KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY, KUMASI, GHANA

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Impact of climate change and land use/land cover change on soil fertility in the cotton Basins of Côte d'Ivoire

(BSc. Geology, MSc. Soil Sciences)

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CERTIFICATION

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

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DEDICATION

This work is dedicated to God,

my father, Mr. Gaoussou KONE (of blessed memory),

my mother, Hazata FOFANA,

and my sister and brothers

Only GOD knows your contribution to this work and my life.

May HE bless you.

Thanks to you all who are the lighthouse on my way towards achieving any success in life

Abstract

The study assessed the impact of alterations in land use and land cover, as well as fluctuations in climate patterns, on soil fertility within the cotton-producing area of Côte d'Ivoire. The study entails evaluating how farmers perceive and cope with climate change, determining the current state of soil fertility, evaluating land suitability and management options for cotton production, and simulating the way the land in the region will be utilized and the vegetation that will cover it in the future. To evaluate smallholder farmers' perceptions of climate change adaptation options, a structured questionnaire with closed questions was used to collect data from 355 farmers located in the cotton basin of Côte d'Ivoire. The findings revealed that most respondents acknowledged the existence of climate change in the area and its detrimental impact on farmers' livelihoods, leading them to adopt coping mechanisms. To determine the status of soil fertility, the study analyzed 64 soil samples collected in 2013 and 2021 in the same fields where cotton was grown. Specifically, the analysis focused on the physical and chemical properties of the topsoil layer, ranging from 0 to 20 centimeters in depth. Between 2013 and 2021, the chemical properties of the soil (concentrations of Ca^{2+}, Mg^{2+}, K^{+}, and Base Saturation (BS)) saw only a slight improvement, leaving soil fertility as a significant constraint on cotton production. Targeted, site-specific soil management is necessary to address this issue. The study evaluated soil suitability for cotton cultivation in eight villages in the Côte d'Ivoire cotton basin by characterizing two representative soil profiles (0-100 cm) per village which were described in terms of their soil chemical and physical properties. The soils were "moderately suitable" (S2) or "marginally suitable" (S3) due to poor chemical properties, such as the Sum of Basic Cations (SBC) and organic carbon (OC). The study also used Landsat images to track changes in land use and land cover (LULC) between 1998 and 2020 and predicted future LULC for 2035 and 2063 using the TerrSet software and the CA-Markov chain. From 1998 to 2020, there was a reduction in the share of forestland and Savannah with each zone decreased by -11.09 % and -21.56 % respectively at Korhogo, -14.09 % and -1.78 % respectively at Ferkessedougou, -0.33 %, and -14.8 % respectively at Boundiali, and -6.9 % and -31.33 % respectively at Mankono, while water body, cropland, and settlement/bare land increased. From 1998 to 2035, the results revealed that the share of cropland and, settlement/bare land within the department continue to increase in the study area by 4.54 % and 28.2 %, respectively at Korhogo, 5.34 %, and 10.45 % at Ferkessedougou, 14.95 %, and 0.01 % at Boundiali, and 1.12 %, and 37.04 % in the zone at Mankono. From 1998 to 2063, the results revealed that the share of cropland and, settlement/bear with the department's land could continue to increase. The findings of this study could aid in improving and optimizing soil management practices within the cotton-producing region of Côte d'Ivoire.

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LIST OF ABBREVIATIONS AND ACRONYMS

AGRA: Alliance for a Green Revolution in Africa

ANOVA: Analysis of variance

BS: Base Saturation

CEC: Cation Exchange Capacity

CIDT: Compagnie Ivoirienne pour le Développement des Textiles

CIRAD : Centre de coopération Internationale en Recherche Agronomique pour le Développement

CNRA: Centre National de Recherche Agronomique

CORAF: Le Conseil Ouest et Centre africain pour la Recherche et le Développement Agricoles

ENVAL : Laboratoire de l'Environnement et de l'Alimentation de Côte d'Ivoire

FAO: Food and Agriculture Organization of the United Nations

GIS: Geographic Information System

IPCC: Intergovernmental Panel on Climate Change

INRA: Institut National de la Recherche Agronomique

INTERCOTON: Interprofessional Agricultural Organisation of the Cotton Sector

LCLUC: LULCC: Land use and land cover Change

LCSEP: Laboratoire Central Sol, Eaux, Plantes

MINESUDD: Ministère de l'Environnement et du Développement Durable

NPKSB: Nitrogen, Phosphorus, Potassium

OPA: Professional Agricultural Organisations

SEB: Sum of Exchangeable Bases

SOC: Soil Organic Carbon

SODEXAM: Société d'Exploitation et de Développement Aéroportuaire, Aéronautique et Météorologue

SOM: Soil Organic Matter

UNCCD: United Nations Convention to Combat Desertification

UNFCCC: United Nations Framework Convention on Climate Change

LCM: Land Change Modeler

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CHAPTER 1: GENERAL INTRODUCTION

1.1. Background

The Earth's climate has undergone alterations, evident in the 20th century, encompassing noticeable shifts such as the escalation of average global air and ocean temperatures, a rise in global sea levels, modifications in atmospheric and oceanic circulation, and fluctuations in regional weather patterns that impact seasonal rainfall conditions. The fundamental cause of these transformations can be attributed to the extra heat within the climate system triggered by greenhouse gases, predominantly generated by human actions such as the combustion of fossil fuels, agricultural practices, and land clearance. These actions contribute to the elevation of greenhouse gases in the atmosphere, which can trap heat, leading to severe heat waves, coastal inundation, and disruptions to rainfall patterns that pose a significant threat to both human and natural systems. Climate change also has an impact on soil, and alterations in land utilization and soil quality can either expedite or decelerate the pace of climate change. An effective response to the climate emergency, ensuring adequate food production, and successfully adapting to climate fluctuations necessitate the presence of healthier soils and the implementation of sustainable land and soil management practices (DCEEW, 2022; EEA, 2019). Land constitutes one of the most vital natural resources and provides the basis for human livelihood and well-being through the provision of multiple ecosystem services. Globally, land degradation occurring due to unwarranted land use/land cover change (LULC) is continuing to affect the landscape's multifunctionality potential, affecting the provision of ecosystem services from healthy ecosystems (Sena and Ebi, 2021). As described by Montanarella *et al.,* (2018), this research defines land degradation as an adverse trajectory in land conditions resulting from human-induced processes, both direct and indirect, encompassing factors such as anthropogenic climate change. It is characterised as a sustained decline or depletion over time of at least one of the following: biological productivity, ecological integrity, or human value. This interpretation encompasses both forested and non-forested land, with forest degradation specifically referring to land deterioration within forested regions. As stated by the IPCC (2019), soil degradation is a specific subset of land degradation processes that directly impact the soil. Land degradation is the result of human activities or processes that affect the quality and worth of the environment, particularly the land, leading to the deterioration of the natural state of the soil in any ecosystem. Land degradation, characterized as a deterioration in land quality resulting from human activities, has emerged as a significant worldwide concern from the 20th century onwards and continues to hold a prominent position on the global agenda in the 21st century. In the context of Calabar South (Nigeria), the significance of land degradation is amplified due to its direct influence on both food security and the overall quality of the environment (Eni *et al.,* 2012).

The Food and Agricultural Organization (FAO) defines land degradation as the persistent decline in the functionality and productivity of an ecosystem over an extended period. This problem has been present since the Neolithic era, around 7,500 to 10,000 years ago, which coincides with the growth of agriculture and the human population. Land degradation (LD) poses a major threat to food security, livelihoods sustainability, ecosystem services, and biodiversity conservation. The total area of arable land in the world is estimated at 7616 million acres or only 24 % of the total area of the land surface, and currently, about half of this area is cultivated (AbdelRahman,2023). Within the African continent, approximately 65 % of the overall land area is impacted by the deterioration of cultivated land, stemming from a multitude of factors including population increase, conflicts, inappropriate land management practices, deforestation, shifting cultivation, insecure land ownership, climate change, and the inherent characteristics of fragile soils found across diverse agro-ecological zones (Sean,2015). According to Dotterweich (2008), Lamourdia and Tourino-Soto (2007), and Sivakumar and Ndiang'ui (2007b), research indicates that greenhouse gas concentrations, notably carbon dioxide, and methane, have been on the rise in the atmosphere for more than 3,000 years as a result of expanding agricultural land, deforestation, and the domestication of wild animals (Ellis *et al.*, 2013). The advent of agriculture and animal husbandry played a pivotal role in fostering societal progress, political structures, and economic advancement, the expansion of agricultural land led to the depletion of forests and grasslands. Furthermore, the dependency on cultivated annual grasses for food cultivation has contributed to soil degradation as a consequence of periodic mechanical disturbances. More recently, urbanization has significantly altered ecosystems (Hermans *et al.*, 2019). The study of worldwide environmental transformations, including the decline of soil fertility, places significant emphasis on changes in land utilization and coverage, driven by the rapid growth of the tropical population. Due to the surging requirement for timber, firewood, pasture, shelter, and food crops, natural land covers, specifically tropical forests, are being rapidly damaged or transformed into farmland, posing a significant concern (Islam & Raymond, 2000).

Soil characteristics can be significantly affected over a short period due to agricultural intensification and changes in land use. There is still much ambiguity surrounding the impact of the current global climate shifts on soil alterations. The role of humans as a factor in soil formation has been a contentious topic in the field of pedology, as many soils worldwide have undergone severe changes or degradation due to human detrimental activities (Hartemink, 2003; Wu & Tiessen, 2002). The decline in soil fertility has become a significant challenge in agricultural practices within Côte d’Ivoire, especially in the cotton-producing region. There is growing attention on the influence of climate change on soil conditions and how changes in temperature, rainfall, and atmospheric composition affect them (Eric, 2012). Cotton cultivation holds substantial importance as an agricultural export commodity in Côte d'Ivoire, primarily concentrated in the central and northern regions. It contributes 1.7 % to the country's GDP, ranking fourth after cocoa, rubber, and cashew nuts (Didi *et al.,* 2018). According to Zagbaï *et al*., (2006), cotton has been crucial for the development of rural areas in the production zones since the 1970s, and despite its relatively low national importance, it remains the primary source of income for the savannah zones. According to Michael (2018), the annual average production of cotton fiber was 150,000 tonnes between 1995 and 2004. However, by the conclusion of the 2017-2018 cotton season, this figure had risen to 413,000 tonnes per year. It is worth noting that Côte d'Ivoire exports over 90 % of its cotton fiber production annually. Since 1960, the associated crop of cotton has gradually disappeared from the agrarian landscape, giving way to plots of pure cotton cultivation. In the 1960s, cotton cultivation accounted for barely 10 % of the land area, in 2002 it occupied about 49 % of the land area (Zagbaï *et al.,* 2006), cotton dominates the farming system in the Ivorian cotton basin, accounting for 63 % of the total cultivated area (Bassett, 2017). Cotton takes up on average 55% of agricultural labour time in 2002, compared to 12 % in 1960 (Le Guen, 2004). Cotton increases the duration of land use and thus reduces the length of fallow periods (Tariq et *al.,* 2022).

1.2. Problem statement

In recent years, numerous research works have examined the consequences of changes in land use and land cover (LULC) on biodiversity and land degradation (Geist & Lambin, 2002). Studies have highlighted that land use practices play a significant role in soil degradation. Past research has indicated that alterations in land use and subsequent conversions can negatively impact soil physical and chemical characteristics, ultimately resulting in land degradation (Fu et *al.,* 2010).

The fertility of soil holds crucial significance in crop cultivation, particularly in tropical regions where soil limitations can impede yields in the absence of fertilization. In Côte d'Ivoire, cotton production faces several limitations, including soil fertility reduction and unpredictable rainfall patterns, which have contributed to low yields of around 1400 kg/ha (N'goran *et al.,* 2009). The decline in soil fertility within the cotton-producing region of Côte d'Ivoire has been linked to a range of factors, such as excessive land exploitation, land pressure, and inappropriate agricultural practices (Zagbaï *et al.,* 2006). Changes in regulating processes are predominantly attributed to human activities, and comprehending the impact of human-induced land-use change at the landscape scale is crucial for a comprehensive understanding of fertility components (Pennock & Veldkamp, 2006). The conversion of deforested land for cultivation purposes, among other land-use changes, has the potential to swiftly degrade soil quality. However, the precise extent of soil fertility decline in the intricate lithology of the cotton zone has yet to be comprehensively determined. Deteriorating soil fertility has emerged as a significant concern in the agricultural management of cotton production in the cotton zone of Côte d'Ivoire. This is attributed to the gradual exhaustion of nutrients, the imbalance in organic matter, and the acidification of the soil, leading to soil degradation.

1.3. Objectives

This study sought to evaluate the impact of climate change and land use/land cover change on soil fertility in the cotton production zones notably, in the department of Korhogo, Ferkessédougou, Boundiali, and Mankono in the Northern and Central part of Côte d'Ivoire. The objective of this study was to examine whether there exist any knowledge deficiencies regarding the effects of land use and the depletion of soil organic matter, as well as if there exist any knowledge gaps on the impact of climate change and cotton yield.

The specific objectives are to:

i. assess farmers' perceptions and adaptation strategies to climate change in the Côte d ‘Ivoire cotton production zones;
ii. estimate soil fertility status in cotton-based cropping systems in Côte d’Ivoire;
iii. evaluate land suitability and management options for cotton (*Gossypium hirsutum*) production in the Côte d’Ivoire cotton production zones;
iv. model land use and land cover in the Côte d ‘Ivoire cotton production zones.

1.4. Research questions

The primary objective of this study was to investigate how climate change and land use/land cover change impact soil fertility within the cotton production zones of Côte d'Ivoire. The research focused on addressing the following specific inquiries:

i. what are farmers' perceptions and adaptation strategies to climate changes in the cotton production zones of Côte d'Ivoire?
ii. what is the soil fertility status in cotton-based cropping systems in Côte d’Ivoire?
iii. what are the land suitability and management options for cotton (Gossypium hirsutum) cultivation in the Côte d’Ivoire cotton basin?
iv. what are the future land use and land cover dynamics in the Côte d ‘Ivoire cotton production zones?

1.5. Structure of Thesis

Chapter one presents a general introduction. This contains the background, the problem statement, the objectives, and the research questions. **Chapter two** presents a review of the literature, which provides definitions of key concepts used and the state-of-art literature/information on soil fertility, cotton crop, land use, and land cover mapping methods.

Chapter three describes the local cotton farmers' perceptions of Climate Change and adaptation strategies in the Côte d 'Ivoire cotton production zones. **Chapter four** is devoted to soil fertility status in cotton-based cropping systems in Cote d'Ivoire. **Chapter five** deals with land suitability assessment and management options for cotton (*Gossypium hirsutum*) production in the Côte d'Ivoire cotton production zones. **Chapter six** deals with the dynamics of land use and land cover in the Côte d 'Ivoire cotton production zones. **Chapter seven** is devoted to the synthesis, conclusion, and recommendations.

CHAPTER 2: LITERATURE REVIEW

2.1. Definition of Key Concepts

- **Impact**: The outcomes of actualised risks on both natural and human systems arise from the interactions between climate-related hazards (including extreme weather events and climate events), exposure, and vulnerability. The impacts typically encompass effects on various aspects such as human lives, livelihoods, health and well-being, ecosystems and species, economic, social, and cultural assets, services (including ecosystem services), and infrastructure. These impacts also referred to as consequences or outcomes, can be either detrimental or advantageous. For further reference, see Adaptation, Exposure, Hazard, Loss and Damage, and Vulnerability (IPCC, 2018).

- **Land Use Land Cover**: Land cover pertains to the physical features, both natural and human-made, that encompass the Earth's surface, whereas land use encompasses the diverse range of human activities undertaken on that surface. The broader term LCLUC, as defined by Lambin and Geist (2006), encompasses alterations in land cover and/or land use resulting from human actions, including activities like agricultural land clearance, grazing, timber harvesting, abandonment of farmland, shifting cultivation, reforestation, and afforestation (Ellis *et al.* 2010).

- **Soil properties:** The constitution of soil is accountable for its characteristics, which are shaped by diverse biotic and abiotic elements present in varying proportions. The physical, chemical, and biological attributes of soil are established by the interplay of these constituents, as observed by Sapkota (2020).
- **Climate change**: According to the IPCC (2014), climate change is characterized as a notable and enduring alteration in the state and variability of the climate system, persisting for extended periods, often spanning decades or more. This change can be triggered by natural internal processes, external forces, or human-induced modifications to the atmosphere's composition or land use. While the IPCC acknowledges the contribution of both natural and human factors to climate change, the UNFCCC directly or indirectly attributes it to human activities.
- **Climate variability**: As stated by the IPCC (2014), Climate Variability is defined as fluctuations in the statistical characteristics of the climate across various spatial and temporal scales, extending beyond individual weather events. This term is commonly employed to describe deviations in climatic patterns over a specific timeframe, such as a season or year, from long-term patterns observed during the corresponding calendar period. These deviations, referred to as anomalies, serve as indicators of climate variability. The primary sources of climate variability include internal variability, resulting from natural processes within the climate system, and external variability, attributed to natural or human-induced external factors.

- **Soil fertility:** Soil fertility pertains to the capacity of soil to sustain the growth of plants and facilitate advantageous soil processes. It is influenced by the soil's chemical, physical, and biological properties. While the physical and chemical properties are well understood, the biological component is more dynamic and changes more frequently (Lyn, 2012). Soil fertility is affected by factors such as soil properties, clay minerals, and soil biology, which help to break down organic matter into nutrient forms that can be used by plants. Chemical properties like Cation Exchange Capacity (CEC) also play a role in soil fertility by determining the soil's capacity to hold cations and nutrients, as well as protect groundwater from contamination. (FAO, 2020).
- **Soil Organic Carbon**: Soil organic carbon is a measurable component of soil organic matter, typically comprising less than 10 % of the overall mass of most soils. However, it holds considerable importance in the physical, chemical, and biological processes of agricultural soils. Soils with a higher concentration of carbon are anticipated to exhibit enhanced productivity and an increased ability to filter and purify water.

2.2. Cotton crop

2.2.1. Cotton (Gossypium hirsutum) as a tropical cash crop

Cotton is a member of the Malvaceae family, which includes plants such as hibiscus, hollyhock, and okra. The plant in question is a shrub characterized by wide, three-lobed leaves and capsules that enclose seeds or bolls enveloped in soft, fluffy fibers, making them easily suitable for spinning. As the cotton fibers dry, they naturally become flattened and twisted. Cotton encompasses various species, such as Gossypium hirsutum, Gossypium barbadense, Gossypium herbaceum, and Gossypium arboreum, with the first two being the predominant ones cultivated in practice. Cotton holds substantial global significance as an agricultural commodity, with significant levels of production and consumption worldwide (Dohmen *et al.*, 2011; Hans, 2020). The term "cotton" originates from the Arabic word "al qutn," which was later adapted into the Spanish term "algodón," eventually becoming "cotton" in English. While cotton is a perennial plant, it has been domesticated to be cultivated as an annual crop (Amanet *et al.*, 2019). Cotton cultivation primarily takes place in tropical and sub-tropical regions across the globe. In Africa, cotton serves as a significant cash crop, providing a source of income for smallholder farmers. The cultivation of cotton is crucial for over 2 million impoverished rural families in Africa, enabling them to generate cash revenue (Boughton *et al.*, 2006). Cotton, a member of the Malvaceae family and the Gossypium genus encompassing nearly 50 species, holds the distinction of being the most significant fiber crop globally. The primary cultivation of cotton involves four predominant species, namely Gossypium hirsutum L., Gossypium barbadense L. (also known as Egyptian cotton), Gossypium herbaceum L. (Asiatic cotton), and Gossypium arboreum L. (Asiatic cotton). Among these species, upland cotton (G. hirsutum) stands out as the most widely grown, making up more than 90 % of global cotton production. This dominance is primarily attributed to its remarkable capacity for high yields. Cotton's historical significance dates back to the sixth millennium, with the oldest cotton fiber remains found in the Neolithic burial of the Mehrgarh region in Pakistan. The cotton plant has many valuable parts, including its fiber, which is the primary raw material for textile companies, and its seeds, which are useful for producing oil and livestock feed. Cotton fibers are also employed in the manufacturing of cellulose for industries such as textiles, plastics, and explosives. An array of significant cotton products encompass garments, gloves, bags, socks, jackets, bedding, vegetable oil, curtains, and bed-sheets. While cultivated cotton is now grown on an annual basis, it should be noted that the species originally exhibited a perennial growth habit.

2.2.2. Global Production Trends of Cotton

Cotton holds the top position as the predominant fiber crop globally and is grown across various regions of the world (Michael, 2018). Asia is the biggest cotton cultivator, accounting for 70 % of the global cotton production, while the Americas grow nearly 20 %. In terms of the total global cotton cultivation area, Africa makes up 6 % while Europe accounts for less than 2 %. Over the past six decades, the extent of cotton cultivation worldwide has fluctuated between 30 and 35 million hectares. As of 2016, the global cotton cultivation area reached 30.2 million hectares, with Asia accounting for 19.5 million hectares, North America 3.8 million hectares, South America 1.6 million hectares, Africa 4.5 million hectares, Europe 0.4 million hectares, and Australia 0.28 million hectares (Khawar & Bhagirath, 2019). Over the past few decades, there has been an expansion of cotton cultivation in Asia, Australia, and Africa, accompanied by a decline in North and South America as well as Europe. African cotton is renowned for its superior quality as it is harvested using a labor-intensive handpicking method, in contrast to the mechanized systems employed in developed nations (Jeffrey *et al.*, 2011). For cotton seeds to germinate, they require favorable temperatures ranging from 18 to 32°C and an adequate water supply of 600 to 1200 mm throughout their growth cycle (FAO, 2012). Cotton can grow in almost all well drained soils. However, suitable soils for achieving high yields are considered the deep well drained sandy loam soils, with enough clay, organic matter and a moderate concentration of nitrogen and phosphorus. The best yields are often achieved in loamy soils that are rich in calcium carbonate. A gentle slope generally helps the water drainage and is sometimes desired (Wikifamer,2017).

The cotton sector in West Africa experienced growth by expanding the cultivation of crops and increasing the land area dedicated to cotton production. This expansion, coupled with the adoption of modern inputs such as fertilizers, herbicides, insecticides, and improved cotton seeds, resulted in higher cotton yields in countries like Mali and Burkina Faso. In Africa, cotton planting typically occurs following the onset of the first rainfall. In regions with limited rainfall, farmers employ the use of balanced fertilizers and mulching techniques to mitigate excessive moisture loss during the growing season (Colin *et al.,* 2006). Monoculture cultivation of cotton with heavy pesticide and fertilizer application depletes soil nutrients and reduces yield, therefore integrated soil fertility management is required to maintain soil productivity (Kimera, 2018). The initial accomplishment of cotton in West Africa can be exemplified in Mali and Burkina Faso. Cotton yields increased in both countries from 200 to 1400 kg/ha from 1963 to 1980. This was mainly due to the increased usage of contemporary inputs like; fertilizers, herbicides, insecticides, and better cotton seeds (Amanet *et al.,* 2019).

2.2.3. Historical background of Cotton production in Côte d’Ivoire

The development of cotton in northern Côte d'Ivoire is intricately linked to the historical socio-political context of the country and the government's efforts to foster progress in the northern region. Following independence, a significant socio-economic disparity existed between the North and South, with the latter benefiting from well-established cash crops such as cocoa, coffee, and timber, while the North lacked comparable opportunities. Consequently, a considerable number of people, especially young individuals, migrated from the North to the South, transforming the North into a source of agricultural labor for plantations in the South (Ajayi *et al.,* 2009). Cotton cultivation in northern Côte d'Ivoire can be traced back to the 18th century when it was traditionally grown as a secondary crop within a mixed cropping system that included staple food crops (Hau, 1988). This approach was advantageous for farmers as it required less labor-intensive work, allowing for simultaneous weeding in the mixed-cropped fields (Konan & Atsai, 1990). The development of cotton was facilitated through collaborative efforts between the French Cotton

Development Company (CFDT) and the French Institute for Cotton and Textile Research (IRCT). The IRCT played a pivotal role in early initiatives focused on improving cotton varieties, leading to the introduction of higher-yielding cultivars that replaced the low-quality, low-yield varieties prevalent in the 1950s (Bassett, 1988). Local cotton varieties were cultivated until 1962 when they were replaced by ISA 2005, and later in 1984, by a glandless variety known as ISA GL7, developed by the former Institut des Savanes (IDESSA) (Ochou *et al.*, 1998).

The contribution of each of the main crops to the total gross value added in all five regions is shown in Figure 1. These data confirm the place of cotton in agriculture production, which contributes 48 % of the total gross agricultural value added of the five regions, as the main income-generating crop in the zone of cotton production. Cashew is a crucial crop in the area that generates significant wealth, contributing an average of 25 % of the overall agricultural value added. Although it is a recent addition to the north of Côte d'Ivoire, it has quickly become a central focus. Additionally, other crops such as maize, rice, and groundnut are also important contributors to the gross agricultural value added in the five regions analysed, although they have a relatively smaller but still significant share.

