anim-Kwapong, D. J., & Frimpong, E. B. (2008). Ghana climate change impacts, vulnerability, and adaptation assessments. *Environmental Protection Agency (EPA)*, Accra, Ghana.

Araya, A., Keesstra, S.D., Stroosnijder, L., 2010. A new agro-climatic classification for crop suitability zoning in northern semi-arid Ethiopia. *Agricultural and Forest Meteorology, 150*(8–9), 1057–1064.

Aryee, J. N. A., Amekudzi, L. K., Quansah, E., Klutse, N. A. B., Atiah, W. A., & Yorke, C. (2017). Development of high spatial resolution rainfall data for Ghana. *International Journal of Climatology, 38*(3), 1201–1215.

Asare-Nuamaha, P., & Botchway, E. (2019). Understanding climate variability and change: Analysis of temperature and rainfall across agro-ecological zones in Ghana. *Heliyon*, *5*(10), e02654.

Asante, F. A., & Amuakwa-Mensah, F. (2015). Climate change and variability in Ghana: Stocktaking. *Climate, 3*(1), 78–99.

Asilevi, P. J., Quansah, E., Amekudzi, L. K., Annor, T., & Klutse, N. A. B. (2019). Modeling the spatial distribution of global solar radiation (GSR) over Ghana using the Ångström-Prescott sunshine duration model. *Scientific African*, *4*, e00094.

Atehnkeng, J., Ojiambo, P. S., Donner, M., *et al*. (2008). Distribution and toxigenicity of *Aspergillus* species isolated from maize kernels from three agro-ecological zones in Nigeria. *International Journal of Food Microbiology*, *122*(1–2), 74–84.

Baah, D.B. (2018). Changing rainfall patterns in Ghana: implication for small-scale farming. *Journal of Geography*, *5*(1) 1–13.

Babbie, E. (2003). *The practice of social research.* Belmont: Wordsworth Publishing Company.

Baidu, M., Amekudzi, L. K., Aryee, J. N., Annor, T. (2017). Assessment of long-term spatio-temporal rainfall variability over Ghana using wavelet analysis. *Climate*, *5*(2), 30.

Barber, R., and Shaxson, T.F. (1996). *Agro-ecological zoning guidelines*. Food and Agriculture Organization of the United Nations.

Barnes, C. A., & Roy, D. P. (2008). Radiative forcing over the conterminous United States due to contemporary land cover land use albedo change. *Geophysical Research Letters*, *35*(9).

Barry, B., Obuobie, E., Andreini, M., Andah, W., & Pluquet, M. (2005). The Volta River Basin: *Comprehensive assessment of water management in agriculture*. International Water Management Institute. Retrieved from http://www.iwmi.cgiar.org.

Bationo, A., Hartemink, A., Lungu, O., Naimi, M., Okoth, P., Smaling, E. and Thiombiano, L. (2006). African soils: Their productivity and profitability of fertilizer use. *Background paper prepared for the African Fertilizer Summit, 9–13 June 2006*, Abuja, Nigeria.

Behera, M. D., Borate, S. N., Panda, S. N., Behera, P. R., & Roy, P. S. (2012). Modeling and analyzing the watershed dynamics using Cellular Automata (CA)–Markov model–A geo-information-based approach. *Journal of Earth System Science, 121*(4), 1011–1024.

Betts, A. K., Hamilton, J., Ligon, S., & Mahar, A. M. (2016). Integrating solar energy and climate research into science education. *Earth's Future*, *4*(1), 2–13.

Bierbaum, R. M., Fay, M., & Ross-Larson, B. (2010). *World development report 2010: Development and climate change*. Washington, DC: World Bank.

Bessah, E., Amponsah, W., Ansah, S. O., Afrifa, A., Yahaya, B., Wemegah, C. S., Tanu, M., Amekudzi, L. K., & Agyare, W. A. (2022). Climatic zoning of Ghana using selected meteorological variables for the period 1976–2018. *Meteorological Applications, 29*(1), e2049. https://doi.org/10.1002/met.2049

Bisht, H., Gautum, S., Puranik, H. V., & Nain, A. S. (2019). Agro-ecological zonation of Uttarakhand using geo-spatial techniques. *The Indian Journal of Agricultural Sciences, 89*(11), 1792–1796.

Boateng, E. (2005). Geographic Information Systems (GIS) as a Decision Support Tool for Land Suitability Assessment for Rice Production in Ghana. *Western African Journal of Applied Ecology*, 7 (1).

Boko, M., Niang, I., Nyong A., Vogel, C., Githeko, A., Medany, M., Osman-Elasha, B., Tabo, R., & Yanda, P. (2007). Africa Climate Change: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment, Report of the Inter-governmental Panel on Climate Change. In: Parry, M. L., O. F. Canziani, J. P., Palutikof, P. J., Van der Linden & Hanson, C. E. (eds.). Climate change 2007: Impacts, adaptation, and vulnerability. Cambridge University Press.

Brammer, H. (1962). Soils. In J. B. Wills (Ed.), *Agriculture and land use in Ghana* (pp. 84–114). Ministry of Agriculture, Accra, Ghana. London: Oxford University Press.

Bryman, A. (2014). *Social research method* (5th ed.). UK: Oxford University Press.

Bunn, C., Läderach, P., Pérez Jimenez, J. G., Montagnon, C., & Schilling, T. (2015). Multiclass classification of agro-ecological zones for Arabica coffee: An improved understanding of the impacts of climate change. *PLoS ONE, 10*(10), e0140490.

Caldiz, D. O., Gaspari, F. J., Moreno Kiernan, A., & Struik, P. C. (2002). Agro-ecological zoning at the regional level: Spatio-temporal variation in potential yield of the potato crop in the Argentinian patagonia. *Agriculture, Ecosystems & Environment*, *88*(1), 3–10

Cariño, M. M., Olivas, A. L. B., Cariño, D. M., Solorio, C. A. O., Tagles, H. F. D., & Flores, G. C. (2021). *Agro-climatic zoning of the state of Nayarit*. México. Atmósfera. Available at https://api.semanticscholar.org /CorpusID:238848805

Carter, D. B. (1954). Climates of Africa and according to Thornthwaite (1948) classification. *John Hopkins University Publication (in) Climatology*, *7*(14).