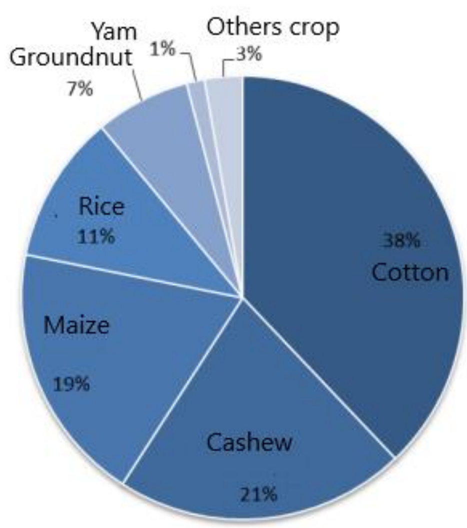

Figure 1. Relative share in the gross value added in the cotton basin of Cote d'Ivoire

During this period, the cotton cultivation area expanded to reach 400,000 hectares, positioning Côte d'Ivoire as the third-largest cotton producer in Africa, trailing behind Burkina Faso and Mali (Partheeban, 2017). The arrival of cotton led to transformative shifts in agricultural practices and farming systems, as cotton took on a prominent and crucial position in the economy of northern Côte d'Ivoire. However, the cotton sub-sector experienced a crisis in the early 2000s, resulting in a sharp decline in cotton production due to internal and external factors, including the socio-political crisis, global financial crisis, fall in fiber prices, an influx of counterfeit and smuggled textile products, leading to a drastic drop in production from 400,000 to 180,000 tons in just one year (OMC, 2016). As a result of this crisis, farmers found themselves in a precarious financial state, unable to fulfill their debts to cotton companies, thereby creating a challenging situation for the companies involved (Ajayi *et al.*, 2009).

2.2.4. Fertilizer and labor for cotton production

According to Bauer and Roof (2004), a 4-ton yield of cotton requires approximately 112 N kg ha^{-1}. Taking into account the fertilizer efficiency of sandy soils and the potential for leaching, about 140 kg ha-1 of nitrogen fertilizer is necessary. When deficient, cotton plants need up to 200 N kg ha-1 to achieve high returns, as stated by Hammad *et al.*, (2011). It is recommended that N fertilizer be applied in split doses for sandy soils that are susceptible to leaching. In addition, in Côte d'Ivoire, the recommended fertilizer doses are (200 kg ha^{-1}) of NPK (15N 15P $15K^+$ $6S^+$ 1B) and 75 kg of urea (46 % N) which equals only 65 kg N ha^{-1} (Kouadio *et al.*, 2018). Continuous cropping on the same piece of land and extension of cultivated land to marginal areas have undermined the sustainability of farming systems in the West African cotton zone (Pouya *et al.*, 2013). Fertilization in cotton cultivation aims at satisfying nutrient requirements over time, correcting the soil's current deficiencies in mineral elements, and restoring the crop's exports in the field.

Two types of fertilizers mostly used are:

- ✓ Base fertilizer, NPKSB (10N-18P_2O_5-18K_2O-6S-1B_2O_3, or 15N-15P_2O_5-15K_2O_6S-1B_2O_3) to be applied at the time of plowing or the latest 15 days after cotton sowing. The recommended dose for cotton is between 200 kg ha^{-1} and 300 kg ha^{-1} of NPK fertilizer (15-15-15 or 10-18-18) depending on the type of soil.
- ✓ Cover fertilizer, urea [$CO(NH_2)_2$] with 46 % nitrogen, to be applied 30 to 45 % days at the latest after sowing. It is advisable to apply urea at a dose of between 50 kg ha^{-1} and 75 kg ha^{-1} for cotton. The spreading of urea coincides with several other agricultural works: weeding and insecticide application for cotton cultivation, sowing or weeding maize, sowing rainfed rice, and weeding groundnuts. The dose recommended amount of urea is rarely reached by farmers (Emmanuel, 2014).

The production of cotton is a labor-intensive activity carried out by small-scale farmers who lack access to mechanised equipment. The harvesting process involves handpicking, which is a time-consuming but effective method of obtaining mature and clean cotton bolls. The cultivation of cotton in Africa is predominantly characterised by subsistence farming and is influenced by several factors, including unpredictable weather patterns, limited technological advancements, and reliance on family labour (Amanet *et al.,* 2019).

2.2.5. Climatic constraints to cotton production in Côte d'Ivoire

Agriculture in Côte d'Ivoire is mostly dependent on rainfall. Therefore, variations and fluctuations in climate can significantly affect crop yields, including cotton production (Charles *et al.,* 2018). Although cotton is relatively drought-tolerant and can produce appreciable yields in areas with less than 500mm of annual rainfall, it requires adequate moisture until maturity for optimal quality and yield. Insufficient rainfall during the vegetative stage can lead to a decline in flower and boll growth, while prolonged drought can cause flower abscission and reduce yields. Excessive moisture can also result in unwanted vegetative growth, and both insufficient and excessive moisture levels can lead to lower yields (Amanet *et al.*, 2019).

2.2.6. Socio-economic characteristics of cotton production

The World Trade Organisation (WTO) (2016) acknowledges cotton cultivation as one of the few success stories of modern African agriculture, providing a significant source of income for farmers in northern and central Côte d'Ivoire. Before the military-political crisis in September 2002, approximately 3.5 million people directly or indirectly relied on cotton cultivation for their livelihoods. Cotton was originally grown in conjunction with food crops, but has since become a major cash crop and a significant driver of the economy in the Savannah regions. The Inter-professional Agricultural Organisation of the Cotton Sector (INTERCOTON), which is comprised of agro-industrial and commercial operators represented by the Professional Agricultural Organisations (OPA), has created jobs and contributed to the development of social and community infrastructure, such as roads, healthcare centers, and schools, in the northern regions of Côte d'Ivoire. Cotton is the third-largest export product of Côte d'Ivoire, following cocoa and coffee, and generates an annual turnover of approximately 190 million USD, contributing to the country's predominantly agriculture-based economy. In the Savannah areas of Côte d'Ivoire, cotton cultivation plays a crucial role in the economy. (Zagbaï *et al*., 2006).

The growth of cotton cultivation in Côte d'Ivoire started in the 1960s after the country gained independence, and it continued to expand in the 1970s and 1980s with strong support from the Ivorian government. In the northern region of the country, where there were few cash crops compared to the forest zone that relied on cocoa, coffee, rubber, and palm oil, cotton was considered the driving force of agricultural development, becoming the leading crop in the rotation of annual crops. However, in the early 2000s, the Ivorian cotton industry faced significant structural changes that were implemented during a period of political and social unrest, leading to operational disruptions and instability. Despite being one of the most prosperous in West Africa, the industry started to decline rapidly in 2002 due to political and implementation difficulties as well as the global cotton situation. (Tillie *et al.*, 2018; Gergly, 2010).

2.3. Assessing Soil Fertility

When crops are harvested, they remove nutrients from the soil, which may cause soil fertility to decrease if it's not replenished with inorganic fertilizers or manure. This results in a decrease in soil organic carbon, pH, Cation Exchange Capacity (CEC), and essential nutrients for plant growth. Soil fertility degradation can manifest in various ways, including nutrient depletion, nutrient leaching, soil acidification, organic matter loss, and the accumulation of harmful elements like aluminum. This information comes from Hartemink's 2003 research. During the 1990s, various studies found that sub-Saharan African countries, along with other tropical countries, were facing soil fertility degradation issues. These studies primarily relied on nutrient balance or budget analysis, estimating fluxes and pools based on published data, pedotransfer functions, or other methods. Most of the studies focused on the country or subcontinental level. (Hartemink, 1996). In a notable study conducted by Stoorvogel and Smaling (1990), they analysed nitrogen (N), phosphorus (P), and potassium (K) budgets for the cultivated soils of 38 sub-Saharan African countries from 1983 to 2000. According to Hartemink (2006), in almost all sub-Saharan African countries, the amount of nutrients taken out from the soil is more than the amount of nutrients added to it. In specific areas, the decrease in soil fertility can be attributed to reduced intervals of fallow periods in shifting cultivation practices and the limited or complete absence of inorganic fertilizer application, as highlighted by Gaiser *et al.*, (2011). In some cases, soil fertility in certain areas has been maintained or even improved by transferring biomass from other lands, making it important to have sound scientific methodologies and approaches for analysing and assessing soil fertility decline. Chemical data of the soil collected from various time frames or land-use systems, which can be obtained from soil surveys, evaluations, and fertilizer programs, have not been used extensively, but recent spectroscopy techniques have significantly expanded the amount of data on tropical soils (Hartemink, 2006; Shepherd *et al.,* 2003). According to Hartemink (2006), various methods such as pedotransfer functions and soil inference systems exist to derive soil properties, but it is essential to obtain reliable data to validate and improve the models and to understand soil behavior and human-induced changes. In order to assess the degradation of soil fertility, it is essential to establish the spatial and temporal parameters of the systems under investigation, consider the available data types and their spatial and temporal variability, and employ suitable soil sampling techniques and analysis methods to yield significant findings. To ascertain whether there has been a decline in nutrient levels, pH, or Soil Organic Carbon (SOC), it is necessary to select specific spatial and temporal boundaries for the analysis. As an illustration, the spatial boundary can be defined as the specific plot under consideration, while the temporal boundary can be determined by the duration of cultivation on that plot. By establishing these defined parameters, it becomes feasible to assess whether there was a decline in soil fertility within a wheat field from 1980 to 2005 (Hartemink, 2006). There are three possibilities for changes in soil nutrient pools. The initial scenario is that the nutrient pool has grown as a result of nutrient inputs surpassing nutrient outputs, or due to a decline in nutrient outputs while the inputs have remained constant, or possibly a combination of both factors. The second scenario is that the nutrient pool maintains stability. The third scenario is that the pool diminishes, resulting in a decline in soil fertility caused by nutrient output surpassing input over a specific timeframe. This decline may occur due to a sudden increase in erosion or leaching rates or decreased nutrient inputs. The disparity between nutrient input and output is the determining factor in assessing whether soil fertility experiences a decline (Pachepsky *et al.*, 2006). Cresswell *et al.*, (2004) suggest that remote sensing can be employed to assess specific forms of soil degradation like erosion and salinisation, but its suitability for accurately quantifying a decline in soil nutrient levels remains limited. When studying soil fertility decline, three main data sources are typically used to evaluate changes in soil chemistry resulting from agricultural practices: According to Hartemink (2006), a combination of expert knowledge, nutrient balances, and monitoring of soil chemical properties are essential for assessing the situation. Collecting data from various sources can range from being straightforward to requiring long-term commitments, and each source possesses its advantages and disadvantages. The selection of a data collection approach is typically driven by the research design and financial constraints.

2.3.1. Soil analysis and soil nutrient status

Over the years, soil scientists have been exploring techniques to evaluate the availability of vital nutrients, such as phosphorus, potassium, and magnesium, to plants. Despite the presence of these nutrients in substantial amounts in the soil, not all of them are readily available for plants. Analytical procedures have been developed to determine "plant-available" nutrients, which are quick and reproducible. A dependable method for establishing fertilizer recommendations has been developed, which relies on assessing the nutrient availability in the soil. However, the accuracy of soil analysis is contingent upon the proper application of sound sampling techniques. Soil analysis can offer insights into multiple factors that impact soil chemical characteristics, including soil pH, soil organic matter content, and the presence of minerals like P, K, and Mg. These minerals may exist in distinct reservoirs within the soil, as illustrated in Figure 2. Although soil acidity usually doesn't affect crop growth directly within the pH range of 5.5-7.5, it can impact the availability of other nutrients. Soil organic matter content, which has no established critical values for most soils (Johnny, 2011), can affect soil structure and/or nutrient availability.

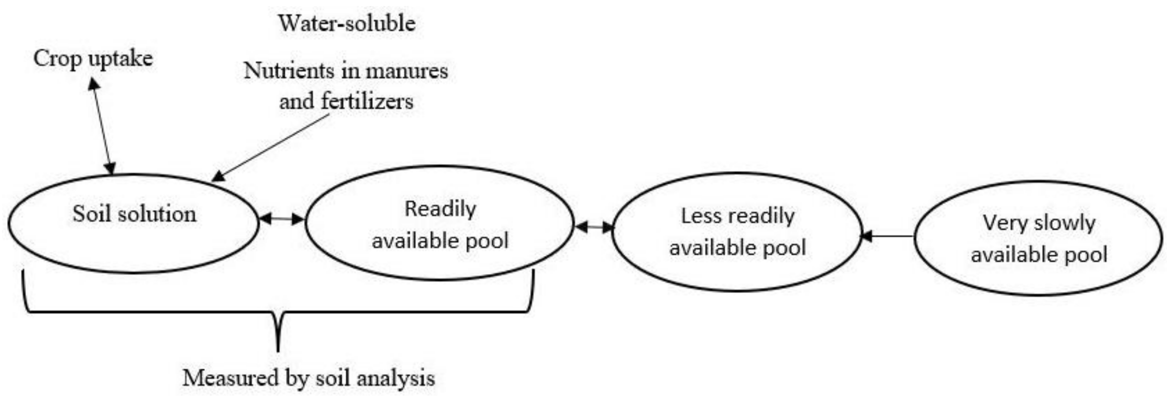

Figure 2. A simple schematic representation of the phosphorus, potassium, and magnesium soil polls reserves of differing plants (source: Potash Development Association (PDA) (2023)

2.3.2. State of soil fertility in Africa

As stated in the Soil Atlas of Africa by Jones *et al.,* (2013), soil degradation is a danger to roughly 25 % of Africa's arable land. Desertification and erosion are among the causes of this degradation, but the most significant factor is the loss of soil fertility due to the depletion of nutrients and organic matter from continuous cropping (Andriesse & Giller, 2015). The well-being of our soils is crucial for the productivity of agricultural systems, the food and nutrition security of our communities, the improvement of people's lives, and the alleviation of poverty worldwide, as emphasised by Heger *et al.,* (2018). According to Annan (2008) and Sanginga *et al.,* (2009), the investment in soil health by the Bill and Melinda Gates Foundation (BMGF) and the Rockefeller Foundation is a response to the recommendation made by the Heads of State during the African Fertilizer Summit in Abuja, Nigeria in 2006. This investment is part of the African Green

Revolution initiative being implemented by the Alliance for a Green Revolution in Africa (AGRA). The investment seeks to raise the current fertilizer utilization in Africa, aiming to increase it from an average of 8 to 50 kg nutrients ha^{-1} by 2015. The Soil Health Program of the African Green Revolution, implemented by the Alliance for a Green Revolution in Africa, strives to enhance agriculture sector growth by revitalising soil fertility and enhancing land management practices. It is projected that sustainable access to fertilizers and improved land management could increase crop productivity by 50-100 % in Africa. During the 1990s, Stoorvogel and Smaling observed patterns of nutrient loss in agricultural systems across sub-Saharan Africa. These systems experienced a decline in soil fertility, which became the main factor contributing to reduced per capita food production. On average, crop production systems in the region fall short of replenishing nutrient uptake by 20 kg/ha N, 10 kg P_2O_5, and 20 kg K_2O every year, even with manure and fertilizer application. Over the past three decades, around 660 kg of nitrogen per hectare, 75 kg of phosphorus per hectare, and 450 kg of potassium per hectare have been depleted from approximately 200 million hectares of cultivated land across 37 African countries.

Consequently, the soils in the region fail to supply sufficient nourishment for the population, leading to over 236.5 million people experiencing undernourishment in sub-Saharan Africa, with a prevalence rate exceeding 23 % (FAO, 2017). Mafongoya *et al.,* (2007) state that soil productivity can face constraints due to a range of factors, such as limited nutrient retention capacity, elevated acidity levels, insufficient organic matter, compromised soil structure, and inadequate water retention capacity. These limitations can be worsened by excessive exploitation through continuous cropping and insufficient application of nutrients. According to Stoorvogel & Antle (2001), nitrogen losses from arable land in Zimbabwe and Malawi were estimated to be 31 kg ha^{-1} and 68 kg ha^{-1} respectively. Bationo *et al.,* (2003) reported that Swaziland, Mozambique, and Madagascar experience annual NPK losses exceeding 60 kg ha^{-1}, while Lesotho has losses ranging from 30 to 60 kg ha^{-1}.

2.3.3. State of soil fertility in Cote d'Ivoire

Birmingham (2003) notes that the soils in Côte d'Ivoire are composed of fine-textured soils formed from metamorphic rocks of the Basement Complex. These soils have not undergone rejuvenation due to tectonic activity, making them old and highly weathered. Typically, the degree of fertility depletion in these soils increases in the southward direction. In the southern zone, after more than 50 years of cocoa farming (*Theobroma cacao*), soil fertility has deteriorated to the point where the productivity of cocoa plantations has declined. To mitigate this declining soil fertility and encourage cocoa productivity, farmers must use organic and mineral fertilizer according to best fertilization practices: which require in-depth knowledge of soil composition (Kassin *et al.*, 2010).

2.4. Assessing changes in land use/land cover in the cotton production zone

2.4.1. Land-use changes based on cotton plots by satellite image processing

To accomplish this objective, the research employed remote sensing data and geographic information systems (GIS) to generate a comprehensive map illustrating alterations in land use and land cover attributed to human activities and their influence on cotton cultivation. The efficacy of employing remote sensing and GIS in land use mapping has been substantiated by several investigations (Bal *et al.*, 2018). However, since remote sensing data alone may not suffice to identify land use trends in cotton production, the study adopted a collaborative approach between remote sensing and other techniques.

2.4.2. Data sources and image pre-processing

In order to fulfill the research objectives, this study utilised past satellite imagery of land use and land cover (LULC) within the designated region from 1998, 2009, and 2020. These images were employed to analyse the land use patterns and evaluate the effects of agricultural land use transformations, such as the conversion of forested areas into cropland. The study primarily used Landsat 7 and 8 OLI images, which have the world's longest collection of space-based land remote sensing data, with additional data from other sensors when necessary to account for poor quality Landsat images (Wu *et al.*, 2008). The images were captured during the dry season (December to March) from the US Geological Survey website to enhance surface features and minimise the impact of vegetation. The research also rectifies radiometric and geometric errors that may have arisen due to sensor and atmospheric effects.

2.4.3. Images classification

In this study, a supervised classification was used. Supervised classification is a technique that aims to define classes based on their similitudes to a set of clearly identified training areas that have been characterised spectrally (Foody, 2002). The primary objective of this study was to use supervised image classification to identify agricultural land each year by analysing the images captured between December and March. This process included creating a signature for supervised classification, selecting band combinations, and labeling pixels using a maximum likelihood classifier. The signature for supervised classification was established based on local knowledge and satellite imagery.

2.4.4. Impact of land use/land cover (LULC) changes on soil degradation

Land degradation is a significant global concern as it has the potential to negatively affect the environment and food security. Human actions such as deforestation, clearing vegetation, excessive grazing, and farming practices without erosion control measures all contribute to the degradation of land. Modifications in land utilisation and land coverage, such as the transformation of native grasslands or forests into cultivated fields or grazing areas, leading to the depletion of biomass, modify vegetation, and disrupted soils, resulting in the depletion of soil carbon and other nutrients, as well as alterations in soil characteristics and biodiversity. Certain transformations in land coverage, such as the establishment of forests following the abandonment of cultivated areas, have the potential to enhance carbon and nutrient levels in both above-ground and below-ground components. The alteration of land use has been expedited by population growth and migration, driven by the need for sustenance, habitation, and resource acquisition. Croplands and grasslands, encompassing both natural grasslands and managed grazing lands, account for 13.0 % of the total land area. Managed forests and naturally tree-covered regions constitute 28 %, while areas covered by shrubs make up 9.5 %. Artificial surfaces, which include urbanised areas, occupy 1 % of the land. Land management practices that do not result in a modification of land cover, such as forest harvesting and regrowth, intensified grazing, and crop cultivation, have the potential to cause soil degradation, depending on the specific characteristics of these practices. Land degradation is a widespread problem affecting all types of land cover. About 24 % of the Earth's land area (equivalent to 35 million square kilometers) is currently degraded. According to Bai *et al.* ,(2008), around 23 % of degraded land is covered by broadleaved forests, while 19% is under needle-leaved forests, and approximately 20-25 % is located in range-lands. According to Teferi *et al.*, (2016), changes in land use and land cover (LULC) are clear and easily identifiable signs of human activities taking place on the land. As a result, Africa is responsible for 65 % of the overall extensive degradation of croplands worldwide. The primary factors contributing to land degradation in Africa include demographic growth, conflicts, and wars, improper soil management, deforestation, shifting cultivation, land tenure insecurity, variability in climatic conditions, and inherent characteristics of vulnerable soils found in different agro-ecological zones (Sivakumar *et al.*, 2007a). The quality of soil is impacted by changes in land use and land cover, according to Amarendra *et al.* (2014). Maximillian *et al.*, (2019) define soil degradation as the decline in land productivity resulting from a reduction in soil fertility, degradation, and loss of soil biodiversity. The degradation of land and soil encompasses several processes such as soil erosion, loss of soil cover, salinification, acidification, and compaction. The severity of soil degradation and its remediation options vary depending on the type of degradation process. For instance, soil erosion and salinification are extremely severe as they may force farmers to either abandon their land or incur substantial management costs to continue cultivating it (Gomiero, 2016). The influence of human activities on soil properties can vary depending on the specific land use practices employed. Activities such as plowing, grazing, harvesting, fertilizing, and others can modify the chemical and physical attributes of the soil. Numerous studies have demonstrated the relationship between land use and soil properties, particularly concerning soil nutrients and carbon sequestration (Debela *et al.*, 2015). Land degradation is a multifaceted occurrence influenced by diverse elements, including physical, socio-economic, and political factors, as well as unsustainable agricultural methods. The cultivation of land in areas that have been deforested or are unsuitable can lead to a rapid decline in soil quality, as important ecological components of the environment cannot counteract the negative impacts (Alemu, 2015). To summarize, soil degradation can cause permanent damage to land productivity, leading to an increase in agricultural costs. Soil degradation can arise from a range of factors, including agricultural, industrial, and commercial pollution, urban sprawl, excessive grazing, unsustainable agricultural methods, and prolonged climate shifts (Yifru *et al.*, 2011).

2.4.5. Land suitability assessment for cotton growing areas using remote sensing

To evaluate the land quality for cotton cultivation in the savannah zone, satellite images and soil investigations were utilised. The study concentrated on the monitoring of soil processes that impact land quality using satellite information to identify the most suitable areas for growing cotton. The investigation also identified the existing land qualities of cotton-growing areas through the use of satellite images and soil resource maps. Additionally, soil studies were conducted in specific locations to describe the land quality (Mohammed *et al.,* 2015). Sys *et al.,* (1993) identified multiple factors that can influence the appropriateness of land for cotton cultivation and compiled a database incorporating different aspects including landforms, slope, rainfall patterns, soil pH, calcium carbonate content, available phosphorus levels, organic matter content, cation exchange capacity (CEC), soil texture, and soil depth.

2.5. Summarized the literature review

In conclusion, soil degradation poses a significant global concern with adverse impacts on the environment and food security. Human activities, such as deforestation, vegetation clearance, overgrazing, and inadequately controlled agricultural practices, contribute to this issue. In Côte d'Ivoire, cotton cultivation plays a vital role in the economy, accounting for 48 % of the agricultural sector's total gross value added. However, meeting cotton's fertilization needs remains challenging, leading to a decline in soil fertility in the cotton-growing region. To address this critical situation, a comprehensive approach that combines expert knowledge and soil chemical monitoring is necessary. It involves evaluating land degradation, implementing measures to mitigate fertility decline, and enhancing cotton productivity. Achieving these goals requires assessing perceptions and adaptation strategies of cotton producers to climate change, studying soil fertility evolution in cotton-based cropping systems, evaluating land suitability and management options, and quantifying the extent of land degradation through land use and occupation modelling.

CHAPTER 3: EVALUATION OF FARMERS' PERCEPTIONS AND ADAPTATION STRATEGIES TO CLIMATE CHANGE IN THE CÔTE D ‘IVOIRE COTTON BASIN

3.1: Local Cotton Farmers’ Perceptions of Climate Change Events and Adaptation Strategies in the Cotton Basin of Cote d'Ivoire

This is based on: Ismail Koné[1], Wilson Agyei Agyare[2], Thomas Gaiser[3], Nat Owusu-Prempeh[4], Konan-Kan Hippolyte Kouadio[5], Emmanuel N’Goran Kouadio[6] & William Amponsah[2]. (2022): Local Cotton Farmers’ Perceptions of Climate Change Events and Adaptation Strategies in Cotton Basin of Cote d'Ivoire. *Journal of Sustainable Development*; Vol. 15, No. 3; 2022 ISSN 1913-9063 E-ISSN 1913-9071. doi:10.5539/jsd. v15n3p108

Abstract

Climate change represents a major potential threat to the viability of rural households’ livelihoods in sub-Saharan Africa. This study focused on the perceptions of climate change and adaptation strategies of local cotton farmers in Côte d'Ivoire, identified as particularly vulnerable to climate change. A survey was conducted among 355 smallholder farmers distributed in four departments of the cotton basin of Côte d'Ivoire (Korhogo, Boundiali, Ferkessédougou, and Mankono). Using changes in the weather pattern as indicators of climate change, the results showed that the majority of respondents believe climate change is evident in the study area and has negative effects on their livelihoods. Respondents reported an increase in temperature and a decrease in rainfall amounts in Korhogo and Boundiali departments, which were consistent with the climate data. The main coping strategies adopted by the farmers were shifting planting dates and timing of cultural activities, adopting new crop varieties, ploughing before planting, diversifying crops, and making specific sacrifices to divine powers depending on the type of belief of the farmer. The farmers’ adoption of adaptation strategy depended on their perception of climate change and the available

coping strategy. Lack of sufficient knowledge and government support were the major constraints that hindered cotton farmers to adapt effectively, leading to low cotton productivity in the study area. Therefore, policy implications will be crucial to help farmers make better adaptation choices in the face of climate change.

Keywords: climate change, farmers' perceptions, adaptation strategies, cotton crop, Côte d'Ivoire

3.2. Introduction

Natural disasters caused by climate change phenomena and disturbances have heavy influences on agriculture (Agossou, 2008). Climate change is an increasingly perceptible threat to the viability of rural households' livelihoods in sub-Saharan Africa, particularly where communities depend mainly on the exploitation of natural resources (Kabore *et al*., 2020). The climate is the main determinant of agricultural productivity and greatly influences food production and the economy as a whole. Therefore, the potential effects of climate change on agricultural productivity are of great concern (Doumbia and Dipieu, 2013). Direct consequences on agriculture are shorter average growing seasons, droughts, reduced productive potential of ecosystems, lower crop yields, and expansion of bare areas (Belem *et al*., 2018; PNIA, 2014; Bambara *et al*., 2013). In addition, changes such as rising temperatures and changing rainfall patterns are likely to lead to an acute decline in rainfed crop production in some African countries (IPCC, 2013). These climate changes exacerbate the existing vulnerabilities of the poorest people due to their limited adaptive capacities and high dependence on climate-sensitive resources such as water resources and agricultural production systems that rely on semi-subsistence production for survival (Assoumana *et al*., 2016; Agossou *et al*., 2012).

Like most developing countries, agricultural production remains the main source of livelihood for most rural communities in Côte d'Ivoire. It plays a crucial role in the country's economic development and contributes significantly to the gross domestic product (GDP). Cotton cultivation is the fourth largest agricultural export after cocoa, rubber, and cashew nuts and contributes 1.7 % to the nation's GDP (Didi *et al*., 2018). It is the lung of the economy in the rural north of Côte d'Ivoire and directly supports 180,000 producers, or about 2.5 million inhabitants (Oudin, 2020). Unfortunately, the agricultural sector is very dependent on climate conditions which are characterized by unreliable and erratic rainfall patterns. The Far North covers an area of 164,861 km² and accounts for 51.12 % of the national territory, with an estimated population of 4,106,735 million inhabitants in 2014. It consists of 11 regions (Bafing, Bagoué, Béré, Bounkani, Folon, Gontougo, Hambol, Kabadougou, Poro, Tchologo, and Worodougou). This region encompasses the poorest areas of the country, characterized by a low population density per square kilometer, low human development, and inadequate socio-economic infrastructure."

The economy of this vast area is primarily centered around cash crops (cashew nuts, mangoes, cotton, and sugarcane) as well as subsistence crops such as rice, corn, millet, yams, cassava, and peanuts. Livestock farming, including cattle, pigs, sheep, goats, poultry, and some fishing activities, also contributes to the economy. Additionally, these regions hold significant natural resources such as copper, gold, manganese, nickel, bauxite, monazite, and colombo-tantalite (Francine,2022).

The agro-climatic parameters present constraining features for agriculture, especially in the far north, which sometimes experiences severe droughts (MINESUDD, 2013). Recent studies (Agoh *et al*., 2021; Dekoula, 2020) have shown that the climatic system of Côte d'Ivoire is characterised by a reduction in rainfall trends, a reduction in the length of the agricultural season, persistence of negative anomalies, and an increase in minimum temperatures. These have modified rainfall patterns and agricultural production systems. Despite the increase in strategic adaptation measures and resources devoted to promoting sustainable land management and increasing agricultural productivity by the government of Côte d'Ivoire, cotton producers still face many challenges, including declining seed cotton yields. A larger proportion of cotton farmers in the northern region are already facing the effects of climate change in the form of climatic hazards, declining soil fertility, declining yields, and the impact of pests and diseases on the cotton crop (Zagbaï *et al.*, 2006). This phenomenon compromises the development of rain-fed agriculture and therefore makes farmers vulnerable in terms of food security. There is an urgent need to adopt mitigation measures and develop new policies to avoid the worst effects of climate change (Willbanks *et al.*, 2007).

Assessing the perceptions of cotton farmers on climate change and their adaptation strategies could be the first step toward reducing the impacts of climate change on cotton productivity. To achieve this, it is essential to have data on the climate and to define relevant adaptation measures based on those developed locally. This requires a process based on a comprehensive analysis of the situation, the development of an appropriate action plan that takes into account the perceptions and suggestions of local populations, and the political will to determine the priority of the required actions (Agossou, 2008).

Moreover, studies on the impact, mitigation, and adaptation to climate change in recent times have been in the spotlight of the media. This is because climate change events have fueled several political and scientific debates, being the subject of many scientific investigations. According to (Lobell *et al.*, 2008), one of the main reasons for the vulnerability to climate change observed in Sub-Saharan Africa is the heavy dependence of their economy on predominantly rain-fed agriculture. Famers also perceive climate change through its negative impacts on agricultural production and the natural environment. Indeed, West African farmers emphasise that the drop in rains, increase in temperature, more frequent heat waves, and strong winds explain between 30 and 50 % of the decrease in agricultural production depending on the crops and area (Mertz *et al*., 2010). Also, the Sudan Savannah region which forms, a vast portion of the northern area of Côte d'Ivoire, is not immune to the reality of this phenomenon (Adaman, 2016). In response to the negative consequences of climate change, African farmers have adopted adaptation strategies, the most common of which in Burkina Faso are: varietal adaptation, the use of soil and water conservation techniques, the use of organic manure, and modification of sowing dates (Ouédraogo *et al*., 2010). Indirectly, climate change is also manifested at the level of agricultural labour, the prices of agricultural commodities; and agro-industrial processing units (MEPN, 2008). Taking into account these uncertainties and the enormous threat to the livelihoods of farmer households, producers in vulnerable areas develop in one way or another other strategies to improve their survival.

As observed by Ruault (2007), farmers' practices, the technical choices they make, and the changes associated with them in the face of the negative impacts of climate change are only intelligible in terms of their understanding. However, to date, little is known about how local farmers in the cotton basin of Côte d'Ivoire perceive the phenomenon of climate change and the disparities in adaptation skills between farmers, and whether these perceptions are consistent with measured climate observations. A study combining aspects of climate change perception and endogenous adaptation strategies of cotton farmers in the Ivorian cotton basin is needed to fully understand how rural communities in the cotton basin are coping with the adverse consequences of climate change.

Consequently, this study is designed to assess the perceptions of cotton farmers, who are exposed to the adverse effects of climate change, daily and assess the local measures they are developing to combat this phenomenon. This study highlighted the limitations in adaptation strategies that prevent cotton producers from adapting effectively. The objectives of this study were therefore to (i) analyse the past dynamics of climatic parameters in the study area (ii) assess the perceptions of climate change by local cotton farmers in the cotton basin of Côte d'Ivoire (iii) examine the adaptation strategies of the cotton farmers in the face of climate change.

3.3. Material and Methods

3.3.1. Description of the Study Area

The study was conducted in four cotton-producing departments of Côte d'Ivoire. These are Korhogo, Boundiali, and Ferkessédougou of the Northern cotton basin and Mankono department of the Central cotton basin (Figure 3). The Northern and Central cotton basins are the two most important cotton production areas out of the five cotton basins of Côte d'Ivoire. The study area is located between longitudes 2- °30'-and 8 °- 30'- West and latitudes 6 °- 50'- and 10- ° 30'-North and covers an area of approximately 201,693 km² out of the country's 322,462 km² (Dekoula, 2019). Two rainfall regimes characterize these zones: the tropical transition regime and the equatorial attenuated transition regime. Three classes of soils are distinguished in this zone: tropical ferruginous soils, and hydromorphic soils and, soils on basic rocks (Koné, 2007). The vegetation of the study area is subdivided into three main types namely, (i) the Forest Zone in the central western part (ii) the Guinean Savanna zone in the eastern part, and (iii) the Sudanian Savanna Zone in the northern part. Three of the country's four main rivers: Sassandra, Bandama, and Comoé flow through the Ivorian cotton basin. They flow from North to South (Dekoula, 2019). These four departments were selected for the study because the areas are subject to strong climatic variations and have, therefore, been identified as the most vulnerable agro-ecological zones (MINESUDD, 2013). As agriculture in this area had been severely compromised by climatic variations, it was important to conduct the study in the area to help provide the various actors with effective tools for their decision-making.

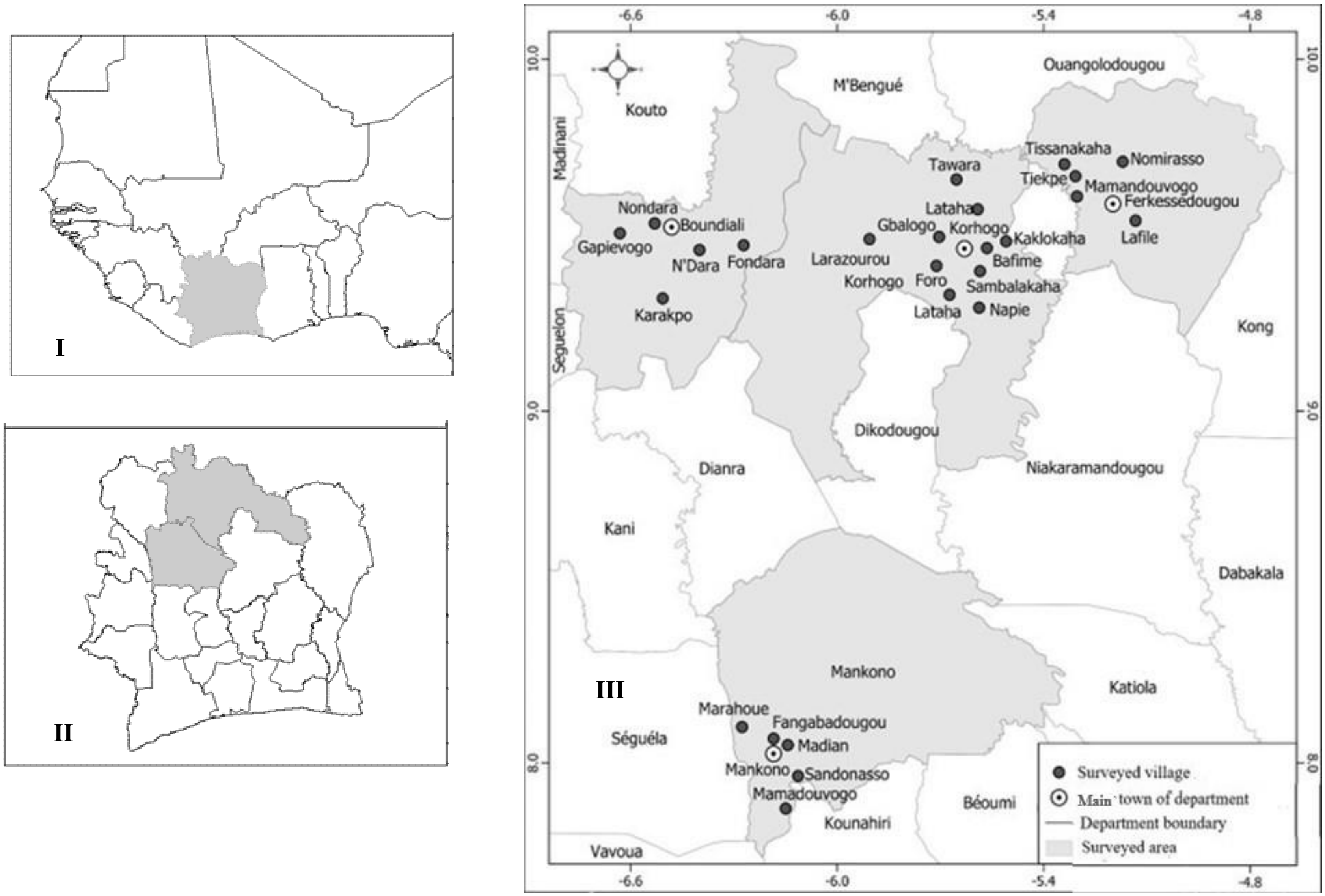

Figure 3. Study area showing the cotton production basin and location of the surveyed village in Cote d'Ivoire

I: West Africa map; **II**: Cote d’Ivoire map; **III**: Study area map

3.3.2. Meteorological Data

The two main meteorological data used were rainfall and temperature. The rainfall data provided in this study are sourced from the Société d'Exploitation et de Développement Aéroportuaire, Aéronautique et Météorologue (SODEXAM). This meteorological data is a secondary source of data because it was collected by agents present at the meteorological stations which cover the study region. These were supplemented by those from the database of the Central Soils, Water, and Plants Laboratory (LCSEP) of the National Agronomic Research Center of Cote d'Ivoire (CNRA). The data has a sufficiently long series to show the evolution of rainfall over a long period and the intra-seasonal rainfall descriptors. The temperature data was downloaded from the Google engine (ERA5 Copernicus ECMWF). The climate data spans the period from 1970 to 2020.

3.3.2.1 Methods of Demonstrating Climate Change

Tests for the detection of breaks in rainfall and temperature series were developed to demonstrate climatic variability within a chronological period (Fossou *et al.*, 2014). Indeed, a break is defined as a change in the probability law of random variables whose successive realisation defines the time series studied (Servat *et al.*, 1998). In this study, for the detection of ruptures, we applied the Pettitt test. The Pettitt test is non-parametric and derives from the Mann-Whitney U test. The absence of a break in the series (Xi) of size N constitutes the null hypothesis. The implementation of the test assumes that for any time t between 1 and N, the time series (Xi) from i=1 to t and from t+1 to N belong to the same population. The variable to be tested is the maximum absolute value of the variable $U_{t,N}$. Pettit's variables (U) are defined by the following equation:

$$U = \sum_{i=j} \sum_{j=t+1} D_{ij} \qquad (1)$$

where: Dij = sgn (xi-xj) with sgn (x) = 1 if x> 0, 0 if x = 0 and -1 if x <0.

The probability (Prob) of exceeding a value k is defined and makes it possible to assess the importance of the break. Prob (kn> k) ≈ 2 exp / Prob (kn> k) ≈ 2 exp ($-6 k^2 / n^3 + n^2$) the absence of a break in the series of size

N constitutes the null hypothesis. If the null hypothesis is not rejected, an estimate of the date of the rupture is given at this moment, defining the maximum in the absolute value of the variable U.

3.3.2.2. Survey of Farmers' Perception and Adaptation Strategies

Sample Size

In total, a sample size of 355 respondents (farmers) was drawn from 27 villages in the four departments of the study area (Table 1). The target populations for this study were cotton farmers in the department of (Korhogo, Boundiali, Ferkessédougou, and Mankono) cotton basins of Cote d'Ivoire. The sample size (n) proportion from each department was determined using the equation developed by Krejcie & Morgan, (1970) as follows:

$$\mathrm{n} = \frac{x^2 Np(1-p)x^2}{e^2(N-1)+x^2\,p(1-p)} \qquad (2)$$

where n represents the sample size, N represents the population size, e is the acceptable sampling error, X^2 represents the chi-square of the degree of freedom 1 at a confidence of 95% (which is 3.841) and p is the proportion of the population (i.e 0.5 if unknown).

3.3.2.3. Data Collection Procedure

The study used both quantitative and qualitative information. A structured questionnaire with closed ended questions was administered to respondents on smartphones via the "KoboCollect" application to collect information. Data were collected in 2021 through a field survey by face-to-face interviews with cotton farmers. Data and information collected include perceptions of changes in rainfall amount, length of the growing season, temperature, wind strength, socio-demographic characteristics of climate change, and farmers' adaptation strategies over the past 30 years. The indicators of the phenomenon of climate change are the meteorological parameters whose evolution over time reflects climate change over the last 50 years. The majority of the questions involved items or statements designed in a closed format where respondents had multiple-choice answers to select as applicable while a few of them were open-ended questions. Thus dichotomous, multiple-choice, and five-point Likert-scale formats were employed in designing the closed-ended questionnaire. The adopted dichotomous closed-ended questioning format was in the form of a ‘Yes’ or ‘No’ response type and the Likert scale format provided a response scale in which respondents specify their level of agreement to a statement with five options: (1) Strongly disagree; (2) Disagree; (3) Neither agree nor disagree; (4) Agree; (5) Strongly agree. These questioning methods were employed to reduce the number of responses by limiting the respondents and to produce data that could easily be statistically analyzed. Moreover, the Likert-scale questionnaire type allows for testing of the reliability and validity of the key constructs of the study (Dawes, 2008; Sachdev & Verma, 2004; Saleh & Ryan, 1991). During the survey, the perceptions of individual farmers with similar socio-economic conditions, belonging to the same social network, or having farms within a given landscape unit were measured. This type of perception measurement took into account live experiences or future expectations and was related to the goals, wants, and needs of the farmer (Agossou, 2008). Before the actual survey, the questionnaires were pre-tested using 50 respondents with a similar socio-economic background to the respondents of the study to test for the validity and reliability of the data collection instrument. This led to minor modifications of the questionnaire to improve understanding and capture perceptions not included in the initial questionnaire.

Table 1. Distribution of respondents in the different departments of the study area

Department	Villages	Number of villages surveyed	Number of cotton producers
Mankono	Marahoué	5	20
	Sandonasso		17
	Mamadouvogo		20
	Midian		17
	Fangabadougou		10
Korhogo	Tawara	10	20
	Lataha		20
	Kaklokaha		7

	Bafime		6
	Sambelakaha		3
	Fahala		4
	Foro		11
	Larazourou		13
	Gbalogo		10
	Napie		4
Boundiali	N'Dara	6	15
	Ponondougou		12
	Fonondara		10
	Nondara		10
	Karakpo		16
	Gapievogo		16
Ferkessédougou	Tandokaha 1	6	17
	Dekokaha		17
	Momirasso		16
	Tiekpè		14
	Mamadouvogo		15
	Tiassanakaha 2		15
Total		27	355

3.3.2.4. Ethical Consideration

Ethical approval was sought from the School of Graduate Studies Board Ethics Committee of the Kwame Nkrumah University of Science and Technology, Kumasi to conduct the study. Permission was sought from the Management of the cotton companies operating in the study sites. The purpose and importance of the study were disclosed to the authorities and participants. Oral consent was sought from participants before the study started and respondents were assured of the confidentiality of the information they provided. Participants were not financially induced or coerced to take part in the study as it was explained to them that their participation was purely voluntary. Thus, the study was guided by the Belmont guideline (Belmont, 1979) concerning fairness in the selection of participants, consent to participate in studies, and efforts were made to reduce risks or harm to participants.

3.3.2.5. Statistical Analysis

The XLSTAT statistical software, (version 2021.5) was used for the detection of breaks in the rainfall and temperature series. The valid responses gathered at the end of the survey period were extracted and analysed quantitatively in line with the research objectives. Descriptive and inferential analytical methods were employed to analyse the data with SPHINX (Ver.5.1) software at a statistical significance of 5 % error (0.05), i.e., at a 95 % confidence level. Descriptive statistics were used to analyse the socio-economic profile, farmers' perception of climate change, and adaptation strategies of the surveyed households. The internal validity of the Likert-scale results was tested with Cronbach's alpha reliability ($\alpha = 0.69$). This suggests that the data collection instrument is 69 % reliable and will produce the same results if the study is repeated. The percentages and distributions of the characteristics of the smaller holder cotton farmers were determined with univariate and bivariate analysis. Pearson's chi-square was used to test and describe the relationship between the independent socio-economic and demographic categorical variables. The cross-tabulation obtained by calculating the mean and standard deviations allowed the analysis of local perceptions of climate change and adaptation strategies. Details of the procedure are presented in the following flowchart (Figure 4).

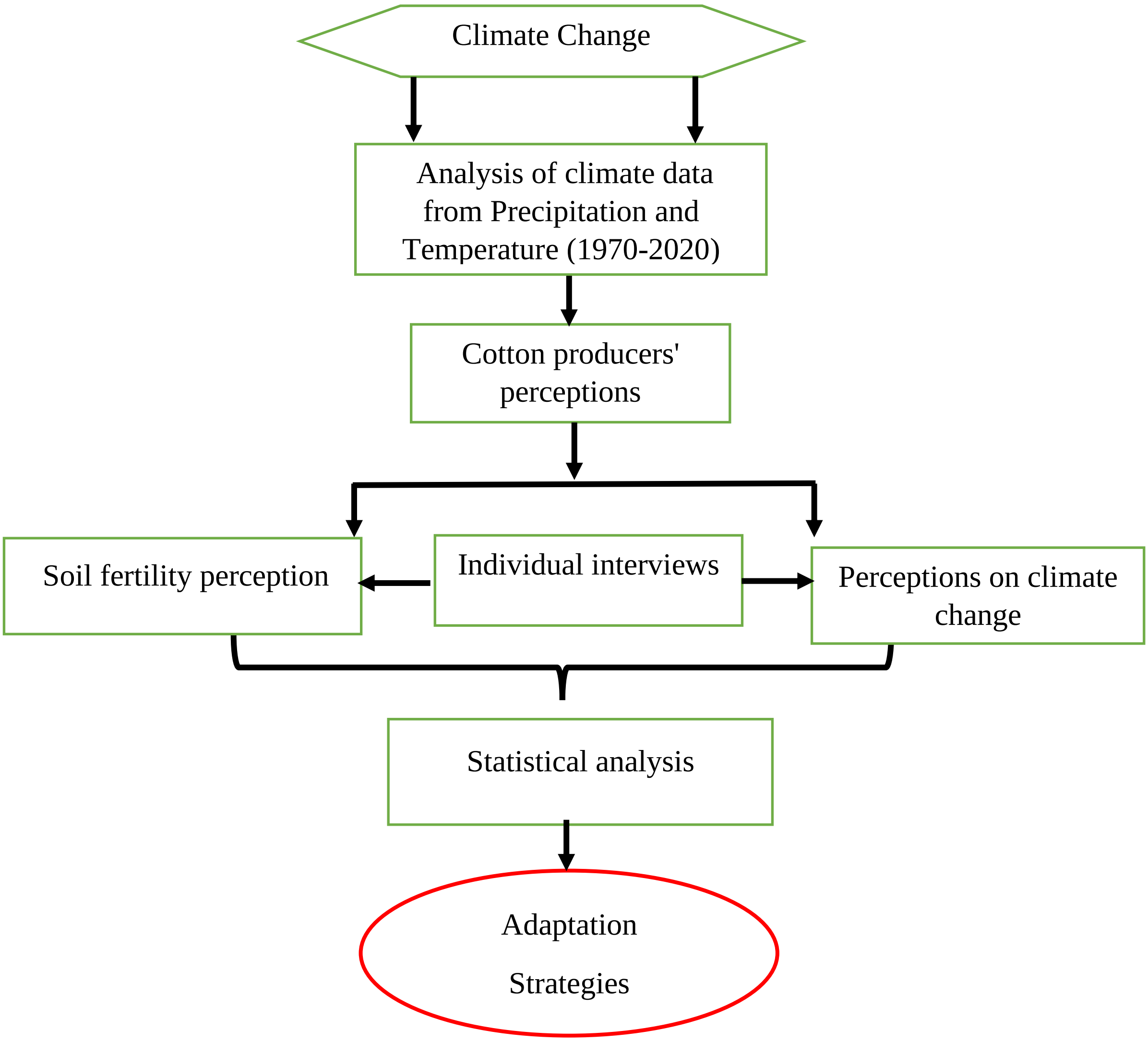

Figure 4. Conceptual framework of the research methodology

3.4. Results

3.4.1. Socio-Economic and Demographic Characteristics of Cotton Producers

The results of the analysis of the socio-economic and demographic characteristics of the cotton farmers are shown in Table 2. The parameters were: age, gender, marital status, level of education, experience in cotton cultivation, mode of access to the plot, and the economic activities carried out. The results showed that cotton cultivation is an activity mainly practiced by men, i.e., 99.4 % against 0.6 % of women in the surveyed areas. The ages of these producers were between 20 and 70 years with an average age of 45 years. The age group between 40 and 50 years was the majority (38 %) in this study while almost all the respondents were married (98.9 %).

Table 2. Socio-economic and demographic characteristics of cotton farmers

Variables	Percentage (%)
Age	
Below 20	0.3
20-30	3.7
30-40	26.2
40-50	38.0
50-60	21.1
60-70	9.6
Above 70	1.1
Gender	
Male	99.4
Female	0.6
Marital Status	
Married	98.9
single	30.9
widower	0.3
Education	
No Formal Education	72.1
Primary school	20.9
High school	5.4
Quranic school	1.6
Access to cultivation plots	
Inheritance	59.40
Rental	19.20
Loan	13.50
Donation	7.90
Farm power	
Manual labour	92.4
Animal traction	7.6
Source of farm labour	
Family	72.3

Hired	55.5
Experience	
Less than 10 years	14.9
10-20 years	24.5
20-30 years	30.1
30-40 years	19.4
40-50 years	8.5
50-60 years	2.3
Above 60 years	0.3

3.4.2. Endogenous perceptions of Climate Change Indicators

3.4.2.1 Change in Precipitation Indicator

Climate variability is a reality in the Ivorian cotton zones. Local farmers remember abundant and regular rainfall in the past and long rainy seasons. These rains could last several hours during the day. Currently, cotton producers are seeing a disruption in the rainy season. This can be seen, according to cotton growers, in a shorter duration of the rainy season (99.4 %), a decrease in the number of rainy days (98.9 %), and a decrease in rainfall (98.6 %). Respondents perceived the rainy seasons have a late start (91.3 %) while other cotton producers perceived the rainy seasons have earlier onset (7.9 %). According to the producers, the changes in rainfall patterns do not manifest themselves in the same way during the year, there were months where the decrease in the number of rainy days was significant. In general, the respondents reported that the decrease in the number of rainy days was pronounced in the period from March to June with a peak in May and June. This observed decrease in the number of rainy days differed from one area to another. For example, in Boundiali, the decrease was more observed in January, February, March, and May while in Ferkessédougou, the months from March to July were the most affected by this decrease in the number of rainy days. In Korhogo, the months of May and June were the most frequently mentioned whereas, in Mankono the month of May alone was affected by the decrease in the number of rainy days. Regarding the decrease in the amount of rainfall, the farmers reported that this was generally observed between April to June although there were variations in the response from one locality to another. The months from April to August were the most frequently mentioned in Boundiali, while in Ferkessédougou, it was rather the months of March and June that were of concern. Finally, in Korhogo and Mankono, the months from May to September were affected by decreasing amounts of rainfall.