Carter, S.E., & Corbett, J.D. (1997). Using GIS to enhance agricultural planning: The example of Inter-seasonal rainfall variability in Zimbabwe. *Transactions in GIS, 1(*3*),* 207–218.

Chen, B. M. (2001). *The integrated agricultural resources production capability and population supporting capacity in china*. Meteorological Press.

Cline, S. A., & Rosegrant, M. W. (2003). Global food security: Challenges and policies. *Science*, *302*(5652), 1917–1919.

Chikodzi, D., Zinhiva, H., Simba, F. M., Murwendo, T. (2013). Reclassification of agroecological zones in Zimbabwe–The rationale, methods and expected benefits: The case of Masvingo Province. *Journal of Sustainable Development in Africa*, *15*(1), 104–116.

Codjoe, S. N. A., & Owusu, G. (2011). Climate change/variability and food systems: Evidence from the Afram Plains, Ghana. *Regional Environmental Change*, *11(*4), 753–765.

Congalton, R. G., & Green, K. (2019). *Assessing the accuracy of remotely sensed data: Principles and practices* (3rd ed.). Boca Raton. FL: CRC Press. https://doi.org/10.1201/9780429052729.

Corbett, J. D. (1996). The changing face of agroecosystem characterization: Models and spatial data, the basis for robust Agroecosystem characterization. *Proceeding of the Third International Conference on the Integration of GIS and Environmental Modelling*, Santa Fe, New Mexico.

Creswell, J. W. (2014). *Research design: Qualitative, quantitative, and mixed methods approaches* (4th ed.) Thousand Oaks, CA: SAGE Publications.

Crotty, M. (1998). *The foundations of social research: Meaning and perspective in the research process*. Thousand Oaks, CA: SAGE Publications.

Dale, V. H. (1997). The relationship between land-use change and climate change. *Ecological applications*, 7 (3), 753–769.

Darfour, B., & Rosentrater, K.A. (2016). Agriculture and food security in Ghana. *Agricultural and Biosystems Engineering Conference Proceedings and Presentations*, 478, 1–16.

Dalgaard, T., Hutchings, N. J., & Porter, J. R. (2003). Agroecology, scaling and interdisciplinarity. *Agriculture, Ecosystems & Environment*, *100*(1), 39–51.

Darko, H. F., Karikari, A. Y., Duah, A. A., Akurugu, B. A., Mante, V., & Teye, F. O. (2021). Effect of small-scale illegal mining on surface water and sediment quality in Ghana. *International Journal of River Basin Management*. https://doi.org/10.1080/15715124.2021.1928053

Dash, N.K. (2005). *Module: Selection of the research paradigm and methodology*. Online Research Methods Resource for Teachers and Trainers. Retrieved fromhttp://www.celt.mmu.ac.uk/ research methods/ Modules/Selection_of_methodology/index.php.

De la Rosa, D., Anaya-Romero, M., Diaz-Pereira, E., Heredia, N., & Shahbazi, F. (2009). Soil specific agro-ecological strategies for sustainable land use – A case study by using MicroLEIS DSS in Sevilla Province (Spain). *Land Use Policy*,*26*(4), 1055-1065.

De Vries, F. P., Teng, P., & Metselaar, K. (1993). *Systems approaches for sustainable agricultural developmen*t. Kluwer Academic Publishers and International Rice Research Institute.

Department for International Development (DFID) (2005). Climate change in Africa. Key sheets on climate change and povert*y*. Retrieved from http://www.dfid.gov.uk/pubs/files/climatechange/10africa.pdf.

Drummond, M. A. (2007). Land-use and land-cover change. In A. Loveland & J. W. Merchant (Eds.), *Land Change Science: Observing, Monitoring, and Understanding Trajectories of Change on the Earth's Surface* (pp. 219-234). Springer.

Drummond, M. A., Loveland, T. R., & DeFelice, T. P. (2012). Land-use and land-cover change in global and regional context. In T. R. Loveland, D. C. Stehman, T. S. Sohl, & A. L. Gallant (Eds.), *Land Change Science, Remote Sensing, and GIScience* (pp. 19-48). CRC Press.

Easterling, W. E., Aggarwal, P. K., Batima, P. *et al*. (2007). Food, fibre and forest products. In M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. vander Linden, & C. E. Hanson (Eds.), Climate Change 2007: *Impacts,* *Adaptation and Vulnerability* (pp. 273–313). Cambridge University Press.

Environment Protection Agency (EPA) (2008). *Ghana climate change impacts, vulnerability and adaption assessment*. Accra, Ghana: EPA.

EPA (2010). *Ghana Climate Change Impacts, Vulnerability and Adaptation Assessments*. Accra, Ghana: EPA.

Environmental Systems Research Institute (ESRI) (2015). *ArcGIS Desktop: Release 10.5.1*. Redlands, CA: Environmental Systems Research Institute.

Espie, P., Griffiths, G., Jessen, M., et al. (2006). Climate for crops: Integrating climate data with information about soils and crop requirements to reduce risks in agricultural decision-making. *Meteorological Applications 13(4), 305–315.*

Frankfort-Nachmias, C., & Nachmias, D. (2008). *In Research methods in the social sciences*. Retrieved from http://store.vitalsource.com/.

Fischer, G.W. and Anoine, J. (1994). *Agro-Ecological land resources assessment for agricultural development planning: A case study of Kenya*: Land and Water Development Division, Food and Agriculture Organization of the United Nations and International Institute for Applied Systems Analysis. Rome.

Fischer, G., & Van Velthuizen, H. T. (1996). Climate change and global agricultural potential project: A case study of Kenya. *International Institute for Applied Systems Analysis*, Laxenburg, Austria.

Fischer, G., & Heilig, G. K. (1997). Population momentum and the demand on land and water resources. *Philosophical Transactions of the Royal Society B: Biological Sciences, 352*(1356), 869–889

Fischer G., Makowski, M., & Granat, J. (1999). AEZWIN: An interactive multiple-criteria analysis tool for land resources appraisal. *International Institute for Applied Systems Analysis and Food and Agriculture Organization of the United Nations, Rome*.