3.4.3. Endogenous Perception' perceptions of soil fertility status

Soil fertility is severely tested with the development of cotton cultivation (extension of cultivated areas, reduction of fallow time). Sixty-seven percent against thirty-three percent of cotton producers said that their soil has become impoverished. This soil poverty depends on the localities visited (Figure 5). As shown on the map soil degradation is more pronounced in Ferkessédougou, a department further north of the study area than in the others. In this locality, 99 % of cotton growers affirmed that their soils were no longer suitable for growing cotton against 81.4 % in Korhogo, 70.7 % in Boundiali, and 20.9 % in Mankono.

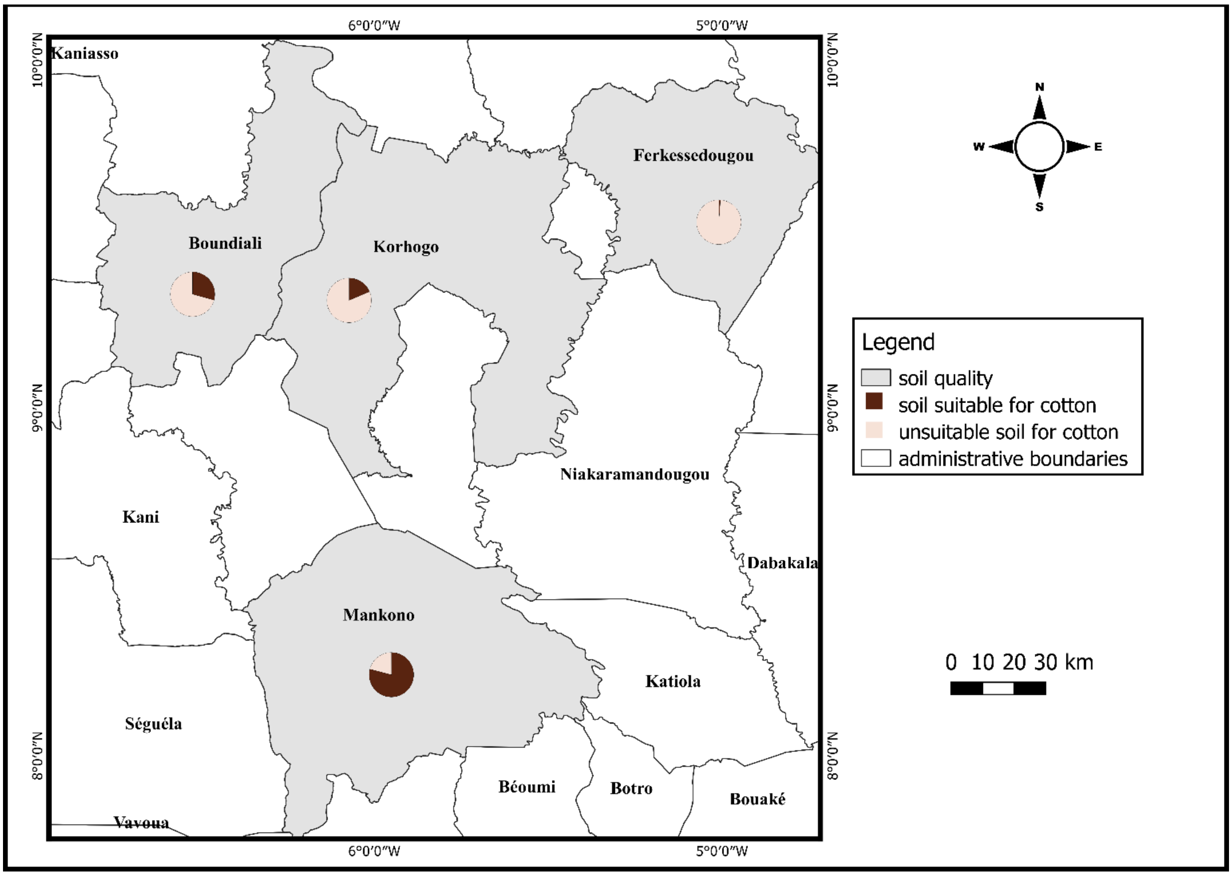

Figure 5. Cotton farmer's perception of soil fertility status in each department of the study area

3.4.4. Endogenous perception of land degradation indicators by cotton growers

Cotton producers highlighted eight indicators of land degradation. Inappropriate cultivation practices (64.8 %), agricultural expansion (66 %), water erosion (49.6 %), excessive use of chemical fertilizers (11.3 %), and animal husbandry (2.5 %), illegal logging (29.2 %) are the factors contributing to land degradation acting to the decrease in soil fertility (Figure 6). Land degradation negatively affects cotton development as 69.5 % of cotton growers believe that cotton does not grow well, 48.1 % believe that cotton does not produce well and 45.3 % of the cotton plant is weak. Most of the cotton producers have observed a very pronounced land degradation (74.1 %).

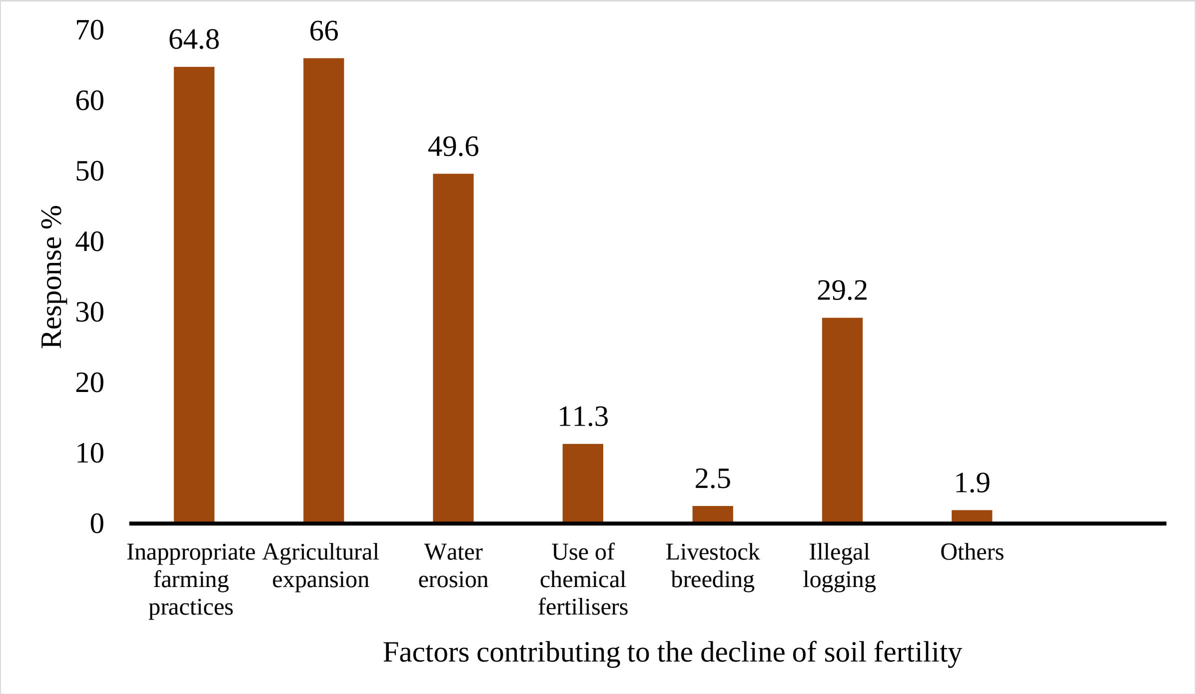

Figure 6.Factors contributing to the decline of soil fertility according to cotton growers

3.4.5. Extreme Temperature and Wind Indicator

The cotton farmers reported observed changes in temperature (Figure 7). They perceived the increase in temperature through its impact on their cropping activities (93.8 %). The high temperatures associated with the months from January to April influenced their site preparation activities for cotton production (ploughing, application of collected herbicides). Again, respondents reported that the presence of strong winds in cotton production was a recent phenomenon. According to 95.5 % of farmers surveyed, the winds have become more violent and more frequent. They appeared in the form of whirlwind of sand and caused significant damage to crops by breaking the stems of the cotton plants. The strong winds were generally observed in March, April, and October. In Boundiali, respondents indicated that violent winds were rather prevalent in, the months of August and October. While, in Ferkessédougou, the months of April, May, and October were associated with violent winds. In Korhogo, farmers observed strong winds in March, August, September, and October whereas the farmers in Mankono observed, the presence of destructive winds from February to April.

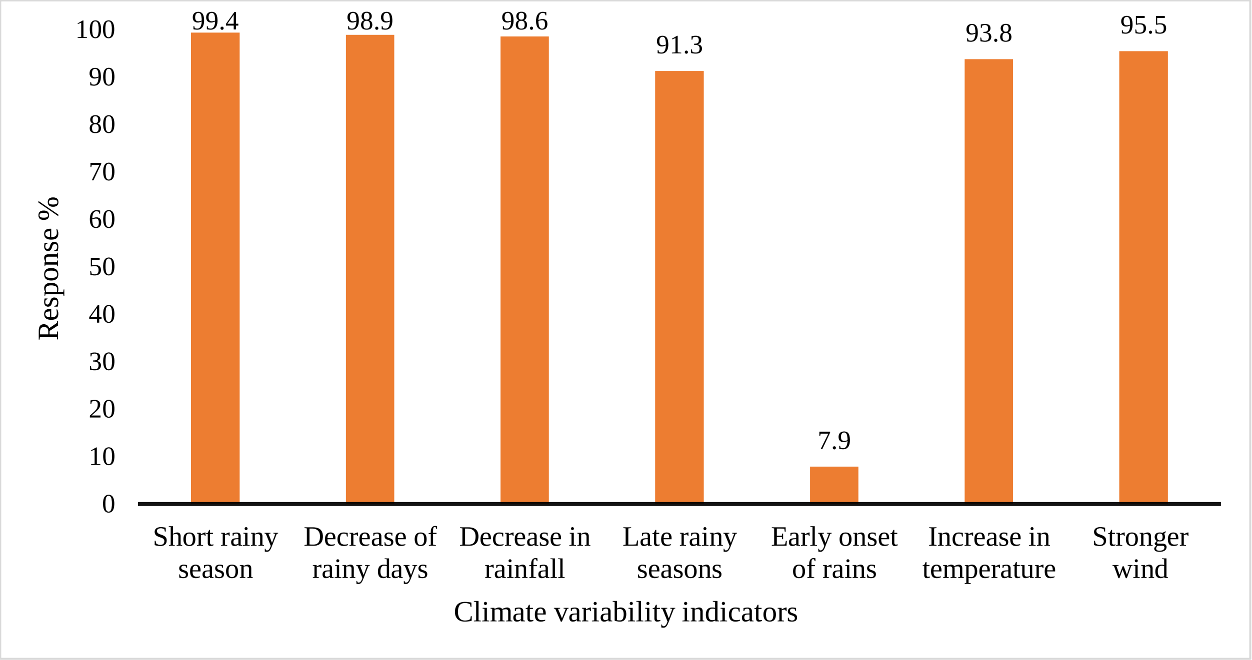

Figure 7. Cotton farmer's perception of changes in rainfall, temperature, and strong winds in the study area

3.4.6. Perception of climate change of farmers with farming experience of cotton growing

Farmers, particularly those with extensive experience in growing cotton, are on the front line of the impact of climate change. Their unique perspective provides valuable information on the evolving challenges and opportunities associated with climate variability and change. Analysis of the link between perception of climate change and farming experience of cotton cultivation revealed that farmers with less than 30 years farming experience (20-29 years) in cotton cultivation perceived the issue of climate change very well, much more so than those with longer farming experience (>30 or 50 years) (Figure 8).

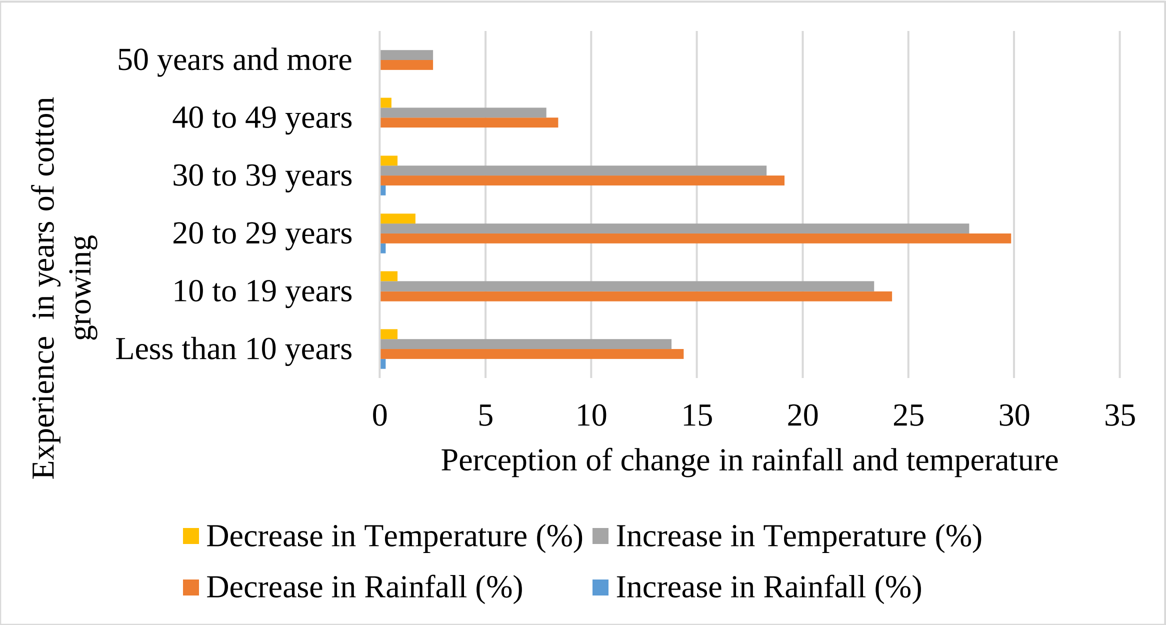

Figure 8. Cotton farmer's perception of changes in rainfall, temperature, with farming experience of cotton growing

3.4.7. Adaptation Measures of Cotton Producers in the Face of the Effects of Climate Change

Faced with the consequences of climate change, cotton producers had developed adaptation strategies to cope with the effects of climate change on their livelihoods. The adaptation strategies of the respondents in the face of climate change effects on their livelihoods are presented in Figure 9. The cotton farmers had resorted to the use of new, more adapted short-cycle cotton varieties. Overall, these varieties had been adopted by almost all farmers (87.3 %). The respondents reported other adaptation strategies such as the use of organic manures to restore the fertility of overexploited soils (80 %), ploughing before sowing (30 %), and, sacrifices to the divine beings before cultivating their cotton fields (40 %). This climatic context also led 36 % of cotton farmers to diversify their cotton production by intercropping with groundnuts and maize to guarantee some form of income in the event of cotton crop failure. Crop diversification refers to mixed cropping and aims to increase financial returns from crops so that farmers are not dependent on a single crop to generate their farm income. Diversification of income sources was also a component of the strategies developed by the local people to ensure the sustainability of their livelihoods and their survival. Also, staggering sowing dates and the timing of cropping activities have a strong influence on the performance of the cropping system throughout the cycle. The optimal sowing date is determined primarily by the arrival of rain and/or the water regime of the plot. As a result, the farmers indicated that their plot preparation had to be done as early as possible to allow the sowing of cotton seeds as soon as the first "useful" rains come. As a practice in the Côte d'Ivoire cotton basin, the cotton used was sown in the first decade (D1: 21-31 May). However, due to climate change, many of the cotton farmers (83.1 %) sowed their cotton in the second decade (D2: 1-10 June). But the farmers reported that if the rains start very late, sowing of the cotton seeds was done in the third (D3: 11-20 June) or the fourth decade (D4: 21-30 June).

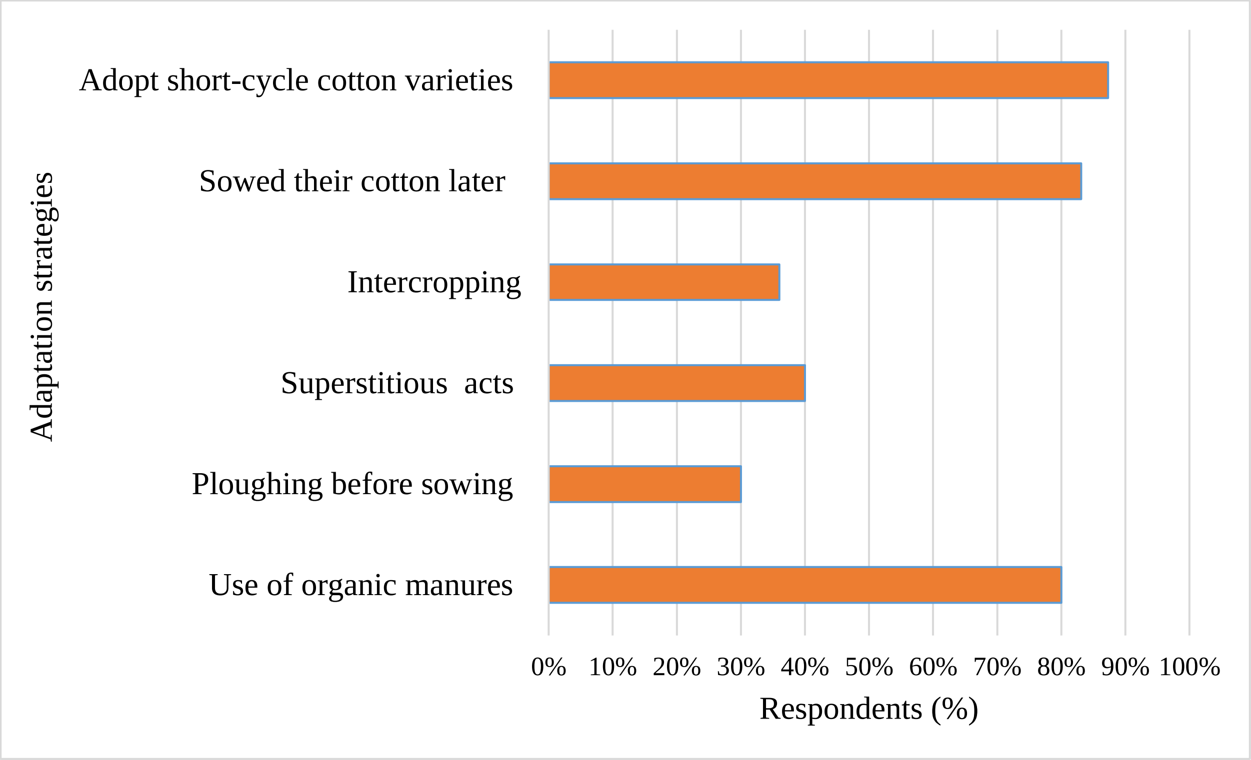

Figure 9. Adaptation strategies of farmers to climate change effects in the study area

3.4.8. Rainfall Breaks and Decline

The results (Figure 10 a, b, c, d) indicate a break in 1998 for the Korhogo station (Figure 10a) and a break in 1999 for the Boundiali station (Figure 10c) at a 99 % level of confidence for the two stations. The observed drop in rainfall in the stations of the two departments was quantified by calculating the deficits due to the breaks detected in the data series. The rainfall deficits obtained were 9.9 % in Korhogo and, 19.60 % in

Boundiali. However, the Pettitt break test did not show any apparent break in the Ferkessédougou (Figure 10b) and Mankono (Figure 10d) rainfall series.

3.4.9. Temperature Breaks and Increases

Concerning temperature analysis, the Pettit test showed apparent breaks in the temperature series in the four departments of the study area (Figure 11 a, b, c, d). The temperatures ranged from 28.67°C to 31.21°C with an average of 29.94°C. The temperatures were therefore below the damaging threshold, which is around 35°C. However, the temperature increased by an average of 0.7°C per decade and showed a break in the 2002 period for the Korhogo station (Figure 11a); 2001 for the Boundiali station (Figure 11c); 2005 for the Ferkessédougou station (Figure 11b); and 2001 for the Mankono station (Figure 11d).

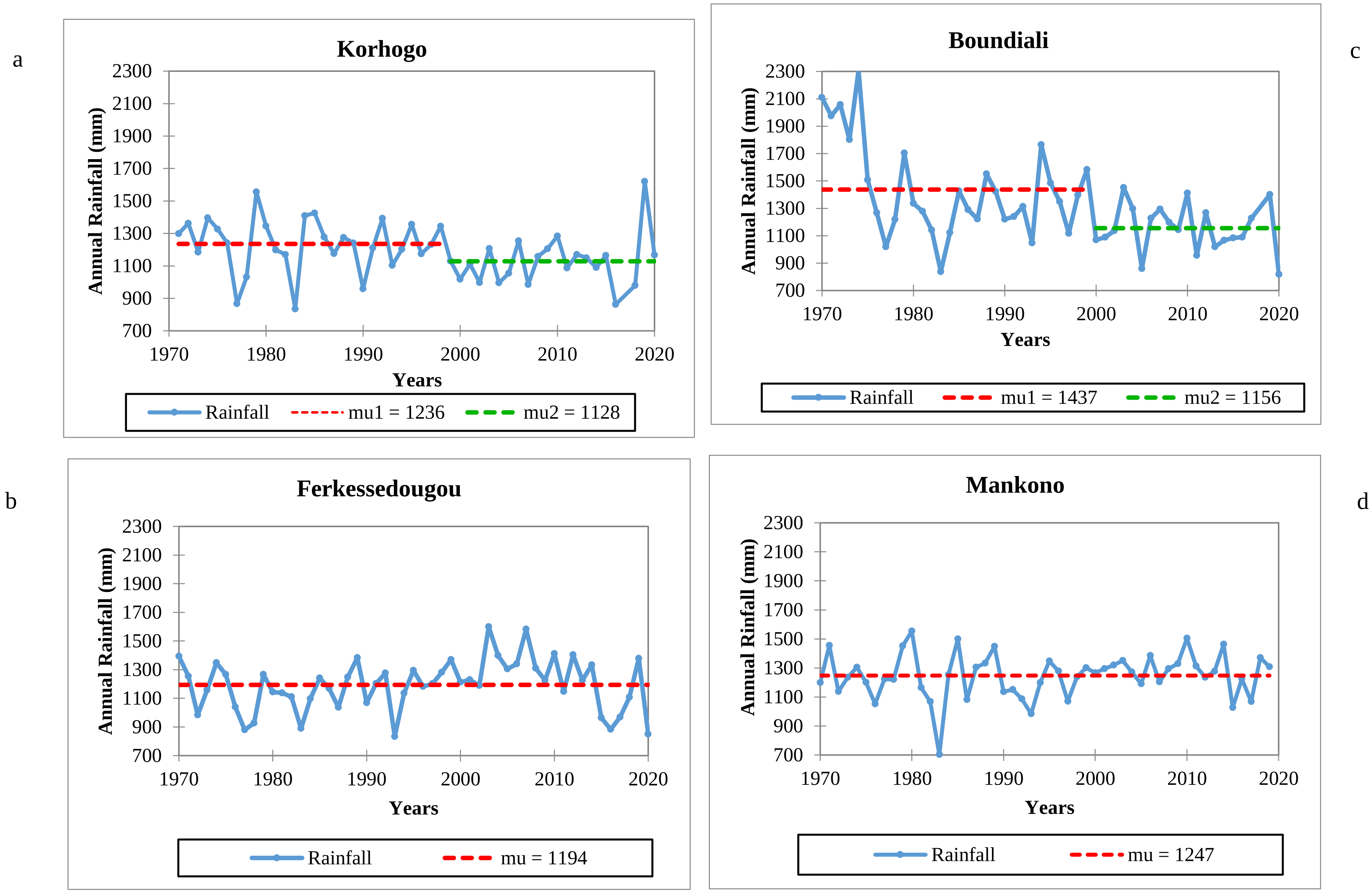

Figure 10. Rainfall fluctuations with Pettitt breakage test for (a) Korhogo, (b) Ferkessedougou, (c) Boundiali, and (d) Mankono department in the study area

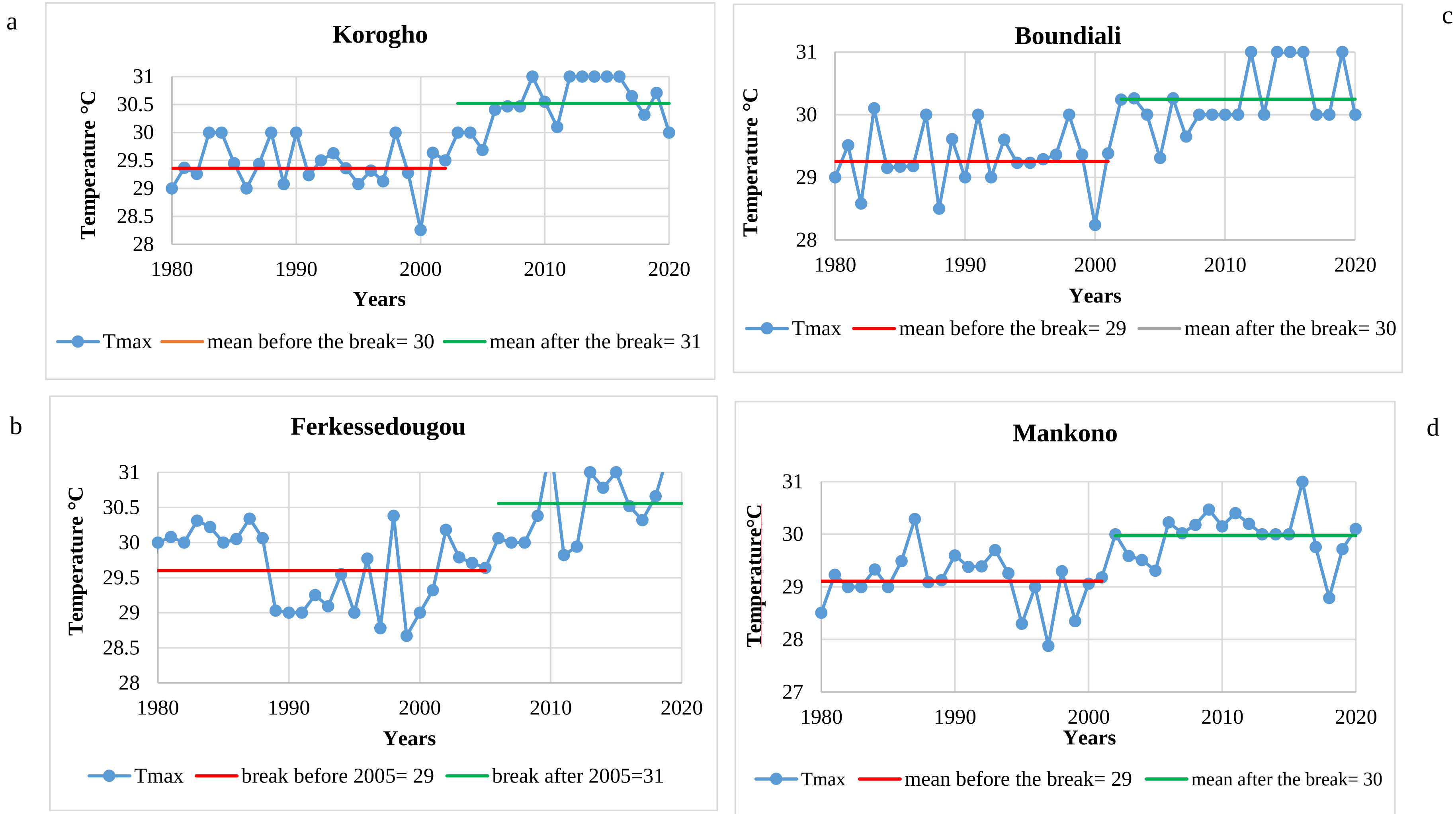

Figure 11. Temperature evolution with Pettitt breakage test for Korhogo (a), Ferkessedougou (b), Boundiali (c), and (d) Mankono

3.5. Discussion

3.5.1. Socio-Economic and Demographic Characteristics in the Study Areas

The survey results showed that the majority of cotton farmers in the study area were in the age groups above 20 years. Furthermore, 82 % of them had between 10 and 50 years of farming experience. Therefore, they should be able to give credible information on climate change and its impacts in the studied area. However, the level of education was very low in all four departments of the study area. The level of education influences farmers' ability to appreciate climate patterns and adaptations. Cotton farmers with primary and secondary education have a better perception of climate change, probably due to their regular contact with the outside world and their better access to information sources such as the mass media (Kabore *et al*., 2020; Assoumana *et al*., 2016). Thus, farmers' level of education increases the likelihood of adapting to temperature and rainfall seasons. Educated farmers are more aware of accessing, understanding, accepting, and adapting to climate change information and improved technologies, which leads to higher productivity. The level of education of the farmer has been found to have a significant relationship with an intensive knowledge of climate change (Jha & Gupta, 2021). There is therefore a need to empower farmers with educational skills and knowledge.

3.5.2. Cotton farmers' perceptions of soil fertility status

In savannah areas, low crop yields are one of the major consequences of the decline in soil fertility. Surveys of cotton growers in the Cote d'Ivoire cotton basin show that seed cotton yields are falling. The experience of the cotton farmer and his historical knowledge of his environment constitutes, for him, benchmarks for assessing soil fertility. This endogenous experience enables him to strengthen his knowledge of the Physico-chemical characteristics of the soil (Traoré *et al.,* 2012). Farmers' assessment is mainly based on phyto-indicators (Kambiré *et al.,* 2015) which are indicators of effects related to yield and floristic composition. According to El-Ramady *et al.,* (2014), the fertility of soil appears as a physical reality expressed by the presence of a plant species or by that species, or by the aspect of the soil. Thus, based on the yield thresholds given by the farmers, most of the soils degraded in the study area manifest a decline in soil fertility. In the absence of soil analysis, the practice of cotton cultivation can be considered a relevant indicator to support farmers' perception of the state of soil fertility. Indeed, this crop requires relatively more fertile land for productivity reasons. The results obtained showed relatively low levels of soil nutrients. Cotton cultivation is perceived by farmers as a factor contributing to land degradation. This can be explained by the intensive use of land and the high application of chemical fertilisers, which are often associated with cotton cultivation. Poor cultivation practices include both poor tillage and poor crop management. This correlates with the work of Amonmide *et al.,* (2019) in Benin.

3.5.3. Farmers with experience in cotton growing and their perception of climate change

The study reveals a finding that cotton farmers with less than 30 years of experience growing cotton have a better perception of climate change than those with more than 40 or 50 years of experience growing cotton. This suggests a shift in perception among the younger generation of cotton farmers, who increasingly recognise the influence of climate change on their way of life, with a particular focus on the impact it has on crops such as cotton. This difference in perception can be attributed to several factors. Firstly, the younger generation of cotton farmers may have grown up at a time when discussions about climate change and its implications were more frequent, leading to greater awareness and sensitivity to the issue. This increased awareness may have enabled them to recognise the effects of climate change on their farming practices and cotton growing. According to Smith *et al.,* (2019) experienced cotton growers have an in-depth knowledge of the local climate and weather patterns. Over the years, they have witnessed subtle and significant changes in temperature, rainfall, and extreme weather events. Their first-hand experience provides a solid basis for their perception of climate change, as they can draw on a longer-term perspective than those with no farming experience.

3.5.4. Cotton Farmers' Perception of Changes in Rainfall Patterns and Relationship with Climate Records

Climatic data spanning the past 50 years were analysed to compare with farmers' perceptions of changes in rainfall patterns in the four departments of the cotton basin. Regarding the duration of the rainy season as well as the amount of rain, a shorter duration of the rainy season (99.4 %), a decrease in the number of rainy days (98.9 %), and a decrease in rainfall (98.6 %) were observed. The rainy seasons had a late start according to 91.3 % of cotton producers. The analysis of long-term rainfall data showed a large variation from season to season in the amount and distribution of rainfall at some locations in the study area.

This situation negatively affects cotton seed yields. Although farmers do not have a quantitative measure of the amount of rainfall received in different seasons, they had a good knowledge of the general climatic conditions, especially concerning variables that have a significant impact on crop performance (Rao *et al*., 2011). In Korhogo and Boundiali departments, the perceptions of the cotton farmers were confirmed by the climatic data. There was an agreement between cotton farmers' perceptions and the perceived break in the rainfall sequence in Korhogo and Boundiali marking a decrease in the amount of rainfall. Although there was no break in the sequence in the other two departments (Ferkessédougou and Mankono), cotton growers perceived a decrease in the amount of rainfall. A large fraction of cotton farmers perceived decreases in annual rainfall despite instrumental records indicating no significant trends for the Ferkessédougou and Mankono departments. This perception might be linked to the greater decrease in rainfall associated with a decrease in seed cotton yield. Furthermore, a large number with no formal education cotton farmers and the high spatio-temporal variability of rainfall patterns could limit their ability to remember events over the years (Assoumana *et al*., 2016).

Several studies on farmers' perceptions of climate change repeatedly showed a clear concordance between observations of climate data and farmers' perceptions of a shorter rainy season (Atiah *et al.,* 2021; Nguyen *et al*. 2016; Rao *et al*., 2011). However, a study in Ghana by Guodaar *et al*., (2021) showed that farmers' perceptions of climate change in northern Ghana deviated from weather records. A possible explanation for the discrepancies between farmers' perceptions and weather observations could be their inability to understand climate change as well as to differentiate between climate variability and change (Darabant *et al.*, 2020). With regards to long-term climate change, farmers' observations in this study that rainfall patterns were changing, corroborated well with perceptions reported in other parts of the African continent such as Burkina Faso and Ghana, where the respective studies by Kabore *et al*., (2020), and Fossou *et al*., (2014) showed good farmer perceptions of the climate change phenomenon.

3.5.5. Cotton Farmers' Perception of Changes in Temperature and Wind, and Relationship with Climate Records

The temperature trends exhibited apparent breaks in the four departments of the study area with an average temperature of 30°C. There was a significant increase in temperature (0.7 °C per decade) over the 50 years. This upward trend in temperature was confirmed by studies by the National Meteorological Directorate, which indicate that Côte d'Ivoire as a whole has warmed by an average of 0.5°C since the 1980s (Kouassi *et al.*, 2020). In addition, this upward trend in temperature was also confirmed by the ECOWAS-SWAC/OECD report (2008) which indicates that temperatures in West Africa have been increasing by between 0.2°C and 0.8°C per decade since the late 1970s. This temperature increase was in line with the perceptions of respondents who perceived rising temperatures through their impact on their production activities (93.8 %). Almost all cotton producers surveyed reported a strong presence of heat in recent decades in the study area. These results were in agreement with studies conducted by Mkonda *et al*., (2018) in Tanzania. The authors compared farmers' perceptions with the results of temporal trends in weather data mainly temperature.

The perceptions of the farmers in all studied areas of Tanzania agreed with the measured weather data manifested as rising temperatures. The majority of farmers correctly perceived the increase in temperature in their locality. They also noted that the increase in temperature has had negative impacts on agricultural production in all areas of Tanzania. Furthermore, other studies (Amadou *et al*., 2015; Fosu-Mensah *et al*., 2010; Kouassi *et al*., 2010) had reported increases in temperature over the years. The temperature remains the only climate parameter and the climate trend was clearly in agreement with the perceptions of farmers in the four departments of the study area. Additionally, the presence of strong winds was a recent phenomenon in recent years for cotton producers. According to 95.5 % of those surveyed, the winds have become more turbulent and more frequent. The winds were increasingly turbulent and had become an important factor in the destruction of cotton plants. The communities around Lake Tana, Ethiopia lamented a rise in wind occurrence and speed (Darabant *et al*., 2020). According to Kosmowski *et al*., (2016), these high winds caused a lot of damage to crops in Niger. Based on these trends, it can be concluded that the perceptions of climate change by cotton farmers in the cotton basin were in line with climate trends.

3.5.6. Cotton Farmers' Adaptation Strategies to Perceived Climate Change Effects

To adapt to the negative effects of climate change, cotton farmers had put in place adaptation strategies. The most important of these were; using new, and more adapted short-cycle cotton varieties; using organic fertilisers to restore fertility to overexploited soils; shifting sowing dates, and timing cultivation activities. Indeed, faced with the scarcity and uncertainty of rainfall, cotton farmers sowed their cotton seeds in the second decade of the growing season to ensure that the cotton plant flowers at the right time of the rains.

Cotton farmers who have developed coping strategies have adopted ploughing before sowing to better exploit the first rains in the hope that they will last. Some producers make sacrifices to implore rain from protective spirits. This finding was in line with the work of Boko *et al*, (2016) that people make offerings to their ancestors to implore the coming of rain.

Crop diversification was also an important coping strategy among cotton farmers according to their farming experience. Indeed, according to the farmers, mixing cotton with maize or groundnuts allowed them to harvest maize and groundnuts when the growing season was too short for cotton to develop successfully. Agronomic research has shown that mixing cotton with groundnuts increases soil fertility, as legumes (groundnuts) are particularly important because of their ability to fix atmospheric nitrogen, which helps to improve soil fertility (Yuvaraj *et al*., 2020). Diversification of crop types is an emerging agronomic practice as a coping strategy attributed to the risk of adverse behavior of farmers in northwestern Ethiopia (Asrat & Simane, 2018). The reasons for these coping strategies are the decrease in rainfall and the scarcity of arable land. Therefore, this approach appeared to be more of a traditional strategy to reduce the risk of cotton crop failure in the study area than a specific response to climate change.

However, to compensate for drought adaptation, farmers were shifting from long-cycle cultivars (late cotton) to short-cycle cultivars (early cotton). According to Kouressy *et al*., (2008) and Djohy *et al.*, (2015), it was evident that the decrease in rainfall had led farmers to adopt shorter cycle varieties than traditional cultivars. Agricultural inputs such as organic and mineral fertilisers were used to boost crop production and thus reduce the negative impact of climate change on cotton production. This was in line with the finding of Sanou *et al*, (2018) who reported the importance of organic amendment in maintaining agronomic soil quality. Formal education was positively associated with the cotton farmer's adaptation decision. As such, cotton farmers with a good level of education were able to develop better adaptation strategies. This was in line with the findings of Asrat & Simane (2018) who reported that formal education improved farmers' ability to reason about induced technologies to adopt strategies to cope with climate change.

3.5.7. Conclusion and Recommendations

This study provided an overview of perceptions and adaptations of local cotton farmers to climate change events in the cotton basins of Côte d'Ivoire. The results showed that cotton farmers in the cotton basin perceived changes in rainfall patterns, temperature, and wind speed. The climate, especially rainfall, due to its irregularity and the downward trend in the amount of rainfall received, was a major limiting factor for cotton productivity. The perceptions of cotton farmers did not fully correspond to the past weather records in the two departments of the study area. Younger generations of cotton farmers exhibit a more pronounced awareness of climate change's influence on their way of life and crops, such as cotton. Although farmers were fully aware of climate change, few of them seemed to be taking measures to adapt their farming activities to cope with the consequent negative effects on their livelihoods. However, farmers' perceptions should not be the only criteria for identifying the gaps and needs of cotton farmers, but rather criteria for exposing them to objective facts that would enable them to take more concrete adaptation measures. Cotton farmers have implemented various adaptation measures to cope with climate change. These measures include the use of climate-resistant cotton varieties; intercropping; use of organic manure. Given the importance of climate change in the cotton basin and its direct implications for cotton production, there is an urgent need to make technological innovations that are oriented toward climate change adaptation measures available to cotton farmers. It would also be necessary to:

- Easy access to credit to enable cotton producers to increase their capacity and flexibility to modify their production strategies according to expected climatic conditions;

- Support producers in the development of mechanised agriculture which favours the use of mounted implements such as ploughs to enable them to follow the new short crop establishment times;

-Farmers should diversify their crops by introducing alternative crops alongside cotton;

- Improved water management techniques, such as efficient irrigation systems, rainwater harvesting, and drip irrigation;

-Cotton farmers should be integrated pest management approaches, including biological controls and judicious use of pesticides, to mitigate the risks associated with changing pest dynamics.

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CHAPTER 4: SOIL FERTILITY STATUS IN COTTON-BASED CROPPING SYSTEMS IN CÔTE D'IVOIRE

This is based on: Koné I, Kouadio K-KH, Kouadio EN, Agyare WA, Owusu-Prempeh N, Amponsah W and Gaiser T (2022) Assessment of soil fertility status in cotton-based cropping systems in Cote d'Ivoire. Front. Soil Sci. 2:959325. doi: 10.3389/fsoil.2022.959325

Abstract

Cotton is the main cash crop in northern Côte d'Ivoire, where intensive cultivation along with low external inputs has led to decline low crop yields due to soil fertility decline. This study assessed the evolution of soil fertility during the 2013 and 2021 periods in the cotton basins of Côte d'Ivoire. More specifically, the study (i) identified the limiting Physico-chemical parameters of soil fertility, and (ii) analysed the state of evolution of soil fertility in 2013 and 2021 in the Côte d 'Ivoire cotton basin. For this purpose, a total of 64 soil samples were taken in 2013 and 2021 on the same cotton plots from 0-20 cm horizon. Analyses of the soil samples were carried out for the following parameters: particle size distribution, pH water, total Nitrogen (N_T), Potassium (K^+), Calcium (Ca^{2+}), Magnesium (Mg^{2+}), Sodium (Na^{2+}), and Cation exchange capacity (CEC). The results of the soil analyses showed that the sandy textured topsoils dominate the whole study area in both years. This leads to a low retention capacity of exchangeable bases. The soil pH varies from slightly acidic to neutral ($6.5 < pH < 7$). The most limiting chemical properties are Cation Exchange Capacity (CEC) and the Sum of the Exchangeable Bases (SEB) in the department of Korhogo, Boundiali, and Ferkessédougou, whiles the most limiting chemical property in the department of Mankono is CEC. However, during the period from 2013 to 2021, the content of exchangeable cations (Ca^{2+}, $Mg^{2+,}$ and K^+) and the Base Saturation (BS) increased significantly in all the departments, especially in the department of Mankono. Although there is a slight increase in the chemical properties of the soils in 2021 compared to 2013, the values were still below the minimum required threshold. This result implies that the soils have poor physico-chemical properties and consequently a low level of fertility, which compromises the sustainability of the cotton production system.

The application of organic and mineral amendments is therefore essential to increase the nutrient content of these soils.

Keywords: cotton crop, soil fertility, productivity, physico-chemical properties, Côte d'Ivoire

4.1 Introduction

Soil fertility management issues are at the centre of debates on the sustainability of agricultural production systems in Africa, particularly in West Africa where farmers are concerned with" soil fatigue" (Kanté *et al*., 2001). The decline in soil fertility markedly accounts for the low agricultural productivity and this is perceived to be widespread in the highland soils of the tropics, particularly in sub-Saharan Africa (Djurfeld *et al.*, 2005). One of the reasons for this low productivity is the extraction of nutrients through continuous cropping with a low external nutrient supply, resulting in declining soil fertility (Karltun *et al*., 2013). Soil fertility is a function of many soil properties, many of which are interrelated. In most cases, the term 'soil fertility' describes the current state of the soil, which means that soil fertility is a combination of the current soil quality (mineral composition, soil texture) and achieved qualities such as soil structure, soil organic matter (SOM) content and phosphorus concentration. Soil fertility is measured either by crop performance (yield) or by indicators such as SOM content, indicator plants, and water-holding capacity (Karltun *et al*., 2013). Thus, managing fertility means acting to maintain, sometimes improve, the organic, mineral, physical, and biological status of soils to achieve a certain level of production sustainably (Kanté *et al*., 2001). Soil fertility decline includes nutrient depletion (more nutrients removed than added), nutrient mining (high nutrient removal and no nutrient addition), acidification (lowering of pH), loss of organic matter, and an increase in toxic elements such as aluminum (Hartemink, 2003).

Like other countries in the Gulf of Guinea, Côte d'Ivoire is facing a continuous decline in soil fertility resulting in stagnant or declining cotton yields (Kouadio *et al*., 2018). Soil fertility degradation through nutrient depletion, mainly by erosion and/or crop removal, is one of the threats facing agricultural systems in Côte d'Ivoire. This affects a large part of the northern territory of Côte d'Ivoire, especially the fragile ecosystems of the northern cotton basin, and eventually leads to a reduction in soil fertility and, consequently a decline in land productivity. The Global Assessment of Soil Degradation (GLASOD, 1990) showed that soil chemical degradation is more significant in many tropical regions. Cotton is the main cash crop in northern Côte d'Ivoire. The continuous increase in cultivated areas has led to soil degradation and lower yields. Like other crops, cotton cultivation is subject to several constraints, notably increasingly irregular rainfall, and declining yields (Zagbaï *et al*., 2006). In the current cropping system, seed yields are still low, estimated at around Côte d'Ivoire at 452 kg/ha and Benin at 418 kg/ha (ICAC, 2019). All other African countries harvested less than 350 kg/ha (ICAC, 2019). Soil fertility decline can be assessed using a set of soil properties from different periods on the same site or different land use with the same soils. The former is easier to interpret, and the latter can be collected quickly, but the differences may be due to inherent differences and not the result of soil management.

To improve degraded soils and restore their productivity, it is necessary to determine the current state of soil properties and to understand the limiting factors for cotton production and their spatial distribution at the regional scale. The objectives of this study were: (i) to identify the limiting physico-chemical parameters of soil fertility for cotton production; (ii) to analyse the state of evolution of soil fertility from the period 2013 to 2021 in the Côte d 'Ivoire cotton basins.

4.2. Material and methods

4.2.1. Soil sampling and analysis

Soil sampling was carried out at each site in the study area during two periods, the first being in 2013 (secondary data) during which topsoil samples from different farmers' fields were taken from 0-20 depth cm and characterised (Figure 12). Soil sampling in 2021 consisted of systematically taking samples from each plot at 0-20 cm topsoil depth using the soil auger. Samples were taken with 17 replicates at each sampling point within a plot to constitute the composite sample. Depending on the size of the plot, samples were taken from a maximum of 5 sampling points on each cotton plot. The 17 equiponderate elementary samples per sampling point were taken to constitute one composite sample. In total, 64 composite soil samples were taken into account for the database in 2013 across the study area. The locations of the sampling points in the 2013 period were recorded with a GPS (eTrex 22x). Soil sampling in the 2021 period was carried out by: (i) using the GPS coordinates of the sites sampled in 2013 and (ii) with confirmation of the exact location of the soil sampling site by the cotton plot owner. In each department of the 2021 sampling period, 20 composite samples were taken in Korhogo, 12 in Ferkessédougou, 22 in Boundiali, and 10 in Mankono, giving a total of 64 composite soil samples in the whole study area. The soil samples were stored in plastic bags to avoid contamination and sent to the ENVAL (Laboratoire de l'Environnement et de l'Alimentation de Côte d'Ivoire) laboratory for analysis of the physico-chemical parameters (pH, total N, exchangeable Ca, K, Mg and Na, CEC, Base Saturation, Sand, Silt and Clay content). The laboratory analytical techniques used for the evaluation of the Physico-chemical parameters of soil samples in 2021 were the same as the methods carried out in 2013.

The determination of the physicochemical characteristics followed the methods described by Tran and Boko (1978). The analyses consisted of the determination of particle size distribution, carried out by sieving and by the use of Robinson's pipette; Total nitrogen was determined by the method of Kjeldahl. The pH water was determined by using a soil-water suspension with a ratio (of 1/2.5). The Cation Exchange Capacity (CEC) was determined according to the NFX 31-130 standard (AFNOR, 1999). This method aims to displace all the cations adsorbed on the exchange sites of the CEC, and then saturate these sites with a single cation (NH_4^+) while the exchangeable cations (Ca^{2+}, Mg^{2+}, $K^{+,}$ and Na^+) were, determined by Atomic Absorption Spectrophotometry (Optima 2100 DV) including exchangeable aluminum.

4.2.2. Statistical analysis

The data obtained were subjected to various statistical tests: ANOVA, descriptive statistics, and homogeneity test with the Statistical Package for the Social Sciences (SPSS) (version 26.0) at a 95 % level of significance (a = 0.05).

4.2.3. Method of assessing soil fertility levels

Soil fertility status assessment was based on analysis and interpretation of data such as total Nitrogen content (N_T), Cation Exchange Capacity (CEC), pH water, Base Saturation (BS), and Sum of Exchangeable Bases (SEB). Soil fertility levels were identified by the method of maximum limitations according to the criteria defined in Table 3.