Fischer, G., Van Velthuizen, H., Shah, M., Nachtergaele, F. O. (2002). Global agro-ecological assessment for agriculture in the 21st century: methodology and results. *International Institute for Applied Systems Analysis*, Laxenburg, Austria.

Fischer, G., Shah, M., Tubiello, F. N., & van Velhuizen, H. (2005). Socio-economic and climate change impacts on agriculture: An integrated assessment, 1990-2080. *Philosophical Transactions of the Royal Society B: Biological Sciences 360*(1463), 2067–2083.

Fischer, G., Shah, M., van Velthuizen, H., & Nachtergaele, F. (2006). *Agro-ecological zones assessment*. *Reprinted from Encyclopedia of Life Support Systems (EOLSS)*. Oxford, UK.

Fischer, G. (2009). World food and agriculture to 2030/50: How do climate change and bioenergy alter the long-term outlook for food, agriculture and resource availability? In *Proceedings of the Expert Meeting on How to Feed the World in 2050*, FAO Rome, Italy.

Fischer, G., Nachtergaele, F.O., van Velthuizen, H.T., Chiozza, F., Franceschini, G., Henry, M., Muchoney, D., & Tramberend, S. (2021). Global agro-ecological zones (GAEZ v4) model documentation.

International Institute for Applied Systems Analysis and Food and Agriculture Organization of the United Nations, Rome.

Flannigan, M., Stocks, B., Turetsky, M., & Wotton, M. (2009). Impacts of climate change on fire activity and fire management in the circumboreal forest. *Global Change Biology*, *15*(3), 549–560.

Food and Agriculture Organization of the United Nations (FAO). (1978). 1978-81. Report on the Agro-Ecological Zones Project. *World Soil Resources Report*, *48* (1–4). Rome: FAO.

FAO. (1984) *Agro-climatological data*. Africa. Vol. 1. Rome: FAO.

FAO. (1991). *The Digitized Soil Map of the World: Notes.* Retrieved from http://cluster3.lib.berkeley.edu/EART/UCONLY/fao/North+Central-Asia/NOTES.DOS.

FAO. (1996). *Agro-ecological zoning guidelines*. FAO Soils Bulletin 73. Rome. Retrieved from www.fao.org.

FAO. (2005). *Agro-ecological zones methodology*. Food and Agriculture Organization of the United Nations. Retrieved from http://www.fao.org/nr/lada.

FAO. (2008). *Water for Agriculture and Energy in Africa: The Challenges of Climate Change*. Ministerial Conference on Water for Agriculture and Energy in Africa. Sirte, Libyan Arab Jamahiriya.

FAO. (2009). *The State of Food Insecurity in the World*. Food and Agriculture Organization.

FAO. (2010). *Climate change implications for food security and natural resources management in Africa*. Twenty-sixth regional conferences for

Africa. Retrieved from http://www.fao.org/docrep/meeting/018/k7542e.pdf

FAO. (2013). *Food wastage footprint: Impacts on natural resources*. Summary report. Food and Agriculture Organization of the United Nations, Rome, Italy

FAO. (2015). *Global forest resources assessment*. Food and Agriculture Organization of the United Nations, FAO: Rome.

FAO (2016). *Land cover classification system: classification* concepts Software Version 3, FAO: Rome, www.fao.org/3/a-i5232e.pdf

FAO. (2020). *Climate change predictions in sub-Saharan Africa: Impacts and adaptations*. Rome: FAO.

FAO/ISRIC/ISSS. (1998). *World reference base for soil resources*. World Soil Resources Report, 84. FAO.

Food and Agriculture Organization of the United Nations and United Nations Environment Programme (FAO & UNEP). (2020). *The state of the world's forests 2020: Forests, biodiversity and people*. Rome. Retrieved from https://doi.org/10.4060/ca8642en

FAO/UNESCO. (1988): *Soil Map of World*. http://en.wikipedia.org/wiki/FAO_soilclassification#FAO_Soilunits

Fokuo, E. K., Darko, D., Gyamfi, C., & Nyarko, J. R. (2022). Assessment of land use/land cover change and its impact on hydrological processes in the Birim River Basin, Ghana. *Environment, Development and Sustainability*, 1-23.

Friedl, M. A., Gray, J. M., Melaas, E. K., Richardson, A. D., Hufkens, K., Keenan, T. F., Bailey, A., & O'Keefe, J. (2014). A tale of two springs:

Using recent climate anomalies to characterize the sensitivity of temperate forest phenology to climate change. *Environmental Research Letters*, *9*(5), 054006. https://doi.org/10.1088/1748-9326/9/5/054006

Gallup, J. L., & Sachs, J. D. (2000). Agriculture, Climate, and Technology: Why are the tropics falling behind? *American Journal of Agricultural Economics, 82*(3), 731–737. https://doi.org/10.1111/0002-9092.00071

Gay, L. R (2003). *Educational research and competencies for analysis and application* (4th ed.). New York: Macmillan Publishing Company.

Gbangou, T., Ludwig, F., van Slobbe, E., Greuell, W., & Kranjac-Berisavljevic, G. (2020). Rainfall and dry spell occurrence in Ghana: Trends and seasonal predictions with a dynamical and a statistical model. *Theoretical and Applied Climatology, 141*(3), 371–387.

Geerts, S., Raes, D., Garcia, M., Del Castillo, C., Buytaert, W., 2006. Agro-climatic suitability mapping for crop production in the Bolivian Altiplano: A case study for Quinoa. *Agricultural and Forest Meteorology. 139(3–4)*, 399–412

Ghana News Agency (GNA). (2011, September 10). Climate change: Time bomb for Ghana's agriculture. *Daily Graphic. Retrieved* from http://www.dailygraphic.com

Ghana Statistical Service (GSS). (2021). *2020 Population and Housing Census of Ghana (PHC)*. Accra, Ghana: GSS.