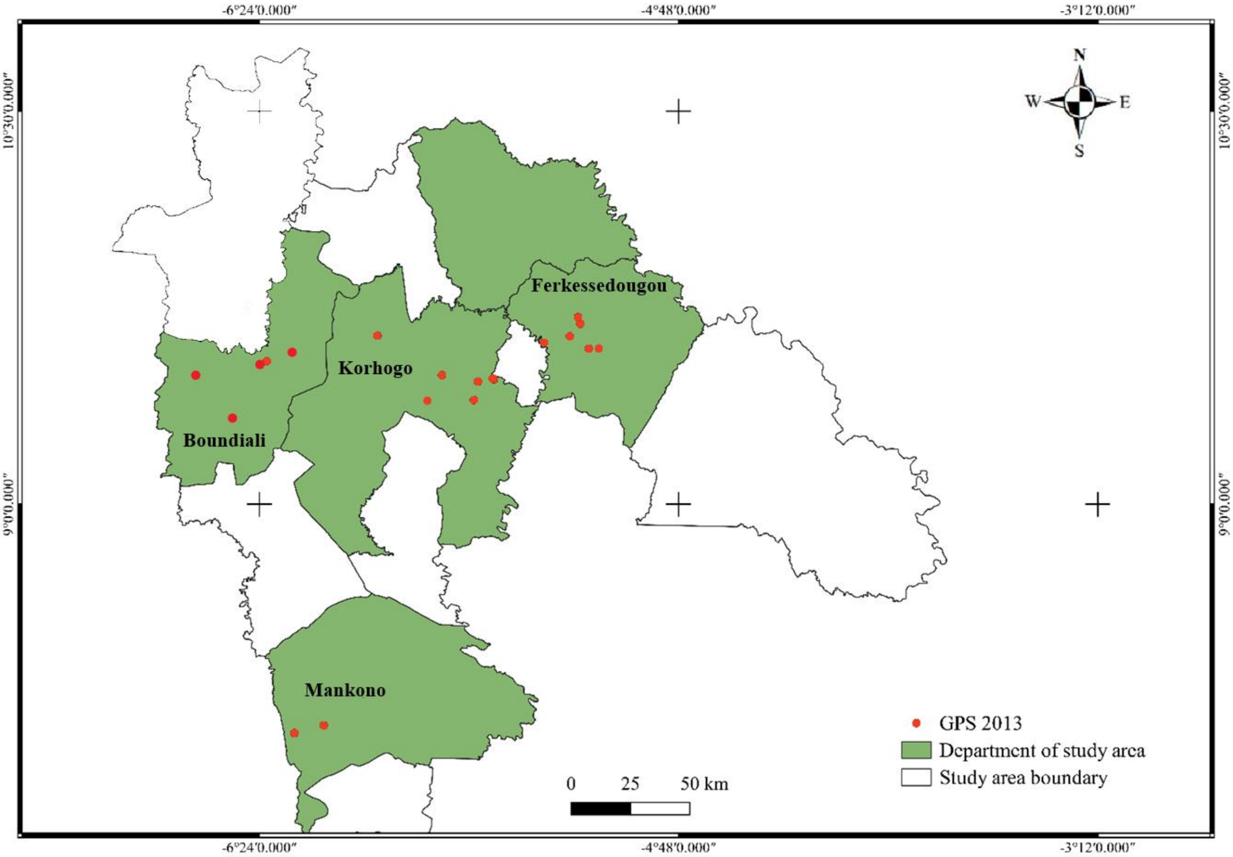


Figure 12. Location of villages where samples were soil taken from cotton plots in 2013 and 2021 at Korhogo, Ferkessedougou, Boundiali, and Mankono

Class 0, optimal fertility level: no limitation, the soil characteristic is optimal; **Class I, high fertility level:** soils are in this class when the characteristics have no or only four slight limitations. This class refers to situations that could slightly reduce yields without requiring special cultivation techniques; **Class II, medium fertility level:** soils are in this class when the characteristics do not present more than 3 moderate limitations possibly combined with low limitations. This class refers to situations that cause a greater decrease in yields or the use of special cultivation techniques. These limitations do not affect profitability; **Class III, low fertility**

level: soils are in this class when their characteristics show more than 3 moderate limitations associated with one severe limitation. This class refers to situations that cause a decrease in yields or the implementation of cultivation techniques that could jeopardise profitability; **Class IV, very low fertility level:** soils are in this class when their characteristics present more than one severe limitation.

Table 3. Evaluation criteria for soil fertility classes in the cotton basin

Characteristics	**Level of fertility**				
	Very high (no limitations)	**High (low limitation)**	**Average (moderate limitations)**	**Low (severe limitations)**	**Very low (very severe limitations)**
	Degree 0	Degree I	Degree II	Degree III	Degree IV
N (%)	> 0.08	0.08-0.06	0.06-0.045	0.045-0.03	< 0.03
Sum of Exchangeable Bases (SEB) (cmol⁺/kg)	> 10	10-7.5	7.5-5	5-2	< 2
BS (%)	> 60	60-50	50-30	30-15	< 15
CEC (cmol⁺/kg)	> 25	25-15	15-10	10-5	< 5
pH	5.5-6.5 6.5-7.2	5.5-6.0 7.2-7.8	5.5-5.3 7.8-8.3	5.3-5.2 8.3-8.5	< 5.2 >8.5

Amonmide *et al.*,(2019)

4.3. Results

4.3.1. Soil fertility status in the northern (Korhogo, Ferkessédougou, Boundiali) and central (Mankono) cotton zones in 2013

4.3.1.1. Particle size distribution

The topsoils in the north and central cotton basins are sandy loam. In the northern part of the cotton basin, the average silt content varies from 31.9 to 14.8 %. The average clay content varies from 11.9 to 7.77 % whiles the sand content is between 77.5 and 56.4 %. The proportions of clay are generally low and lower in the three northern departments of the cotton basin (Korhogo, Ferkessédougou, and Boundiali) (Kouadio *et al.*, 2018). The topsoils in the central part of the cotton basin have on average 10.4 % clay, 17.9 % silt, and 71.7 % sand.

4.3.1.2. Average total nitrogen

The average total nitrogen (N_T) concentration in the topsoils of the north of the cotton basin varies from 0.06 to 0.054 % against the norm of 0.1 to 0.15 %. The centre of the cotton basin (Mankono) has an average total

Nitrogen content of 0.08 %. Overall, the topsoils in the north and central cotton basins are largely poor in total Nitrogen (Table 4).

4.3.1.3. Magnesium

The average concentration of exchangeable Magnesium (Mg^{2+}) varies from 0.6 to 0.5 $cmol^+$ /kg against the norm of 1 to 1.5 $cmol^+$ /kg in the north of the cotton basin. The department of Mankono in the central cotton basin has a moderate magnesium concentration (average of 0.7 $cmol^+$ /kg).

4.3.1.4. Potassium

The average concentration of exchangeable Potassium (K^+) varies from 0.16 to 0.01 $cmol^+$/kg against the norm of 0.2 to 0.4 $cmol^+$/kg in the north of the cotton basin. The exchangeable potassium content is moderate in these three departments (Korhogo, Ferkessédougou, and Boundiali). The department of Mankono in the central has more or less sufficient proportions of potassium (0.2 $cmol^+$/kg).

4.3.1.5. Sum of exchangeable bases

The concentration of the Sum of Exchangeable Bases in the north of the cotton basin varies from 1.62 to 2.94 $cmol^+$/kg against the norm of 5 to 10 $cmol^+$/kg. The central cotton basin has an exchangeable cation concentration of 2.82 $cmol^+$/kg.

4.3.1.6. pH and CEC

The northern cotton zone has pH values ranging from 6.3 to 6.4, compared with the reference value of 6.5 to 7.5. The cation exchange capacity varies from 5.72 to 7.28 $cmol^+$/kg against the norm of 10 to 25 $cmol^+$/kg. The average CEC per department is low and below average. In the central, specifically in the department of Mankono, the average pH is 6.4 whiles the average Cation Exchange Capacity is 4.28 $cmol^+$/kg, which is low compared to the average.

4.3.1.7. Base saturation

The northern cotton zone has Base Saturation rates (BS) that vary from 24.42 to 48.75 % against the norm of 40 to 60 %. The central cotton basin has an average saturation rate of 39.76 % which is moderately low.

4.3.1.8. Sodium and calcium

The average concentration of exchangeable Sodium (Na^+) varies from 0.07 to 0.06 $cmol^+/kg$ against the norm of 0.3 to 0.7 $cmol^+/kg$ in the north of the cotton basin. The department of Mankono in the centre has an average sodium level of 0.12 $cmol^+/kg$. The average concentration of exchangeable Calcium (Ca^{2+}) varies from 0.92 to 2.0 $cmol^+/kg$ against the norm of 2.3 to 3.5 $cmol^+/kg$ in the north of the cotton basin. The department of Mankono in the central has averagely, low proportions of calcium (0.93 $cmol^+/kg$).

Table 4. Average physico-chemical parameters and level fertility soils in the North and Central cotton zone in 2013

Parameter	Units	KORHOGO	FERKESSÉDOUGOU	BOUNDIALI	MANKONO
		Average values			
pH		6.3 Degree 0	6.4 Degree 0	6.4 Degree 0	6.4 Degree 0
N	%	0.071 Degree I	0.096 Degree 0	0.062 Degree I	0.064 Degree I
CEC	$cmol^+/kg$	6.65 Degree III	5.72 Degree III	7.28 Degree III	4.28 Degree IV
BS	%	38.62 Degree II	48.75 Degree II	24.42 Degree III	39.76 Degree II
SEB (Ca^{2+}, Mg^{2+}, K^+, Na^+) Sum of Exchangeable Bases	$cmol^+/kg$	2.55 Degree III	2.94 Degree III	1.62 Degree IV	2.82 Degree III
Most limiting factors		SEB, CEC	CEC, SEB	SEB	CEC
Soil fertility class		IV	IV	IV	IV
Level of fertility		Very low level	Very low level	Very low level	Very low level

Degree 0: Very high (no limitations), Degree I: High (low limitation), Degree II: average (moderate limitations), Degree III: low (severe limitations), Degree IV: very low (very severe limitations)

4.3.2. Soil fertility status in the northern (Korhogo, Ferkessédougou, Boundiali) and central (Mankono) cotton basin in 2021

4.3.2.1. Particle size distribution

In 2021, the soils in the north and central cotton basins were sandy-loam. The silt content varies from 16.0 to 7.8 %. The clay content varies from 5.1 to 2.7 %. The sand content is between 86.3 and 79 %. The proportions of clay are generally low and lower in the three northern departments of the cotton basin (Korhogo, Ferkessédougou, and Boundiali). The central zone of the cotton basin has a clay content of 4 %, silt of 13.7 %, and sand of 81 % (Table 5).

4.3.2.2. Average total nitrogen

The average total nitrogen (N_T) content in the north and central cotton basin is at an average value of 0.07 against the norm of 0.1 to 0.15 %. Overall, the soils in the northern and central parts of the cotton basins study area are largely poor in total nitrogen.

4.3.2.3. Magnesium

The average concentration of exchangeable Magnesium (Mg^{2+}) varies from 0.98 to 0.68 cmol$^+$/kg against the norm of 1 to 1.5 cmol$^+$/kg. Only the department of Ferkessédougou recorded concentrations that tend towards moderate limitations. The department of Mankono in the central cotton basin has an average magnesium threshold (0.99 cmol$^+$/ kg) which also tends toward moderate limitations.

4.3.2.4. Potassium

The average concentration of exchangeable Potassium (K^+) varies from 0.35 to 0.33 cmol$^+$/kg against the norm of 0.2 to 0.4 cmol$^+$/kg. The exchangeable potassium is average in these three departments (Korhogo, Ferkessédougou, and Boundiali). The department of Mankono in the centre has high proportions of potassium (0.50 cmol$^+$/kg).

4.3.2.5. Sum of exchangeable bases

The concentration of the Sum of Exchangeable Bases in the north of the cotton basin varies from 3.89 to 4.43 cmol$^+$/kg against the norm of 5 to 10 cmol$^+$/kg. The centre of the basin has an exchangeable cation concentration of 5.52 cmol$^+$/kg.

4.3.2.6. pH and CEC

The northern cotton zone has pH values ranging from 6.5 to 6.8, compared to the reference value of 6.5 to 7.5. Overall, the pH was neutral in 83 % of cases and basic in only 17 % of cases. The Cation Exchange Capacity varied from 7.43 to 6.93 cmol$^+$/kg against the standard of 10 to 25 cmol$^+$/kg. The average CEC per department is low and below average. In the centre, specifically in the department of Mankono, we have a pH of 6.95, i.e., neutral, with a cation exchange capacity of 8.10 cmol$^+$/kg, which is low compared to the average.

4.3.2.7. Base saturation

The Base Saturation (BS) varies from 55 to 59 % against the norm of 40 to 60 %. Compared to the negative charges available on the clay-humus complex, most of the soils are well saturated with exchangeable cations in the north of the cotton basin. The central cotton basin has a saturation rate of 60 % which is considered acceptable.

4.3.2.8. Calcium and sodium

The average concentration of exchangeable sodium (Na^{2+}) varies from 0.06 to 0.07 $cmol^{+}/kg$ against the norm of 0.3 to 0.7 $cmol^{+}/kg$ in the north of the cotton basin. The centre, on the other hand, has a level of 0.06 $cmol^{+}/kg$ of sodium. The average concentration of exchangeable Calcium (Ca^{2+}) varies from 2.8 to 3.2 $cmol^{+}/kg$ against the norm of 2.3 to 3.5 $cmol^{+}/kg$ in the north of the cotton basin. The department of Mankono in the centre has high proportions of calcium (3.8 $cmol^{+}/kg$).

Table 5. Average physico-chemical parameters and level of fertility soils in the North and Central cotton zone in 2021

Parameter	Units	KORHOGO	FERKESSÉDOUGOU	BOUNDIALI	MANKONO
		Average values			
pH		6.5 Degree 0	6.6 Degree 0	6.8 Degree 0	7.1 Degree 0
N	%	0.071 Degree I	0.068 Degree I	0.068 Degree I	0.067 Degree I
CEC	$cmol^{+}/kg$	6.93 Degree III	7.28 Degree III	7.43 Degree III	8.10 Degree III
BS	%	55.15 Degree I	59.19 Degree I	58.54 Degree 1	59.38 Degree 1
SEB (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}) Sum of Exchangeable Bases	$cmol^{+}/kg$	3.89 Degree III	4.42 Degree III	4.43 Degree III	5.52 Degree II
Most limiting factors		CEC, SEB	CEC, SEB	CEC, SEB	CEC
Soil fertility class		IV	IV	IV	III
Level of fertility		Very low level	Very low level	Very low level	low level

4.4. Limiting chemical parameters of soils in the cotton basin for the period 2013 and 2021

When averaging over all soil profiles of a district, most of the chemical parameters of the soils in the cotton basin for both periods show a high degree of soil fertility limitations. In all districts, the average topsoil has more than one severe limitation, except for the department of Mankono in 2021. Both, Cation Exchange Capacity (CEC) and the sum of Exchangeable Bases (SEB) were 2013 and 2021 the most limiting factors for cotton production in the departments of (Korhogo and Ferkessédougou) (Tables 4 and 5). In Boundiali in 2013 the base saturation (BS) was most limiting. The average total nitrogen (N_T) content was not limiting the cotton production in the four departments of the study area during both periods 2013 and 2021. The pH was close to neutral throughout the cotton basin study area. However, not all pH values were limiting for cotton production. All soils in the four departments of the study area were close to soil fertility class IV with a very low fertility level except in Mankono, where soil fertility class was on average III in 2021. Among the soil samples that were taken during the period 2021, topsoils in Mankono had, on average, the highest soil fertility. The department with the lowest level of soil fertility was Korhogo according to the values of soil chemical properties.

Table 6. Soil status for the years 2013 and 2021 with results/differences

Parameter	Units	KORHOGO			FERKESSÉDOUGOU			BOUNDIALI			MANKONO		
		2013	2021	D	2013	2021	D	2013	2021	D	2013	2021	D
		Average values											
pH		6.3	6.5	0.2	6.4	6.6	0.2	6.4	6.8	0.4	6.4	7.1	0.7
N	%	0.071	0.071	0	0.096	0.068	- 0.03	0.062	0.068	0.01	0.064	0.067	0.003
CEC	$cmol^{+}/kg$	6.65	6.93	0.3	5.72	7.28	1.6	7.28	7.43	0.15	4.28	8.10	3.82
BS	%	38.62	55.15	16.5	48.75	59.19	10.4	24.42	58.54	34.12	39.76	59.38	19.62
SEB (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}) Sum of Exchangeable Bases	$cmol^{+}/kg$	2.55	3.89	1.3	2.94	4.42	1.48	1.62	4.43	2.81	2.82	5.52	2.7
Most limiting factors		SEB, CEC			CEC, SEB			SEB, CEC			CEC		
Level of fertility		Very low level			Very low level			Very low level			low level		

D: difference

4.5. The difference in soil physico-chemical properties between the 2013 and 2021 periods

The different boxplots highlight the most significant variability of each year (box length) and the differences between the 2013 study and the 2021 measurements (median) (Figure 13) (Table 6). In general, many soil fertility indicators changed significantly ($P \leq 0.05$) as revealed by the comparison of means using the ANOVA statistical test. The pH_{H2O} has a mean value of 6 and showed a slightly increasing trend, which was significant in Boundiali and Mankono. Nevertheless, differences were observed within each department of the study area.

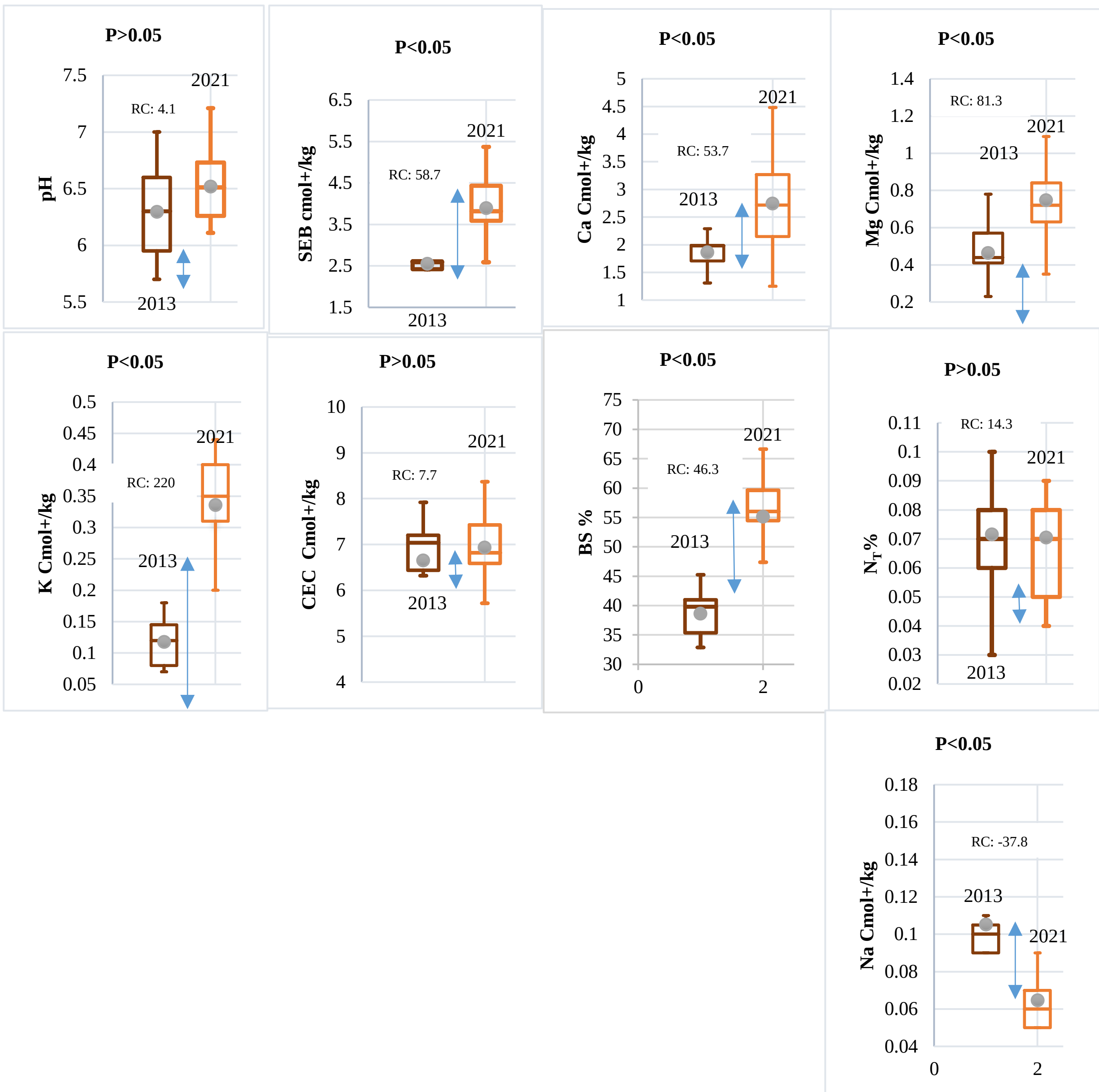
The soil texture is one of the most important properties of soil, and it greatly affects agricultural production, land use, and management. Soil texture is directly related to nutrient retention and drainage capacity. Soil texture in the field is not easily changed and is therefore considered a permanent soil attribute. In this study, the dominant soil texture in the study area at the depth of 0-20 cm was sandy loam texture with a very low proportion of clays. In the Korhogo department, a variation of chemical elements were observed, including mainly exchangeable base concentrations like K^+ which increased from 0.12 to 0.34 $cmol^+/kg$ in 2021, Ca^{2+} which increased from 1.9 to 2.7 $cmol^+/kg$, Mg^{2+} which increased from 0.5 to 0.7 $cmol^+/kg$ and Na^{2+} which decreased from 0.1 to 0.06 $cmol^+/kg$. The percentage of Base Saturation (BS) increased from 38 to 55% in 2021. Similarly, the Sum of Exchangeable Bases (SEB) increased from 2.55 to 3.89 in 2021 $cmol^+/kg$.

In the department of Ferkessédougou, a variation of the chemical elements can be observed. The concentrations of exchangeable bases have more or less increased. K^+ increased from 0.17 to 0.33 $cmol^+/kg$ in 2021, Ca^{2+} from 1.9 to 3.3 $cmol^+/kg$, Mg^{2+} from 0.7 to 0.8 $cmol^+/kg$ and Na^{2+} from 0.1 to 0.06 $cmol^+/kg$. The percentage of total N decreased from 0.09 to 0.06 %. The CEC increased from 5.7 to 7.2 $cmol^+/kg$ in 2021. Similarly, the Sum of Exchangeable Bases (SEB) increased from 2.94 to 4.42 in 2021 $cmol^+/kg$.

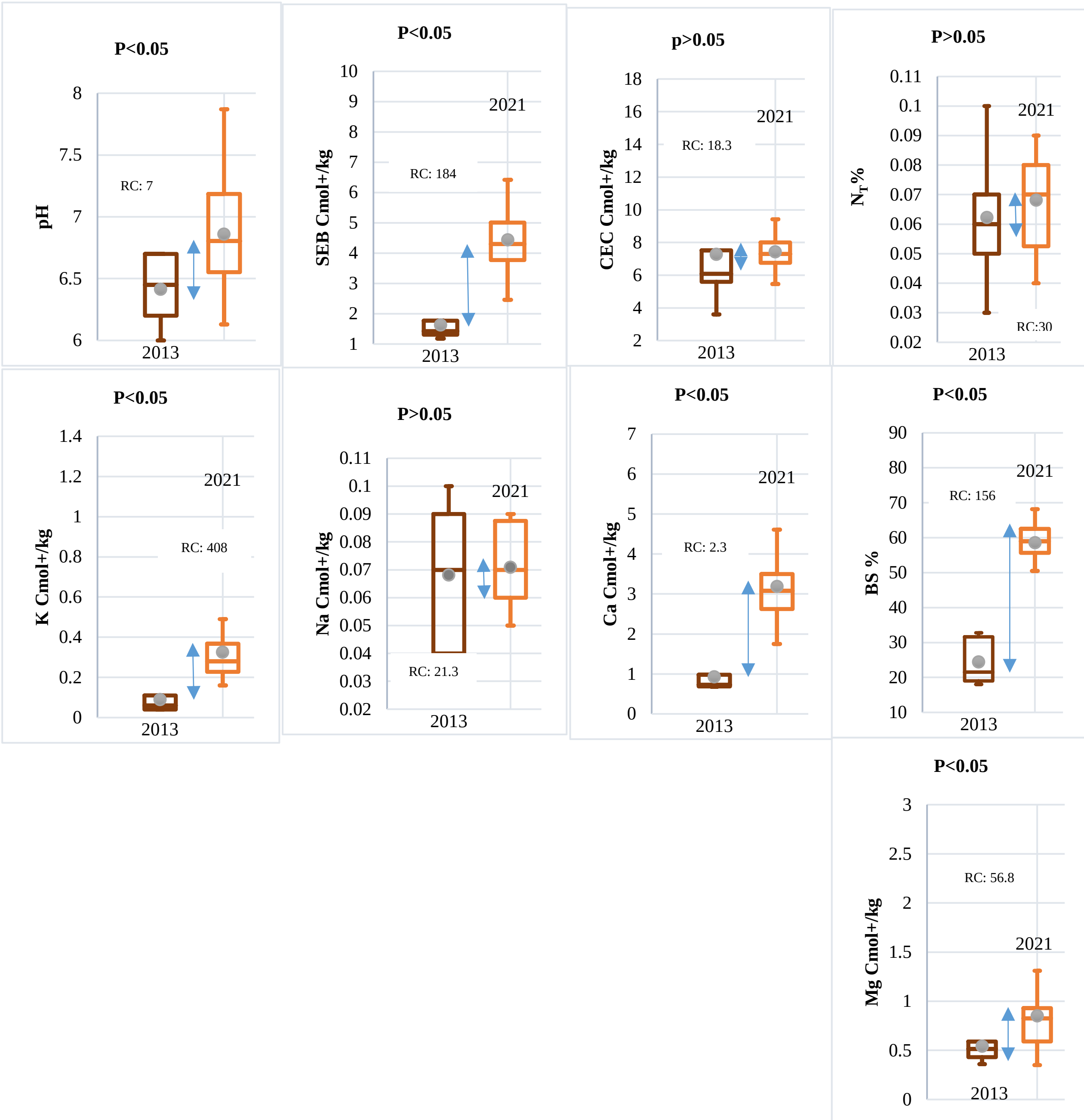
In the department of Boundiali, a variation of the chemical elements can be observed. The concentrations of exchangeable bases have more or less increased. K increased from 0.09 to 0.33 $cmol^+$ /kg in 2021, Ca^{2+} from 0.9 to 3.2 $cmol^+/kg$, Mg^{2+} from 0.54 to 0.85 $cmol^+/kg$, Na^{2+} from 0.06 to 0.07 $cmol^+/kg$. Similarly, the Sum of Exchangeable Bases (SEB) increased from 1.62 to 4.43 in 2021 $cmol^+/kg$. The percentage of Base Saturation

(BS) increased from 24 to 58 %. In the Mankono department, the concentrations of exchangeable bases have more or less increased. K^+ which increased from 0.1 to 0.4 $cmol^+/kg$ in 2021, Ca^{2+} which increased from 0.9 to 3.7 $cmol^+$ /kg, and Na^{2+} which decreased from 0.1 to 0.06 $cmol^+/kg$. The CEC concentration increased from 4.7 to 8.1 $cmol^+/kg$ in 2021. The percentage of base saturation (BS) decreased from 59 to 39 % in 2021. Similarly, the Sum of Exchangeable Bases (SEB) increased from 2.82 to 5.52 in 2021 $cmol^+/kg$.

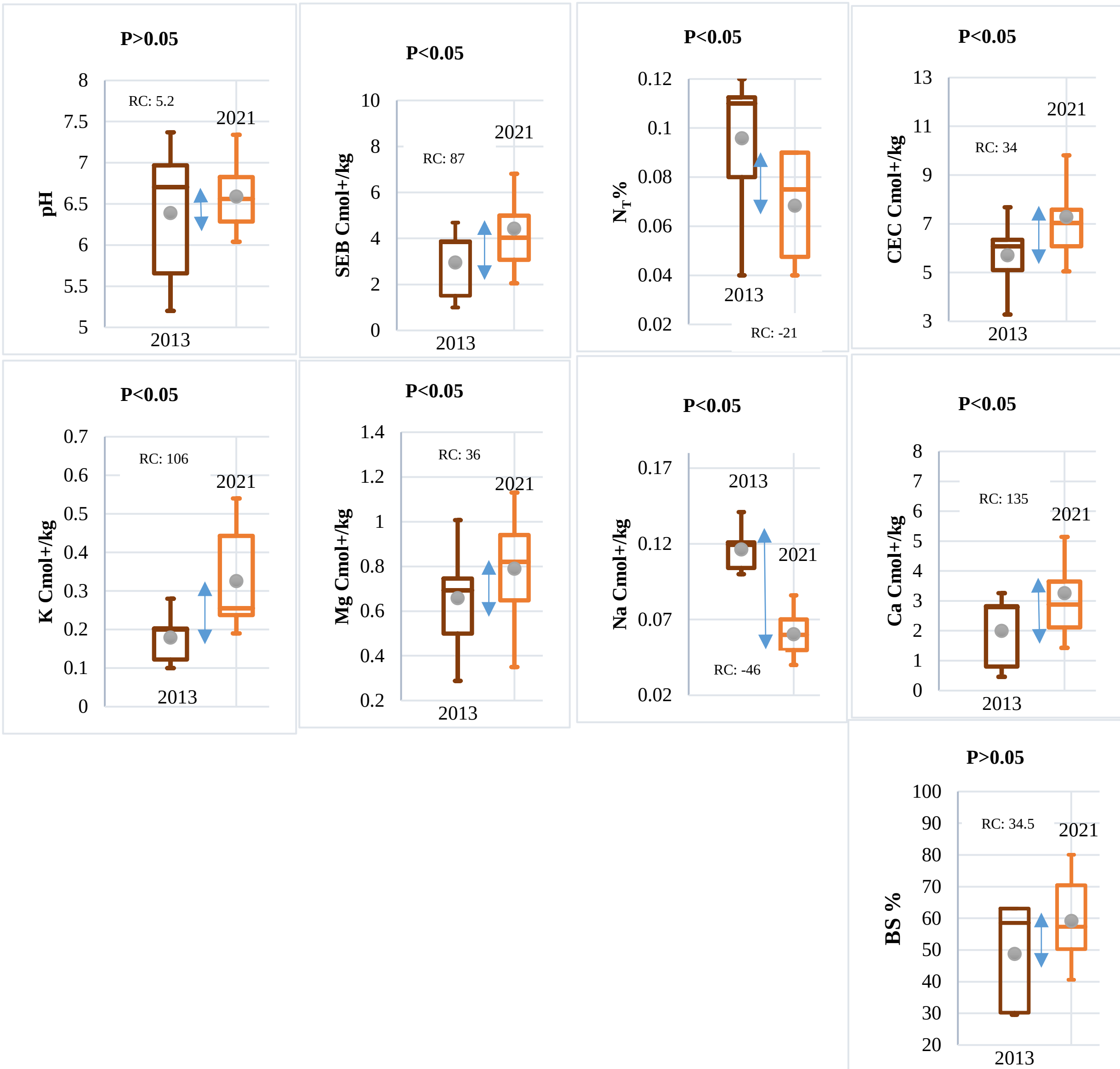
A



B


P<0.05
pH
RC: 7
2013
P<0.05
SEB Cmol+/kg
RC: 184
2021
2013
p>0.05
CEC Cmol+/kg
RC: 18.3
2021
2013
P>0.05
N_T %
2021
RC:30
2013
P<0.05
K Cmol+/kg
RC: 408
2021
2013
P>0.05
Na Cmol+/kg
RC: 21.3
2021
2013
P<0.05
Ca Cmol+/kg
RC: 2.3
2021
2013
P<0.05
BS %
RC: 156
2021
2013
P<0.05
Mg Cmol+/kg
RC: 56.8
2021
2013

C


P>0.05
pH
RC: 5.2
2013
2021
P<0.05
SEB Cmol+/kg
RC: 87
2013
2021
P<0.05
N_T %
RC: -21
2013
P<0.05
CEC Cmol+/kg
RC: 34
2013
2021
P<0.05
K Cmol+/kg
RC: 106
2013
2021
P<0.05
Mg Cmol+/kg
RC: 36
2013
2021
P<0.05
Na Cmol+/kg
RC: -46
2013
2021
P<0.05
Ca Cmol+/kg
RC: 135
2013
2021
P>0.05
BS %
RC: 34.5
2013
2021

D

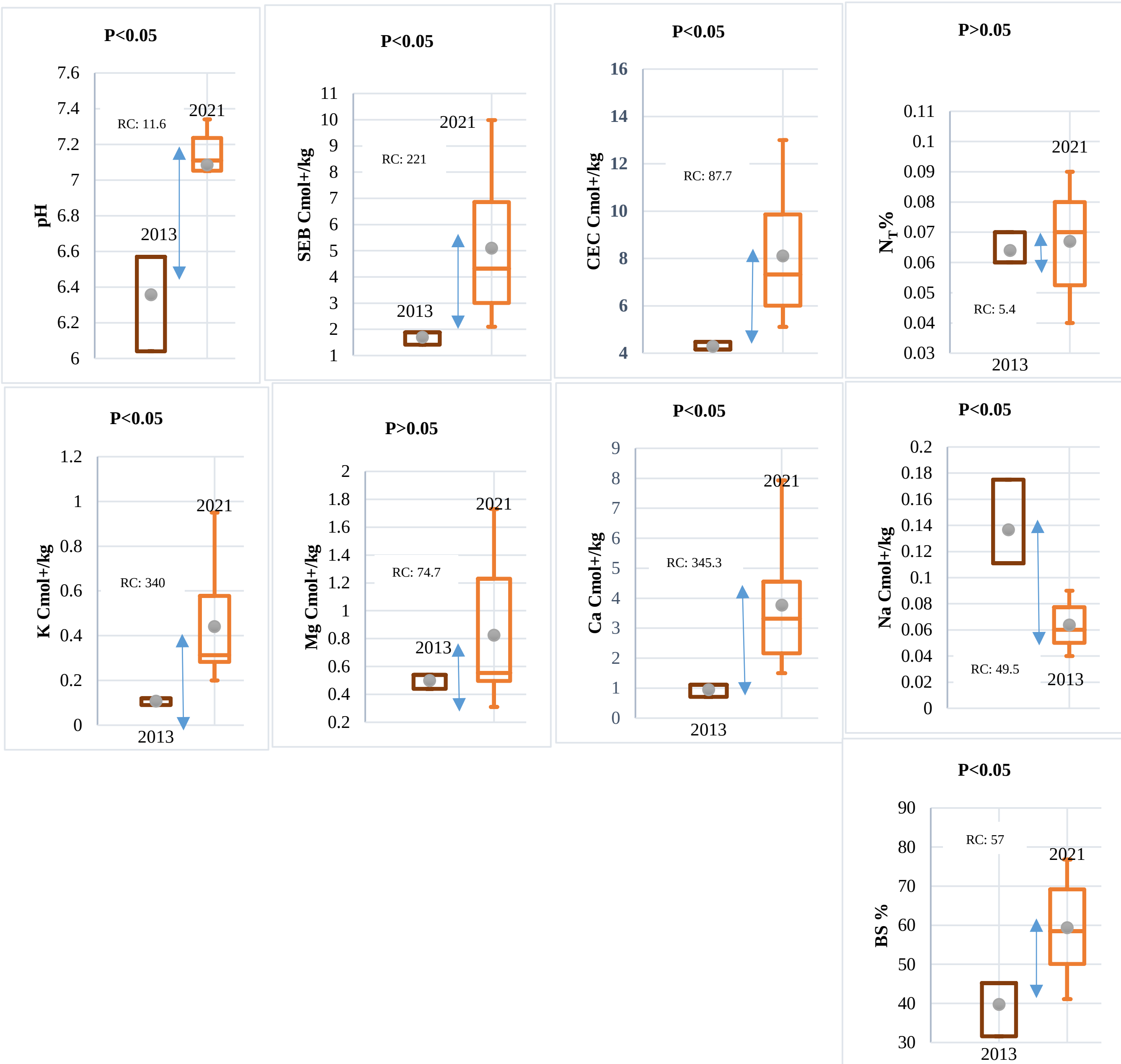


Figure 13. Boxplots of changes in soil chemical properties for the period 2013-2021 in Korhogo (A), Boundiali (B) Ferkessedougou (C), and Mankono (D)

4.6. Discussion

4.6.1. Comparison of Physico-chemical data of soils in the cotton basin between the periods 2013 and 2021

Changes in soil quality can be assessed by measuring appropriate indicators and comparing them with desired values (critical limits or threshold levels) at different time intervals for specific use in a selected agro-ecosystem (Arshad & Martin, 2002). Soil properties during the period 2013 to 2021 show significant differences in each department of the study area. The department of Korhogo shows a variation of chemical properties that in most cases have undergone a slight increase from 2013 to 2021. These variations were observed at the level of exchangeable bases such as Potassium, Calcium, and Magnesium. Sodium decreased from 2013 to 2021. We also observed a slight increase in the percentage of base saturation and the sum of exchangeable bases. Most of the lands in the Korhogo department of northern Côte d'Ivoire have been continuously cultivated for several decades, with fallow lands having virtually disappeared, resulting in a decline in soil nutrient levels during both periods, most notably in 2013. This could be explained by the agricultural practices used on the cotton farms in the Korogho department, which are over-exploiting the soil, inappropriate agricultural practices, and the use of insufficient chemical amendments. Indeed, in 2013, the entire Ivorian cotton basin was under the supervision of a single cotton company, CIDT (Compagnie Ivoirienne pour le Développement des Textiles). The latter had difficulty in meeting the need for mineral fertiliser and in monitoring farmers by implementing appropriate agricultural practices for cotton cultivation, which explains the low nutrient content of the soil in the period 2013. The appearance of new cotton companies over the last five years has made it possible to more or less make up for the nutrient deficits and to strengthen the training of cotton farmers in good agricultural practices. This has led to improvements in nutrient levels in the 2021 period. The department of Ferkessédougou also shows changes in soil chemical properties in the periods 2013 and 2021. These changes are noticeable in a significant increase in the content of exchangeable potassium, calcium, and magnesium. Sodium content, however, is decreasing. The values of cation exchange capacity and the sum of exchangeable bases have increased significantly from 2013 to 2021. Nitrogen has decreased during this period. The department of Boundiali shows an increase in the level of exchangeable bases such as calcium, sodium, potassium, and magnesium. The concentration of exchangeable bases has increased significantly, as has the base saturation.

The three departments belong to the same northern agroecological zone of Côte d'Ivoire with extreme climatic conditions. The differences observed in soil nutrient levels during the period 2013 to 2021 show an improvement in soil fertility levels concerning exchangeable bases and partly CEC, although the absolute concentrations remain low concerning the nutrient requirements for cotton cultivation. This increase in exchangeable bases could be explained by the increasing use of mineral fertiliser and manure. The slightly increasing trend of total nitrogen, which is closely related to the soil organic matter content, in Korhogo and Boundiali may also point to increasing use of manure and improved legume fallows. However, the increases are not significant and in Ferkessédougou the total soil nitrogen content is even decreasing.

These innovations can also be explained by the close monitoring of the cotton producers by the National Agricultural Research Centre (CNRA) and the cotton companies, that have been providing credit facilities for the purchase of inputs for several years. This had a positive impact on the balance of exchangeable cations and, probably also soil nitrogen at least in Korohgo and Boundiali. Among the recommended practices in cotton, cultivation is the use of available natural phosphates, the production of organic manure through composting, crop rotation, mulching of residues, and their use as bedding. Also, the practice of concentrating organic manure on the "infertile" parts of the soil rather than diluting it by spreading it over the entire cotton plot has been introduced to cotton farmers. Although there have been some improvements realised, organic and mineral fertiliser inputs are still insufficient compared to exports, and there is a general deficit in nutrients, especially nitrogen, and potassium. In the Côte d'Ivoire cotton basin, an application of 200 kg per hectare of initial application (NPKSB) ($15N-15P_2O_5-15K_2O+6S+1B_2O_3$) is applied after ploughing, or just after weed control (Kouakou *et al.*,2020); then, 40-45 days after emergence, an application of 50 kg per hectare of urea is made. Organic fertilisation is not visibly popularised in the Ivorian cotton crop; it is done in a rudimentary way by some farmers with cattle herds.

Despite the poor Physico-chemical constraints of the soils in the cotton basins, the farmers persist in growing cotton because it is more economical than other crops. Indeed, cotton cultivation is the main economic resource in the Savannah areas of northern Côte d'Ivoire. Cotton is one of the main cash crops. Farmers derive most of their agricultural income from it to the point that this crop is called white gold. In addition, the prices of cotton seeds are fixed each year by the Ivorian government and the agricultural subsidy provided by the cotton companies contributes to the maintenance of this crop by the producers of northern Côte d'Ivoire. Indeed, cotton contributes to the reduction of poverty in the Savannah region. Thus, producers are becoming more professional in their cooperative organisations to guarantee the financial profitability of production (Edmond *et al.*,2015).

4.6.2. Evaluation of limiting soil properties

Critical limits determine the range of desirable values for a selected soil property that must be maintained for the normal functioning of the soil ecosystem. Within these critical limits, the soil can maintain its specific functions in ecosystems (Arshad & Martin, 2002). The results of the particle size analysis of the soils studied during the periods 2013 and 2021 showed the dominance of sandy-silty textures that are often unfavorable for cotton cultivation. The physical properties of the soil are assumed to be constant over time, and little is known about their natural evolution (Hartmann *et al.*,2020). The proportions of sand and silt largely dominate that of clay throughout the study area, with over 80 % sand. Clay levels were well below 10 %. A clay deficiency is not conducive to water and nutrient retention. Clay is the element that conditions the fixation of mineral elements on the adsorbent complex (Amonmide *et al.*, 2019). The high proportion of sand is thought to be related to the effects of ploughing and continuous land use, which causes the leaching of fine particles (Koulibaly *et al*.,2014). According to Parikh, (2020) and Pypers *et al.*, (2011), silty textured soils are often considered ideal for agriculture as they are easily cultivated by farmers and can be very productive for crop growth. It was found that soil textures composed of loam > clay > sand improve cotton yield and promote good drainage (Wang *et al.*,2021). Thus, the results of the present study indicate that the soils in the study area are not suitable for cotton cultivation. Soil pH has a huge influence on soil biogeochemical processes. Soil pH is described as the “primary soil variable” that influences a myriad of biological, chemical, and physical soil properties and processes that affect plant growth and biomass yield (Neina *et al.*,2019; Borah *et al.*, 2010). Cotton is one of the most sensitive crops to low-pH soils.

The pH values obtained in the four departments of the study area were above the threshold (pH>5.5), i.e., weakly acid to neutral. This pH value varied slightly over the period from 2013 to 2021. However, previous studies have shown that when soil pH falls below 5.5, cotton plants start to show symptoms of Al and Mn toxicity, which affects fibre quality (Singh *et al.*, 2003). As soil pH is measured on a logarithmic scale, even a small change in pH indicates a large change in soil quality and therefore affects soil health and nutrient availability. Soils in the cotton basin study area were deficient in total nitrogen (N_T). This deficit in total nitrogen observed over the period 2013 and 2021 could be explained by the fact that the cotton plots were not regularly fallowed over a long period to maintain high total nitrogen content. As clay minerals are the basis of the clay-humus complex, their low content largely contributes to the fast decomposition of organically bound nitrogen in these soils (Kome *et al.*,2020; Yemefack *et al*.,2004). The CEC content is low in the whole study area, which is explained by the low organic matter and clay content observed in the different soils of the cotton basin study areas. The results confirm those obtained by Solly *et al.*, (2020) and Koull & Halilat (2016) who found that CEC was intimately related to the organic matter and clay content of the soil. The clay content explains the binding of exchangeable cations to the clay-humus complex.

There is therefore a strong effect of clay content that contributes to the total low CEC. In superficial soils, mainly the cation exchange capacity (CEC) and the sum of exchangeable bases (SEB) were limiting for all four departments of the study area (Korhogo, Ferkessédougou, Boundiali, and Mankono). The quantitative values beyond which a further reduction of these properties is limiting depend strongly on the crop. For example, a CEC below about 10 $cmol^{+}/kg$ is a severe limitation that can reduce the yield of the cotton crop. This is a very important soil property that influences soil structure stability, nutrient availability, soil pH, and soil response to fertilisers and other soil amendments (Hazelton *et al.*,2007). Percent base saturation (BS) is the percentage of CEC occupied by base cations Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}. Therefore, soils with a high percentage of base saturation are generally more fertile as they have little or no acidic cations and Al^{3+} which is toxic to plant growth. The soils with high BS contain greater amounts of the essential nutrient cations Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}, which are needed by plants (Leticia *et al.*,2017).

In Korhogo and Ferkessédougou departments, the most limiting factors in both periods (2013 and 2021) are SEB and CEC. The department of Boundiali has SEB as the most limiting factor in 2013 and SEB and CEC as the most limiting factors in 2021. In the Mankono District, the most limiting factor in both periods (2013 and 2021) is only CEC. However, the fertility class between the two periods is different in Mankono. The fertility level in 2013 was class IV which means that the fertility level was very low, and in 2021 the fertility class was III which means that the soil fertility level was also low. In general, the cation exchange capacity and the sum of exchangeable bases during these two periods appeared to be strongly limiting for cotton cultivation. In the Mankono department, during the 2021 period, the sum of exchangeable bases appeared to be also a limiting factor level. The soil fertility classification reveals that on average the soils in Korhogo, Boundiali and

Ferkessédougou departments have lost their agricultural potential and are in class IV. This is due to the low content of the sum of exchangeable bases and the cation exchange capacity of the soils.

Soil fertility in arid and semi-arid conditions is limited by environmental extremes of hot and cold temperatures, as well as low water availability (Hag *et al.*,2021). The agro-climatic parameters present constraining characteristics for agriculture, especially in the North of the basin (Korhogo, Ferkessédougou, and Boundiali) which sometimes experiences severe droughts and the centre of Mankono with less severe climatic conditions (MINESUDD, 2013). With a few exceptions, the soils have low fertility marked by low availability of cation exchange capacity and the sum of exchangeable bases. These limitations are due to the organic matter and cation inputs (Ca^{2+}, Mg^{2+}, K^{+}) from external sources, as these areas are subject to high temperatures (promoting degradation of organic matter) and high rainfall intensities (erosion of topsoil and high leaching rates of cations) (Kouadio *et al.*,2018). Thus, the conservation of top soils and soil water as well as the efficient use of water is a prerequisite for increasing nutrient availability and uptake. The soils of the cotton plots in the departments of Mankono have higher vegetation cover to protect the soil from wind and water erosion than those in the northern departments of Korhogo, Ferkessédougou, and Boundiali. Furthermore, one of the consequences that induce these limiting factors of soil fertility is unsustainable soil management practices and insufficient application of fertilisers. These results are in agreement with the work of (Kouadio *et al.*,2018; Amonmide *et al.*,2019; Dai *et al*., 2013) who demonstrated a rapid decline in soil chemical properties following intensive cultivation with inappropriate cropping practices. Thus, action plans that focus only on one factor, such as mineral fertiliser recommendations, are unlikely to be successful in improving soil fertility in most regions. Each of the priority factors needs to be improved in such a way that none of the identified priorities is limiting. For example, the use of mineral fertilisers in combination with organic matter from plant or animal debris can improve soil fertility and hence crop yields. Examples of such cropping systems are the implementation of half-moon practices (Nyamekye *et al.*, 2018) and improved, fallow systems.

However, all these technical approaches need the inclusion of appropriate recommendations (the right rate, time, and place or method), reliable extension services, access to financial resources, and favorable policies to increase their adoption.

4.7. Conclusion and Recommendations

The study demonstrated the relevance of soil physicochemical parameters in the sustainable management of cotton productivity in the cotton-based cropping systems of Côte d'Ivoire. The results showed that most of the soils in the study area were in a state of degradation and less favorable for cotton cultivation. The chemical analyses indicated mineral element deficiencies in the soils studied. The most limiting chemical properties are CEC and SEB. However, from 2013 to 2021 the content of exchangeable cations (Ca^{2+}, $Mg^{2+,}$ and K^{+}) and the base saturation increased significantly in all the departments which may be due to the more intensive use of mineral fertilisers. Farmers are gradually adopting sustainable crop and soil management Sustainable solutions like the frequent use of organic amendments such as manure, compost, and crop residues, as well as the combination of organic amendments with chemical fertilisers are the best practice that need to be adopted by farmers.

Improving soil fertility is crucial for sustainable agricultural production and to achieve food security. Here are some recommendations to improve soil fertility:

- Soil testing: Before applying any fertilizer, it is important to test the soil to determine the nutrient levels and pH. Soil testing helps to identify specific nutrient deficiencies and the appropriate fertilizers to use.
- Organic matter: Incorporating organic matter into the soil is an effective way to improve soil fertility. Organic matter improves soil structure, water-holding capacity, and nutrient availability. Organic matter can be added to the soil through crop residues, manure, compost, or cover crops.

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CHAPTER 5: LAND SUITABILITY ASSESSMENT AND MANAGEMENT OPTIONS FOR COTTON PRODUCTION IN THE CÔTE D'IVOIRE COTTON BASINS

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Abstract

Over time, there has been a reduction in the cotton harvest in the cotton basin situated in the northern part of Côte d'Ivoire. The decrease in cotton output can be attributed to various biophysical properties, including pests and diseases, water scarcity during certain seasons, degradation of soil quality, and insufficient implementation of crop management techniques. The scarcity of precise pedological data to aid in crop establishment and management is one of the challenges affecting cotton production. Therefore, a land suitability assessment was conducted in affected cotton-producing areas in the Côte d 'Ivoire cotton basins to identify the land qualities that restrict optimal productivity. Composite top soil samples were taken in the four departments (Boundiali, Korhogo, Ferkessédougou, and Mankono) of the study region. The study focused on two villages for each department for suitability evaluation, where a representative soil profile (0-100 cm) was examined on each plot. The findings show that climate does not significantly affect cotton production in the area, but soil fertility is a hindrance to optimal productivity, particularly in terms of the Sum of Basic Cations (SBC) and Organic Carbon (OC). According to the analysis, the soils in Larazourou, Zaguinasso, Bafime, Largatonvo, Marandallah, Ponondougou, and Marahoue are classified as "moderately suitable" (S2) for growing cotton. However, Tandokaha village is only classified as "marginally suitable" (S3) due to its poor soil chemical properties and shallow soil depth. The findings indicate that in order to enhance cotton productivity, it is necessary to implement soil management practices tailored to the specific characteristics of each soil type, emphasising strategies that can effectively improve soil fertility.

Keywords: Soil suitability, Cotton, Soil management, soil fertility, Sum of Basic Cations

5.1. Introduction

The constant human activities have led to tremendous pressure on natural resources, particularly soil, and water, which are vital for human sustenance. As a result, the agricultural area per person is decreasing. It is essential to maintain the health of these resources to meet the growing demand for food, fodder, fibre, and fuel (Surya *et al.*, 2020). Every year, 115 million bales of cotton are produced globally, which are utilized to manufacture approximately 45-50 % of all clothing, household goods, and other commercial items. Cotton is a crucial element of the textile industry, as it is the most commonly used natural fiber worldwide, representing 85% of all-natural fibers, with wool, flax, and hemp being the subsequent ones. According to Shahbandeh (2022), the total global cotton production in 2021 was 112.39 million bales. Cotton is a crucial source of income for farmers and a significant contributor to the local economy in nearly all regions where it is cultivated. In specific areas of Central Asia and West Africa, cotton exports make up over 50 % of the total export value, according to the World Wildlife Fund (2017). Cotton farming is the fourth most important agricultural export in Côte d'Ivoire, after cocoa, rubber, and cashew nuts, and it contributes 1.7 % to the country's Gross Domestic Product (GDP), according to Didi *et al*. (2018). The cotton industry is a significant economic driver for rural northern Côte d'Ivoire, providing livelihoods for around 180,000 farmers and benefiting approximately 2.5 million people (Oudin, 2020). Many constraints have been identified to its development. These factors comprise adverse weather conditions, diminishing soil quality, and the effects of pests and diseases (Zagbaï *et al*., 2006).