Godfray, H. C. J., Beddington, J. R., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., Pretty, J., Robinson, S., Thomas, S. M., Toulmin, C. (2010). Food security: The challenge of 9 billion people. *Science, 327*(5967), 812–818. Retrieved from https://doi.org/10.1126/science.1185383

Gornall, J., Betts, R., Burke, E., Clark, R., Camp, J., Willett, K., & Wiltshire, A. (2010). Implications of climate change for agricultural productivity in the early twenty-first century. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *365*(1554), 2973–2989.

Hale, R. C., Gallo, K. P., Owen, T. W., & Loveland, T. R. (2006). Land use/land cover change effects on temperature trends at U.S. climate normals stations. *Geophysical Research Letters, 33*(11), L11703. Retrieved from https://doi.org/10.1029/2006gl026358

Hasegawa, T., Fujimori, S., Shin, Y., Takahashi, K., Masui, T., & Tanaka, A. (2013). Climate Change Impact and Adaptation Assessment on Food Consumption Utilizing a New Scenario Framework. *Environmental Science & Technology*, *48*(1), 438–445.

Hazeu, G.W., Metzger, M.J., Mücher, C.A., Perez-Soba, M., Renetzeder, C., Andersen, E. (2011). European environmental stratifications and typologies: An overview. *Agriculture, Ecosystem and Environment 142*, 29–39.

He, Z. H., Lin, Z. J., Wang, L. J., Xiao, Z. R., Wan, F. S., & Zhuang, Q. S. (2002). Classification on Chinese wheat regions based on quality. *Scientia Agricultura Sinica*, *35*(4), 359–364

Houghton, R.A., van der Werf, G. R., DeFries, R. S., Hansen, M. C., House, J. I., Le Quéré, C., Pongratz, J., & Ramankutty, N. (2012). Carbon emissions from land use and land-cover change. *Biogeosciences, 9*(1), 835–878.

Intergovernmental Panel on Climate Change (IPCC). (1995). *Climate change: A glossary by the Intergovernmental Panel on Climate Change*. Retrieved from www.ipcc.ch.

IPCC. (2003). *Good Practice Guidance for Land Use, Land-Use Change and Forestry (GPG-LULUCF).* Retrieved from http://www.ipccnggip.iges.or.jp/public/gpglulucf/gpglulucf.html

IPCC. (2007). IPCC. (2007). *Climate change 2007: Synthesis report. Summary for policymakers.* Contribution of Working Group I to the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change. Geneva, Switzerland: IPCCC.

IPCC. (2013). *Climate change 2013: The physical science basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. Retrieved from https://www.ipcc.ch/report/ar5/wg1

IPCC. (2014). *Climate change 2014: Impacts, adaptation, and vulnerability.* Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (AR5). Geneva, Switzerland: IPCC.

IPCC. (2018). PCC. (2018). Summary for policymakers. In V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, et al. (Eds.), *Global warming of 1.5°C: An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development,* *and efforts to eradicate poverty*. Geneva, Switzerland: World Meteorological Organization.

IPCC. (2019). *Climate change and land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*. Retrieved from https://www.ipcc.ch/srccl/download/.

International Center for Tropical Agriculture (CIAT). (2014). *Predicting the impact of climate change on the cocoa-growing regions in Ghana and Cote d'Ivoire*. Retrieved from http://www.acclimatise.uk.com/resources/resources?resource=68.

International Institute of System Analysis (IIASA) & Food and Agricultural Organization (FAO). (2012). *Global Agro-ecological Zones (GAEZ v3.0).* Laxenburg, Austria: IIASA and Rome, Italy: FAO.

International Union of Soil Science (IUSS) Working Group WRB. (2022.) *World reference base for soil resources: International soil classification system for naming soils and creating legends for soil maps* (4th ed.). International Union of Soil Sciences, Vienna, Austria.

Issahaku, A. R., Campion, B. B., & Edziyie, R. (2016). Rainfall and temperature changes and variability in the Upper East region of Ghana. *Earth and Space Science, 3*(8), 284–294. https://doi.org/10.1002/2016EA000166.

Laux, P., Kunstmann, H., & Bárdossy, A. (2007). Predicting the regional onset of the rainy season in West Africa. *International Journal of Climatology*, *28*(3), 329–34. https://doi.org/10.1002/joc.1542.

Janicot, S., Harzallah, A., Fontaine, B., & Moron, V. (1998). West African monsoon dynamics and eastern equatorial Atlantic and Pacific SST anomalies (1970–88). *Journal of Climate, 11*(8), 1874–1882.

Jayathilaka, P. M. S., Soni, P., Perret, S. R., Jayasuriya, H. P. W., & Salokhe, V. M. (2012). Spatial assessment of climate change effects on crop suitability for major plantation crops in Sri Lanka. *Regional Environmental Change*, *12*(1), 55–68. https://doi.org/10.1007/s10113-011-0247-2.

Jingura, R. M., Matengaifa, R., Musademba, D., & Musiyiwa, K. (2011). Characterisation of land types and agro-ecological conditions for production of Jatropha as a feedstock for biofuels in Zimbabwe. *Biomass and Bioenergy*, *35*(5), 2080–2086.

Klutse, N. A. B., Owusu, K., Adukpo, D. C., Nkrumah, F., Quagraine, K., Owusu, A. (2013). Farmer's observation on climate change impacts on maize (Zea mays) production in a selected agro-ecological zone in Ghana. *Research Journal of Agriculture and Environmental Management, 2*(12), 394-402.

Klutse, N. A. B., Ajayi, V., Gbobaniyi, E. O., et al. (2018). Potential impact of 1.5° C and 2° C global warming on consecutive dry and wet days over West Africa. *Environmental Research Letters, 13*(5), 055013.

Klutse, N. A. B., Owusu, K., & Boafo, Y. (2020). Projected temperature increases over northern Ghana. *SN Applied Sciences, 2*, 1339.

Köppen, W. (1928). Versuch einer Klassifikation der Klimate, vorzugsweise nach ihren Beziehungen zur Pflanzenwelt. *Geographie Zeitschrift*, 6, 657–679, 593–611.

Kumar, R. (2005). *Research methodology: A step-by-step guide for beginners*. London: SAGE Publications.

Kurukulasuriya, P., & Mendelsohn, R. (2008). A Ricardian Analysis of the Impact of Climate Change on African Cropland. *African Journal of Agriculture and Resource Economics*, *2*(1), 1-23.

Lambin, E. F., & Meyfroidt, P. (2011). Global land use change, economic globalization, and the looming land scarcity. *Proceedings of the National Academy of Sciences*, *108*(9), 3465–3472. https://doi.org/10.1073 /pnas.1100480108

Lane, A., & Jarvis, A. (2007). Changes in climate will modify the geography of crop suitability: Agricultural biodiversity can help with adaptation. *Journal of Semi-Arid Tropical Agricultural Research*, *4*(1), 1–12.

Läderach, P., Eitzinger, A., Martinez, A., Castro, N. (2012), Predicting the impact of climate change on the cocoa-growing regions in Ghana and Cote d'Ivoire. *Final Report*, *35*. Retrieved from http:// www .ciat .cgiar.org.

Lee, D. B.; Kim, Y. N.; Sonn, Y.K.; Kim, K. H. Comparison of Soil Taxonomy (2022) and WRB (2022) systems for classifying paddy soils with different drainage grades in South Korea. *Land*, *12*(6), 1204. Retrieved from https://doi.org/10.3390/ land12061204,

Lin, Y., Liu, A., Ma, E., & Zhang, F. (2013). Impacts of future climate changes on shifting patterns of the agro-ecological zones in China. *Advances in Meteorology, 2013.*Retreived from https://doi.org/10.1155/2013/976597

Lincoln, Y. S., Lynham, S. A., & Guba, E.G. (2011). Paradigmatic controversies, contra-dictions, and emerging confluences, revisited. In N.

K. Denzin & Y.S. Lincoln (eds), *The Sage handbook of qualitative research* (4th ed., pp. 97–128). Thousand Oaks, CA: SAGE Publications.

Mahmood, R., Pielke, R. A., Hubbard, K. G., Niyogi, D., Dirmeyer, P. A., McAlpine, C., Carleton, A. M., Hale, R., Gameda, S., Beltrán-Przekurat, A., Baker, B., McNider, R., Legates, D. R., Shepherd, M., Du, J., Blanken, P. D., Frauenfeld, O. W., Nair, U. S., & Fall, S. (2013). Land cover changes and their biogeophysical effects on climate. *International Journal of Climatology*, *34*(4), 929–953. https://doi.org/10.1002/joc.3736

Manzanas, R., Amekudzi, L., Preko, K., Herrera, S., & Gutiérrez, J. (2014). Precipitation variability and trends in Ghana: An intercomparison of observational and reanalysis products. *Climate Change*, *124*(4), 805–819.

Martin, K., Sauerborn, J. (2013). Introduction. In *Agroecology* (1-5). Springer, Dordrecht. https://doi.org/10.1007/978-94-007-5917-6_1.

Melton, J. R., Shrestha, R. K., & Arora, V. K. (2015). The influence of soils on heterotrophic respiration exerts a strong control on net ecosystem productivity in seasonally dry Amazonian forests. *Biogeosciences*, *12*(4), 1151–1168. https://doi.org/10.5194/bg-12-1151-2015.

Mendas, A. (2010). The contribution of the digital elevation models and geographic information systems in a watershed hydrologic research, *Applied Geomatics*, *2*(1), 33–42.

Mertens, D. (2010). *Research and evaluation in educational and psychology: Integrating diversity with quantitative, qualitative, and mixed methods approaches*. Thousand Oaks, CA: SAGE Publications.

Merugu, T., Shashikala, A. V., & Mathyam, P. (2015). Variability study on the length of growing period (LGP) using ground and space-based (MODIS) data for the selected mandals of Warangal district. *International Journal of Advancement in Remote Sensing, GIS, and Geography (IJARSGG)*, *3*(1), 48-58.

Metzger, M.J., Bunce, R.G.H., Leemans, R., Viner, D. (2008). Projected environmental shifts under climate change: European trends and regional impacts. *Environmental Conservation*, *35*(1), 64–75.

Metzger, M. J., Bunce, R. G. H., Jongman, R. H. G., Sayre, R., Trabucco, A., & Zomer, R. (2012). A high-resolution bioclimate map of the world: A framework for global biodiversity research and monitoring. *Global Ecology and Biogeography*, *22*(5), 630–638.

Ministry of Food and Agriculture (MoFA). *(2010). Food and Agriculture Sector Development Policy II (FASDEP II)*. MoFA, Accra, Ghana.

Ministry of Food and Agriculture (MoFA). (2016). *Agriculture in Ghana: Facts and figures.* Ministry of Food and Agriculture, Statistics, Research and Information Directorate (SRID), Accra, Ghana.

Ministry of Local Government and Rural Development; *Environment, Science and Technology* (MLG & RD/ ES). (2018). Accra, Ghana.

Monserud, R.A., Leamans, R. (1992). Comparing global vegetation maps with the kappa statistic. *Ecological Modelling*, *62*(1), 275–293.

Montandon, L. M., Fall, S., Pielke, R. A., & Niyogi, D. (2011). Distribution of landscape types in the global historical climatology network. *Earth Interactions*, *15*(6), 1–24. https://doi.org/10.1175/2010ei371.1

Moral, J. B., Pertanika, K., and Rainis, R. (2011). The spatial interconnection between agroecological dissimilarities and poverty in Bangladesh: A case study. *Agricultural Sciences, 34* (1), 93–108.

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., & Veith, T. L. (2007). Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE*, *50*(3), 885–900.

Mugandani, R., Wuta, M., Makarau, A., & Chipindu, B. (2012). Re-classification of agro-ecological regions of Zimbabwe in conformity withclimate variability and change. *African Crop Science Journal*, *20*(2), 9–17.

Mudzengi, B. K., Simba F. M., Murwendo, T. & Mdlongwa T. (2013). Perspectives in climate change and *gender issues: A case study of Masvingo Province in Zimbabwe. Sacha Journal of Environmental Studies*, *3* (1), 1–10.

Mücher, S., De Simone, C., Kramer, H., de Wit, A., Roupioz, L., Hazeu, G. W., Boogaard, H. L., Schuiling, R., Fritz, S., Latham, J., & Cormont, A. (2016). A new global agro-environmental stratification (GAES). *Wageningen Environmental Research Report.* https://doi.org/10.18174/400815

NASA. (2016). *Sentinel-2A launches: Our compliments and our complements.* Retrieved from https://landsat.gsfc.nasa.gov/sentinel-2a-launches-our-compliments-our-complements/.

NASA. (2019). *Moderate Resolution Imaging Spectroradiometer (MODIS) project.* http://modis.gsfc.nasa.gov/about/specifications.php

Nettey S. N. A., Agodzo S. K., Fialor. S. C., Marx, W., Asare, D. K., & Loh, S. K. (2016). Mango growing potential of Ghana: modelling of suitable land areas within Ghana's agro-ecological zones for mango production. *International Journal of Technical Research and Applications*, *4* (5), 50-58.

Niasse, M. (2005). Climate-induced water conflict risks in West Africa: Recognizing and coping with increasing climate impacts on shared water courses. *Journal of Meteorology & Climate Science*, *11*(1), 18–26. International workshop organized by Centre for the Study of Civil War, International Peace Research Institute, Oslo (PRIO) and Centre for International Environmental and Climate.

New, M., Lister, D., Hulme, M., & Makin, I. (2002). A high-resolution data set of surface climate over global land areas. *Climate Research*, *21*(1), 1–25. https://doi.org/10.3354/cr021001.

Nkrumah, F., Klutse, N.A.B., Adukpo, D.C., Owusu, K., Quagraine, K.A., Owusu, A., & Gutowski, W. (2014). Rainfall variability over Ghana: Model versus rain gauge observation. *International Journal of Geosciences*, 5(6), 673–683.

Nkrumah, F., Quagraine, K.A., Quagraine, K.T., Wainwright, C., Quenum, G.M.L.D., Amankwah, A., Klutse, N.A.B (2022). Performance of CMIP6 HighResMIP on the representation of onset and cessation of seasonal rainfall in Southern West Africa. *Atmosphere*, *13*(7), 999. https://doi.org/ 10.3390/atmos13070999

Nyadzi, E., Bessah, E., Kranjac-Berisavljevic, G., & Ludwig, F. (2021). Hydro-climatic and land use/cover changes in Nasia catchment of the White

Volta basin in Ghana. *Theoretical and Applied Climatology*, *146*(3-4), 1297-1314.

Odekunle, T. (2006). Determining rainy season onset and retreat over Nigeria from precipitation amount and number of rainy days. *Theoretical and Applied Climatology, 83*(1), 193–201.

Olesen, J. E., & Bindi, M. (2002). Consequences of climate change for European agricultural productivity, land use and policy. *European Journal of Agronomy, 16*(4), 239–262. https://doi.org/10.1016/s1161-0301(02)00004-7

Oppong-Anane, K. (2006). *Country pasture/forage resources profiles: Ghana.* Food and Agriculture Organization of the United Nations (FAO). Retrieved from http://www.fao.org/ag/AGP/AGPC/doc/Counprof/PDF%20files/ Ghana-English.pdf

Owusu, K., & Waylen, P. (2009). Trends in spatio-temporal variability in annual rainfall in Ghana (1951-2000). *Weather*, *64*(3), 115–120.

Owusu, K., & Klutse, N. A. B. (2013). Simulation of the rainfall regime over Ghana from CORDEX. *International Journal of Geosciences, 4*(5), 785–791.

Owusu, K., & Waylen, P. R. (2013). The changing rainy season climatology of mid-Ghana. *Theoretical and Applied Climatology*, *112*(3-4), 419–430.

Owusu, K. (2018). Rainfall changes in the savannah zone of northern Ghana 1961–2010. *Weather, 73*(1), 6–50.

Osei, M.A., Amekudzi, L.K., Wemegah, D.D., Preko, K., Gyawu, E.S., Obiri-Danso, K. (2019,) The impact of climate and land-use changes on the hydrological processes of Owabi catchment from SWAT analysis. *Journal of Hydrology*. Regional. Studies, 25, 100620.

Paladini (2017). Satellite crop mapping to better understand agro-ecological zones. *Unpublished Doctoral Thesis*. Università di Pisa, Pisa, Italy.

Papadakis, J. S. (1970). *Climates of the world: Their classification, similitudes, differences, and geographic distribution*. Available from https://api. semantic scholar.org/CorpusID:12754645

Patel, N. R. (2003). Remote sensing and GIS application in agro-ecological zoning. In Satellite Remote Sensing and GIS Applications in Agricultural Meteorology*: Proceedings of a Training Workshop*, 213 233. Available from http://www.wamis.org/agm/pubs/agm8/Paper-11.pdf .

Patel, N. R., Endang, P., Kumar, S., & Pande, L.M. (2005). *Agro-ecological zoning using Remote Sensing and GIS*: A case study in part of Kumaon Region. Sustainable Agriculture. Northern Book Center.

Park, T., Ganguly, S., Tømmervik, H., Euskirchen, E. S., Høgda, K.-A., Karlsen, S. R., Brovkin, V., Nemani, R. R., & Myneni, R. B. (2016). Changes in growing season duration and productivity of northern vegetation inferred from long-term remote sensing data. *Environmental Research Letters*, *11*(8), 084001. https://doi.org/10.1088/1748-9326/11/8/084001

Phillips, D. C., & Burbules, N. C. (2000). *Postpositivism and educational research.* Rowman & Littlefield.

Pielke, R. A., Adegoke, J., BeltraáN-Przekurat, A., Hiemstra, C. A., Lin, J., Nair, U. S., Niyogi, D., & Nobis, T. E. (2007). An overview of regional land-use and land-cover impacts on rainfall. *Tellus B: Chemical and Physical Meteorology*, *59*(3), 587–601.

Prentice, I. C., Cramer, W., Harrison, S. P., Leemans, R., Monserud, R. A., & Solomon, A. M. (1992). Special paper: a global biome model based on plant physiology and dominance, soil properties and climate. *Journal of Biogeography, 19*(2), 117–134.

Quiroz, R., Zorogastua, P., Baigorria, G., Barreda, C., Valdivia, R, Curz, M., & Reinoso, J. (2001). Towards a dynamic definition of agro-ecological zones using modern information technology tools. In Scientist and Farmer: *Partners in Research for the 21st centur*y, 361-370.

Ramankutty, N., Foley, J. A., Norman, J., McSweeney, K. (2002). The global distribution of cultivable lands: current patterns and sensitivity to possible climate change. *Global Ecology and Biogeography, 11*(5), 377–392.

Ramankutty, N., Hertel, T. W., Lee, H. L., & Rose, S (2005). Global land use and land cover data for integrated assessment modeling. In *Book Chapter for the Snowmass Conference*, Snowmass, CO, USA.

Ray, D. K., West, P. C., Clark, M., Gerber, J. S., Prishchepov, A.V., Chatterjee, S. (2019). Climate change has likely already affected global food production. *PLOS ONE, 14*(5), e0217148.

Rosenzweig, C., & Parry, M (1994). Potential impact of climate change on world food supply. *Nature, 367*(6459), 133-138.

Rudolf, B., Beck, C., Grieser, J., Schneider, U. (2005). Global precipitation analysis products. *Global Precipitation Climatology Centre (GPCC), DWD, Internet publication,* 1–8.

Saaty, T. L. (1980). *The analytic hierarchy process*. New York, NY: McGraw Hill.

Salinger, M.J., Sivakumar, M.V.K., & Motha, R. (2005). Reducing vulnerability of agriculture and forestry to climate variability and change: Workshop summary and recommendations. *Climatic Change*, *70*(1-2), 341–362.

Schad, P., Spaargaren, O., Dent, D., & Nachtergaele, F (2006). *World reference base for soil resources: A framework for international classification, correlation and communication*. World Soil Resources Reports 103. FAO, Rome.

Schwandt, T. A. (2001). *Dictionary of qualitative inquiry* (2nd ed.). Thousand Oaks: CA: SAGE.

Seljaninov, G.T., (1966). *Agroclimatic map of the world*. Hydrometeoizdat Publishing House, Leningrad.

Schneider, U., Becker, A., Finger, P., Meyer-Christoffer, A., & Ziese, M. (2018). *GPCC full data monthly product version 2018 at 0.25°: Monthly land-surface precipitation from rain-gauges built on GTS-based and historical data.* GPCC: Offenbach, Germany.

Shah, M., Fischer, G., & van Velthuizen, H. (2008). *Food Security and Sustainable Agriculture. The challenges of climate change in Sub-Saharan Africa.* Laxenburg: International Institute for Applied Systems Analysis.

Silverman, D. (2005). *Doing qualitative research* (5th ed). Thousand Oaks, CA: SAGE Publications.

Simon, P. (2014). The importance of classification in empirical science. In A. Brożek & J. Jadacki (Eds.), *Księga pamiątkowa Marianowi Przełęckiemu w darze na 90-lecie urodzin* (pp. 145–157). Lublin: Norbertinum.

Sivakumar, M.V.K., & Valentin, C. (1997). Agroecological zones and the assessment of crop production potential. *Philosophical Transactions of the Royal Society B: Biological Sciences, 352(*1356), 907-916.

Sivakumar, M.V.K., Roy, P.S., Harmsen, K., & Saha, S. K. (2003). *Satellite remote sensing and GIS applications in agricultural meteorology*: *Proceedings of the Training Workshop*, Dehra Dun, India.

Sleeter, B. M., Liu, J., Daniel, C., Rayfield, B., Sherba, J., Hawbaker, T. J., Zhu, Z., Selmants, P. C., & Loveland, T. R. (2018). Effects of contemporary land-use and land-cover change on the carbon balance of terrestrial ecosystems in the United States. *Environmental Research Letters, 13*(4), 045006. Retrieved from https://doi.org/10.1088/1748-9326/aab540.

Smaling, E. M. A. (1993). *An agro-ecological framework for integrated nutrient management, with special reference to Kenya.* Doctoral thesis, Agricultural University, Wageningen, The Netherlands.

Soil Survey Staff. (2022). *Keys to soil taxonomy* (13th ed.). U.S. Department of Agriculture, Natural Resources Conservation Service: Washington, DC, USA

Stanturf, J. A., Warren, M. L., Charnley, S., Polasky, S.C., Goodrick, S.L., Armah, F., & Nyako, Y.A. (2011). Ghana climate change vulnerability and adaptation assessment. *United States Agency for International Development*, Accra, Ghana.

Stehfest, E., Heistermann, M., Priess, J.A., Ojima, D.S., & Alcamo, J. (2009). Simulation of global crop production with the ecosystem model DayCent. *Ecological Modelling, 209*(2–4), 203–219.

Steven, M. D. (1993). Satellite remote sensing for agricultural management: Opportunities and logistic constraints. *Photogrammetric Engineering and Remote Sensing, 48*(4), 29-34.

Subyani, A. M., Qari, M. H. & Matsah, M. I. (2010). Digital Elevation Model and Multivariate Statistical Analysis of Morphometric Parameters of Some Wadis, Western Saudi Arabia. *Arabian Journal of Geosciences*, *5*(2), 147-157. https://doi.org/10.1007/s12517-010-0149-7.

Sultan, B., S. Janicot, & A. Diedhiou (2003). The West African monsoon dynamics Part I: Documentation of intra-seasonal variability. *Journal of Climate, 16*(21), 3389–3406.

Tappan, G. G., Cushing, W.M., Cotillon, S.E., Mathis, M.L., Hutchinson, J.A., Herrmann, S.M., & Dalsted, K.J. (2016*). West Africa land use land cover time series: U.S. Geological Survey data release*. Retrieved on September 12, 2021 from https://doi.org/10.5066/F73N21JF

Tatsumi, K., Yamashiki, Y., Valmir da Silva, R., Takara, K., Matsuoka, Y., Takahashi, K., Maruyama, K., & Kawahara, N. (2011). Estimation of potential changes in cereals production under climate change scenarios. *Hydrological Processes*, *25*(17), 2715–2725. https://doi .org/10.1002/hyp.8012

Taylor, J. L, Acevedo, W, Auch, R. F & Drummond, M. A. (2015). *Status and trends of land change in the Great Plains of the United States-1973 to*

2000. U.S. Geological Survey Professional Paper 1794–B. Retrieved from http://dx.doi.org/10.3133/pp1794B

Teixeira, E. I., Fischer, G., van Velthuizen, H., Walter, C., & Ewert, F. (2013). Global hot-spots of heat stress on agricultural crops due to climate change. *Agricultural and Forest Meteorology*, *170*, 206–215. https://doi .org/10.1016/j.agrformet.2011.09.002

The Herald. (2011, September 10). Redraw boundaries of natural farming, government urged. *The Herald.* Retrieved from www.herald.co.zw.

Thornthwaite, C.W., & Mather, J.R. (1955). *The water balance*. Laboratory of Climatology Publications. Drexel Institute of Technology, *Centerton, 8,* 104.

Thornthwaite, C. W. (1948). An approach toward a rational classification of climate. *Geographical. Review* (38), 55–94.

United Nations Development Programme, UNDP (2006). *The Millennium Development Goals report 2006*. Retrieved on September 12, 2021 from http://unstat.un.org/unsd/mdg/Resource/Static/Products/Progress2006.p df.

UNDP (2013). *Human Development Report 2013*: *The rise of the South: Human progress in a diverse world*. UNDP.

UNDP (2015). *World Population Prospects. Key findings & advance tables*. Revision.

United Nations Environment Programme (UNEP). (2006). *Africa environment outlook 2: our wealth, our future*. United Nations Environment Programme (UNEP), Nairobi.

United Nations, European Commission, Food and Agriculture Organization of the United Nations, International Monetary Fund, Organisation for Economic Co-operation and Development, & World Bank. (2014). *System of environmental-economic accounting 2012: central framework.* Studies in Methods, *Series F*, *109*. Sales No. E.12.XVII.12

United Nations Framework Convention on Climate Change (UNFCCC). (1995). *The Kyoto Protocol to the UNFCCC.* In UNFCCC, Report of the Conference of the Parties Third Session (pp. 4–29). Kyoto: UNFCCC.

UNFCCC. (2010). *Education and outreach (Article 6 of the Convention).* Retrieved from http://unfccc.int/cooperation_and_support/education_and_outreach/items/2529.pp.

UNFCCC. (2019). *Land use, land-use change and forestry (LULUCF).* United Nations Framework Convention on Climate Change (UNFCCC), Bonn, Germany. Retrieved from https://unfccc.int/topics/land-use/workstreams/land-use--land-use-change-and-forestry-lulucf.

Van Wart, J., van Bussel, L. G., Wolf, J., Licker, R., Grassini, P., Nelson, A., *et al*. (2013). Use of agro-climatic zones to upscale simulated crop yield potential. *Field Crops Research*, *143*, 44–55.

Venkateshwarlu, J., Ramakrishna, Y. S., & Rao, A. S. (1996). Agro-climatic zones of India. *Annals of Arid Zone, 35*(1), 1-8.

Vincent, V., & Thomas, R. G. (1960). *An agroecological survey of Southern Rhodesia Part 1: Agro-ecological survey.* Salisbury: Government Printers.

Waugh, D. (1995). *Geography: An Integrated Approach*. Nelson, London.

Wezel, A., Bellon, S., Dore, T., Francis, C., Vallod, D., & David, C. (2009). Agroecology as a science, a movement and a practice. *Agronomy for Sustainable Development, 29(4),* 503–515.

Westerling, A. L. (2016). Increasing western US forest wildfire activity: sensitivity to changes in the timing of spring. *Philosophical Transactions of the Royal Society B: Biological Sciences, 371*(1696), 20150178. https://doi.org/10.1098/rstb.2015.0178

Williams, C.L., Liebman, M., Edwards, J.W., James, D.E., Singer, J.W., Arritt, R., & Herzmann, D. (2008). Patterns of regional yield stability in association with regional environmental characteristics. *Crop Science, 48*(4), 1545-1559.

World Bank (2007). *Agriculture for development. World development report 2008*. Retrieved on July 02, 2022 from http://hdl.handle.net/10986/5990

World Bank (2010). *Economics of adaptation to climate change:Ghana country study*. Washington D.C, USA: World Bank.

World Meteorological Organization (WMO) (2010). *International Meteorological Vocabulary* (182).

Yamba, E. I., Aryee, J. N. A., Quansah, E., Davies, P., Wemegah, C. S., Osei, M. A., et al. (2023). Revisiting the agro-climatic zones of Ghana: A reclassification in conformity with climate change and variability. *PLoS Climate,* 2(1).

Yin, R.K. (2003). Case study desearch: Design and methods. Thousand Oaks, CA: SAGE Publications.

Zhang, X., & Yang, F. (2004). *RClimDex (1.0) user manual.* Climate Research Branch, Environment Canada, 22.

Zhao, M., Pitman, A. J., & Chase, T. (2001). The impact of land cover change on the atmospheric circulation. *Climate Dynamics*, *17*(5-6), 467–477.

Zhao, C., Liu, B., Piao, S., Wang, X., Lobell, D. B., Huang, Y., Huang, M., Yao, Y., Bassu, S., Ciais, P., Durand, J.-L., Elliott, J., Ewert, F., Janssens, I.A., Li, T., Lin, E., Liu, Q., Martre, P., Müller, C., Peng, S., Peñuelas, J., Ruane, A.C., Wallach, D., Wang, T., Wu, D., Liu, Z., Zhu, Y., & Zhu, Z., & Asseng, S. (2017). Temperature increase reduces global yields of major crops in four independent estimates. *Proceedings of the National Academy of Sciences*, *114*(35), 9326-9331.