Soil is an essential aspect of land resources, serving as a foundation for agricultural progress and environmental stability, according to FAO (2014). Therefore, it is considered to be among the most significant reserves of biodiversity on Earth, as per INRA (2018). According to Sanchez (2002), keeping or enhancing soil productivity is a significant obstacle. Enhancing soil fertility and agricultural productivity are crucial aims of agricultural policies in West Africa, as part of the broader objective of achieving sustainable development goals by promoting eco-friendly farming practices and ensuring access to food (CORAF, 2008). Sustainable agriculture depends on sustainable land management, according to Darwish *et al.,* (2015). Land suitability refers to the suitability of land for specific land use, as defined by Driessen and Konijn (1992). According to Doula *et al*., (2017), land suitability refers to the degree to which a specific land use type is suitable for a given area or satisfies the needs of the land user. Evaluating land suitability offers insight into the limitations and prospects of land utilization, leading to informed decisions on the best use of resources. Such information is critical for effective land use planning, as stated by AbdelRahman *et al.*, (2016). The success of a crop largely depends on soil characteristics such as depth, texture, and drainage, which are influenced by climate and topography (Sehgal, 1991). According to the FAO (1993), land capability refers to the appropriateness of a particular land area for certain types of usage. The assessment of land suitability is necessary to determine the most appropriate use of a particular area and identify the factors that limit crop production for specific crops. Consequently, the main aim of this research is twofold: (1) to evaluate the appropriateness of land in the cotton basins of Cote d'Ivoire for cotton farming and (2) to suggest management practices to improve the suitability of the cotton basins for cotton cultivation.

5.2. **Materiel and methods**

5.2.1. Soil Sampling

Soil samples were obtained by utilizing a soil auger, which extracted samples from each plot at a depth ranging from 0 to 20 cm. On each plot, there were 17 sampling points, and from each point, 17 equal portions of soil samples were gathered to create a composite sample. The number of sampling points varied based on the plot's size, ranging from up to five points for larger plots (15ha). In the sampling conducted in 2021, six (6) composite soil samples were gathered in Korhogo, eleven (11) in Ferkessédougou, seven (7) in Boundiali, and thirty (30) in Mankono for each village within the four (4) departments. Consequently, a total of fifty-four 54 composite soil samples were obtained throughout the study area (Figure 14). Soil profiles were produced at a depth of 0-100 cm and then characterised on each plot in the four departments of the cotton basin. For each physico-chemical soil characteristic, the average was calculated to determine the level of these parameters in the topsoil of two selected villages in each department for the land suitability study.

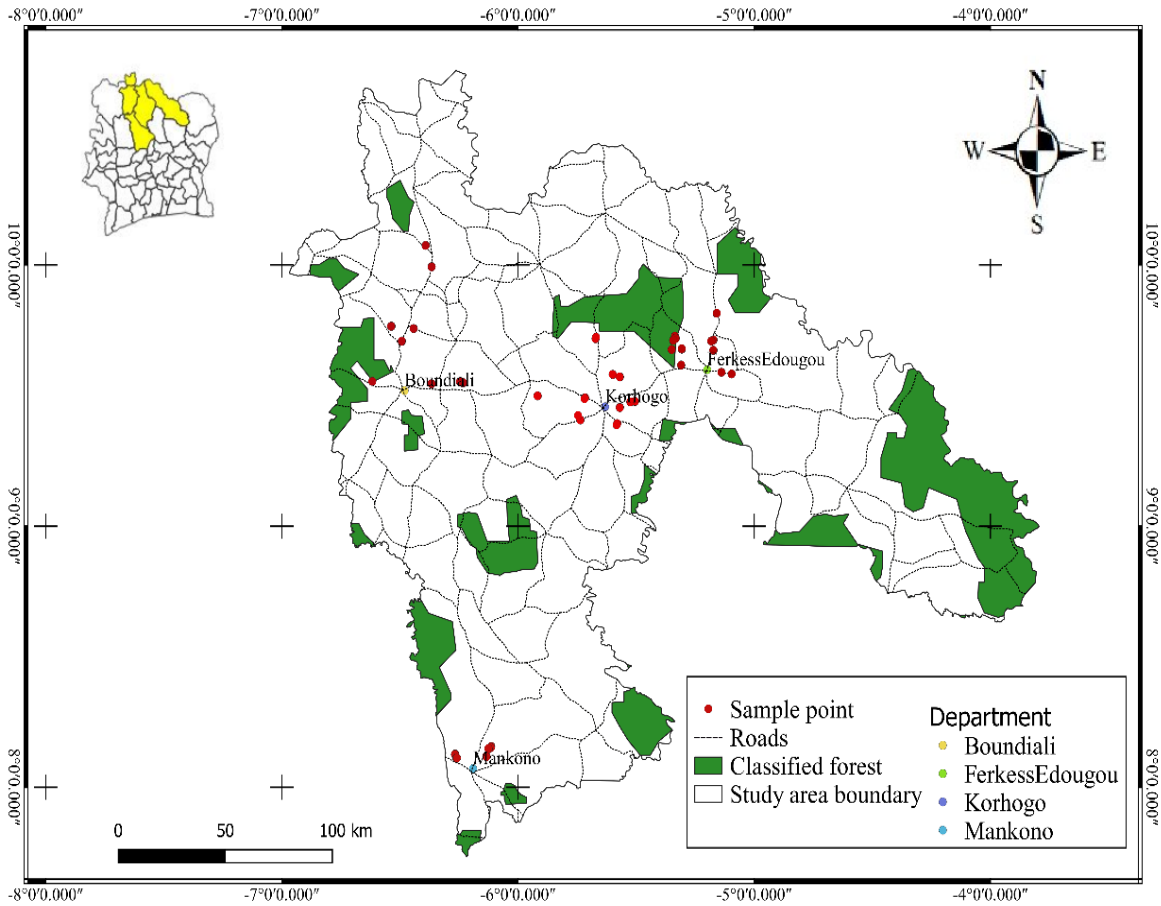


Figure 14. Location of soil sampling points for the cotton plot at Korhogo, Ferkessedougou, Boundiali, and Mankono

5.2.2. Laboratory Analysis

The 54 soil samples were transported to ENVAL (Laboratoire de l'Environnement et de l'Alimentation de Cote d'Ivoire) for analysis. Subsequently, the soil samples were air-dried, crushed, and sieved through a 2 mm mesh size. The soil particles with a size smaller than 2 mm were utilized for analyzing the physical and chemical properties. To determine the particle size distribution, Robinson's pipette method was employed, where 50g of soil was dispersed using a solution of Sodium hexametaphosphate (NaPO3) according to Bouyoucos (1962). The Wet Combustion method of Walkley-Black was employed to determine the Organic Carbon content in the soil, which involves oxidation using potassium dichromate and titration with iron sulfate (Crétenet *et al.*, 2015). Soil pH was measured by combining soil and distilled water in a ratio of 1:2.5, while the Total N and available Phosphorus were determined using the Kjeldahl wet digestion method and the Latham method, respectively (Latham, 1971). The physicochemical properties were determined using the techniques described by Tran Vin An (1978). The Cation Exchange Capacity (CEC) was determined following the guidelines of the NFX 31-130 standard (AFNOR, 1999). The standard procedure included removing all adsorbed cations from the exchange sites of the CEC and subsequently saturating the sites with ammonium (NH_4^+). The concentrations of exchangeable cations (concentrations Ca^{2+}, Mg^{2+}, K^+, and Na^+) and exchangeable aluminum were measured using Atomic Absorption Spectrophotometry (Optima 2100 DV).

5.2.3. Land-suitability evaluation

To assess the potential of land for cotton farming, both static (terrain-soil) and dynamic (climate) factors are considered. Terrain-soil factors such as topography, slope, drainage, and flooding directly affect the physical and chemical properties of the soil, which in turn determine its quality. The assessment of terrain-soil suitability for cotton farming was conducted using the criteria specified in the FAO method (FAO, 1976) and the guidelines provided by Sys *et al.* (1993). The FAO has developed a set of principles and concepts to establish regional and national land evaluation systems. The FAO's Land Evaluation Framework (FAO, 1976) assesses the suitability of each land unit for land use based on a five-member set of suitability levels, including highly suitable (S1), moderately suitable (S2), marginally suitable (S3), not suitable (N1 and N2), but limitations can be improved with management (N1), and not suitable (N2) (Tables 7&8). The land evaluation process includes three phases, namely, (i) acquiring the necessary characteristics or attributes; (ii) identifying the requirements of the land use types; and (iii) comparing the qualities or attributes with the land use requirements to evaluate their suitability. This assessment results in a limitation class for each land attribute, and the suitability class for each land unit was determined based on the number and severity of limitations (as presented in Table 7). The land suitability assessment for cotton cultivation involves comparing the needs of the cotton crop with the characteristics of each land unit. In this study, the land units were defined by the 54 sampling points across the eight villages.

Table 7. Relation between suitability classes and limitations (Sys *et al.*, 1993)

Limitations	Suitability Classes (Land classes)
0:no	S1: very suitable
1: slight	S1: very suitable
2: moderate	S2: moderately suitable
3: severe	S3: marginally suitable
4: very severe	N1: unsuitable but susceptible to correction N2: unsuitable and not susceptible to correction

Table 8. Criteria for determination of land suitability classes (Sys *et al.*, 1993)

Land classes	Criteria
S1: very suitable	land units with no, or only 4 slight limitations
S2: moderately suitable	land units with more than 4 slight limitations, and/or no more than 3 moderate limitations
S3: marginally suitable	land units with more than 3 moderate limitations, and/or one or more severe limitation (s)
N1: actually, unsuitable and potentially suitable	land units with very severe limitations which can be corrected
N2: unsuitable	land units with very severe limitations which cannot easily be corrected

5.2.4. Assessment of climatic suitability

Cultivation practices in the Côte d'Ivoire cotton basin have been defined by the Centre National de Recherche Agronomique de Cote d'Ivoire (CNRA), based on the cultivation calendar as a function of the climatic conditions present in each Agro-ecological zone (MINESUDD, 2013). The assessment of the suitability of climate conditions for cotton cultivation is based on specific climatic factors, including the amount of rainfall experienced during the growing season from June to October, the average temperature throughout the growing season, and the maximum average temperature recorded between June and October. These variables were selected because they are known to significantly impact the growth and yield of cotton crops (Sys *et al.*, 1993). The planting time for cotton in the agro-ecological zone is mainly during the first decade of May (D1: 21-31 May), while the harvesting period is from November to December. The main meteorological parameters considered in this research were rainfall, temperature, and relative humidity. These data were obtained from two primary sources: Société d'Exploitation et de Développement Aéroportuaire, Aéronautique et Météorologique (SODEXAM) and the Laboratoire Central des Sols, de l'Eau et des Plantes (LCSEP) of the Centre National de Recherche Agronomique de Côte d'Ivoire (CNRA). Temperature and relative humidity data were obtained from Google (ERA5 Copernicus ECMWF) and were downloaded at a resolution of 0.05 degrees from 1980 to 2020. The evaluation of climate suitability for cotton cultivation followed the guidelines proposed by Sys *et al.*, (1993) and focused on essential meteorological factors such as rainfall, temperature, and relative humidity, which are known to have a significant influence on cotton production.

5.2.5. Assessment of terrain and soil suitability

The Simple Limitation Method (SLM) was applied to classify the lands, which is known to be particularly appropriate for specific crops such as maize, potato, onion, and cotton, as noted by Jafarzadeh *et al*. (2008). To use the Simple Limitation Method, tables for crop requirements are prepared for each type of land use, defining class-level criteria for each characteristic. The method involves first evaluating the climatic characteristics to determine the climate class level to use in subsequent evaluations. The lowest class level for a specific climatic characteristic is used to determine the climate class level. Similarly, the land class level is determined based on the lowest class level of a particular soil characteristic. In the land evaluation process, the morphological characterisation of the soil profiles (0-100 cm depth) (Figure 4), and the Physico-chemical parameters of topsoil (0-20 cm) were first matched with the requirements of the cotton plant (Table 9). The evaluation of the soils' capacity to sustain cotton cultivation was performed by utilizing the criteria established by Sys *et al.*, (1993). The limitations associated with the soils were ranked on a scale of 0 to 4, which is presented in Table 7 and Table 8.

Table 9. Crop requirement for cotton according to Sys et al (1993)

Land characteristics	Class, degree of limitation, and rating scale					
	S1 0 100 – 95	S1 1 95 – 85	S2 2 85 – 60	S3 3 60 – 40	N1 4 40 – 25	N2 4 25 – 0
Climatic characteristics (c)						
Rainfall during the growing season	1000-850	850-750	750-600	600-500	-	<500
(mm)	<25	25-50	50-75	75-100	-	>100
Rainfall during the ripening stage						
	28-26	26-24	24-22	22-20	-	<24
Mean temp. growing stage (°C)	35-32	32-28	28-26	26-24	-	<24
Mean max temp. growing stage (°C)	<25	25-50	50-75	75-100	-	<100
Mean temp. of the ripening stage (°C)	<50	50-60	60-70	70-80	>80	-
Mean R.H. in the growing season						
Topography (t)						
Slope (%)						
(1)	0-1	1-2	2-4	4-8	-	>6
(2)	0-2	2-4	4-8	8-16	-	>16
(3)	0-4	4-8	8-16	16-30	30-50	>50
Wetness (w)						
Flooding (4)	F0	-	-	F1	-	$F2^+$
Drainage (5)						
	good	-	Moderate	Imperfect	Poor, but	Poor,
	imperfect	-	Moderate	Good	drained	Not drained
Physical soil characteristics (s)						
Texture/Structure	C<60s, SiC					
	Co,SiCL,Si,SiL,CL	C<60v, SCC>60s, L	C>60v, SL, SCL	FS,S,LS,Lcs	-	Cm,SiCmcS
Coarse fragment (%)	0-3	3-15	15-35	35-55	-	>55
Soil depth (cm)	>100	100-75	75-50	50-25	-	<25
Soil fertility characteristics (f)						
Apparent CEC ($cmol^+$/kg)	>24	24-16	<16 (-1)	<16 (+1)	-	-
Base saturation (BS) (%)	>80	80-50	50-35	>35		-
Sum of basic cations (SBC)	>6.5	6.5-4; 6.4-6.0	4-2.8	2.8-1.6	<1.6	-
($cmol^+$/kg)			6-5.6	5.6-5.2	<5.2	
pH_{H20}	6.7-7.	7.0-7.6	7.6-8	8-8.5	-	<8.2
					-	-
Organic carbon (%)	>2.0	2-1.2	1.2-0.8	<0.8	-	-
(6)	>1.8	1.2-0.8	<0.8	-	-	-
(7)	>0.8	0.8-0.4	<0.4	-		
. (8)						
EC_e (dSm^{-1})	<2	2-4	4-8	8-15	>15	-

Sys et al. (1993). Notes: Cm, massive clay;SiCm, massive silty clay;C+60,v, very fine clay vertisol structure; C+60,s, very fine clay blocky structure; CL, clay loam; LS, loamy sand, F0, no flood limitation; F1, slight. (1) Irrigated, (2) Full mechanaziation (3) Animal traction\Manual (4) Medium and fine textured soils (5) coarse texture soils

5.3. Results

5.3.1. Soil morphological description and physico-chemical properties

The surface horizons of the soils in the various cotton production fields were characterised by the following descriptive features for the most part (Figure 17. a, b, c, d, e, f, g, and h). In each department, two villages were chosen to conduct the land suitability study, for each Physico-chemical soil characteristic, the average was calculated to determine the level of these parameters in the topsoil.

In the department of Korhogo, the soils that support cotton cultivation in the villages of Bafime and Larazourou have superficial horizons. The soils in the village of Bafime are red (5 YR 4/6), dry, humus-bearing, lumpy structure induced by coarse material and roots, Sandy Loam (SL) texture, very porous, numerous roots with a preferential sub-horizontal orientation, moderate internal drainage, diffuse transition by colour, more or less regular boundary. The village of Larazourou has soils with a brown colour (7.5 YR 5/3), dry, humic, lumpy structure induced by coarse material and roots, Sandy Clay Loam (SCL) texture, very porous, numerous roots with a preferential sub-horizontal orientation, moderate internal drainage, diffuse transition by colour, more or less regular limit. The soils that support cotton cultivation in the villages of Largatonvo and Tandokaha from the Ferkessédougou department have superficial horizons. The soils of the village of Largatonvo are very dark brown colour (7.5 YR 2.5/2), fresh, humus-bearing, lumpy with induced sub-angular polyhedral structure, Sandy Clay Loam (SCL) texture, porous, very numerous roots with preferential sub-horizontal orientation, good internal drainage, progressive transition. The village of Tandokaha has soils with a dark brown colour (10 YR 3/4), fresh, humic, lumpy structure, Loamy sand (LS) texture, porous, many roots with preferential sub-horizontal orientation, good internal drainage, and diffuse transition. The soils that support cotton cultivation in the villages of Ponondougou and Zaguinasso in the Bondiali department have superficial horizons with the following morphological soil characteristics: The soils of Ponondougou village vary in colour from very dark grey color (10 YR 3/1) to dark yellowish brown (10 YR 3/6) color, fresh, humic, lumpy structure, Sandy Clay Loam (SCL) texture, very porous, many roots with preferential sub-horizontal orientation, good internal drainage, diffuse transition by colour. The village of Zaguinasso has soils with dark reddish brown (5 YR 3/3) to reddish brown (5 YR 4/4) colours, fresh, very humic, lumpy to polyhedral structure, Sandy Loam (SL) texture, very porous, many roots with preferential subhorizontal orientation, moderate internal drainage, diffuse transition by colour, more or less gradual boundary.

The soils that support cotton cultivation in the villages of Maradallah and Marahoue in the department of Mankono in the centre of the cotton basin have superficial horizons with the following morphological soil characteristics: the soils of the village of Maradallah are dark greyish-brown color (2.5 YR 3/2), fresh, humus-bearing, lumpy structure with polyhedral debit, Sandy Clay Loam (SCL) texture, very porous, cohesive, many roots with preferential sub-horizontal orientation, moderate internal drainage, gradual transition. The village of Marahoue has a very dark red soils color (2.5 YR 2.5/2), fresh, very humic, induced lumpy structure, and Sandy Loam (SL) texture, very porous, many roots with preferential sub-horizontal orientation, moderate internal drainage, and diffuse transition. The findings demonstrate that the soils in the examined areas have pH levels above 6, ranging from 6.6 to 7.1, indicating that the surface soils are slightly acidic to slightly alkaline. The pH levels are similar across most of the soils and are approaching neutral. As a result, soil acidity does not impose a significant limitation on cotton growth. However, there are slight variations in pH levels, ranging from 0.1 to 1.0 units, across different locations, leading to alterations in the chemical and physical properties of the soil, including cation exchange capacity and other physical attributes, as observed by Pernes *et al.* (2005). The base saturation percentage in the soils of the studied area falls within the range of 52 to 62 %, which aligns with the findings of previous studies that reported a range of 40 to 60 % (Amonmide *et al.*, 2019). The soils in the study area exhibit relatively low levels of soil organic carbon, ranging from 0.51 % to 0.88 %, as presented in Table 11. This rate is below the average threshold value of 2 % (Dabin, 1970). The Cation Exchange Capacity (CEC) of the soil's ranges from 6.49 to 8.52 $cmol^+/kg$, with relatively low values. The exchangeable bases including Ca^{2+}, Mg^{2+}, Na^+, and K^+ contribute to almost 90 % of the total CEC of these soils, as reported by Reddy *et al.* (2012). Insufficient amounts of these bases in the soil are unfavorable for the growth of cotton plants. The soils in the study area primarily consist of Ca^{2+} as the dominant cation, with concentrations ranging from 2.40 to 3.97 $cmol^{+}/kg$. In all soil samples, Ca^{2+} is the most abundant cation, followed by Mg^{2+}, Na^{+}, and K^{+}. The salt concentrations in the study area soils are within the desirable range, as reflected by their electrical conductivity values ranging from 0.04 to 0.06 dS m^{-1}. This suggests that the soils are not at risk from salinity and are free of soluble salts (Santos & Castro, 2020). Most of the soils analysed exhibited a relatively larger proportion of sand particles in comparison to silt and clay fractions, as revealed by the particle size distribution.

5.3.2. Landform characterisation

The various landforms present in the cotton basin, specifically in the departments of Korhogo, Ferkéssédougou, Boundiali, and Mankono are described as follows: The area has a uniform relief with elevations ranging from 300 to 400 meters on average. Granite inselbergs can be observed in the landscape, occasionally rising to more than 500 meters in height. The Korhogo region consists of lateritic plateaus with elevations ranging from 0 to 3 meters. These plateaus have a very gentle and regular slope towards the Bandama River. The slopes lie immediately below the escarpments, mainly in the form of an elongated area with slopes of 2 % to 8 %. The Boundiali plateaus are defined as a peneplain with an altitude of 400-500m. The flatness of this study area is interrupted by isolated residual reliefs of varied petrographic nature: granitic inselbergs (Boundiali, Korhogo, Ferkéssédougou); hills of melanocratic rocks (Figure 15).

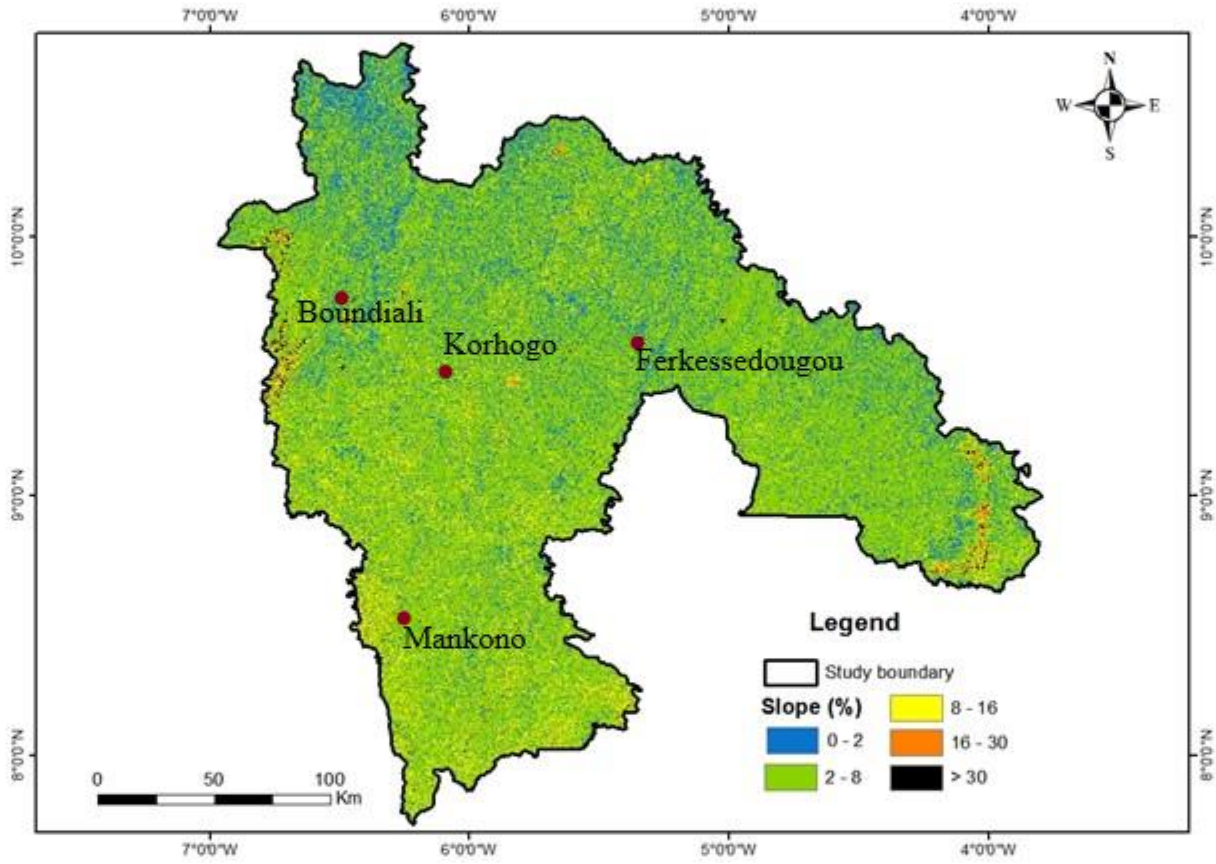


Figure 15. Slope map of the study area

5.3.3. Climate requirement for cotton production

The distribution of various climate factors from the 1980s to the 2020s is presented in Table 10. Cotton cultivation is primarily influenced by rainfall, temperature, and relative humidity, as shown in Figure 16. In the cotton-growing region of the northern Savannah zone, the growing season commences from June to October, while the ripening season occurs between November and December, which is also the harvesting period for cotton. The average rainfall and temperature conditions during the growing and ripening season are appropriate for cotton cultivation. Nevertheless, the relative humidity in the study region does not favor the growth requirements of cotton.

Table 10. Average of climatic variables in the different study areas from 1980 to 2020

Area	RGS mm	RRP mm	TGS (°C)	TGSmax (˚C)	TRS (˚C)	RH
Korhogo	909	23	25.3	32.79	25.5	79
Ferkéssédougou	916	25	25.8	33.12	25.7	77
Boundiali	1027	25	25.4	32.43	25.3	79
Mankono	845	24	24.7	30.94	25.1	83

RGS: Rainfall during the growing season (mm), RRP: Rainfall during the ripening season, TGS: Mean temp. in the Growing season; TGS_{max}: Mean max temp. in the Growing Stage, TRS = Mean Temp of Ripening Stage; RH = Relative Humidity in the growing season

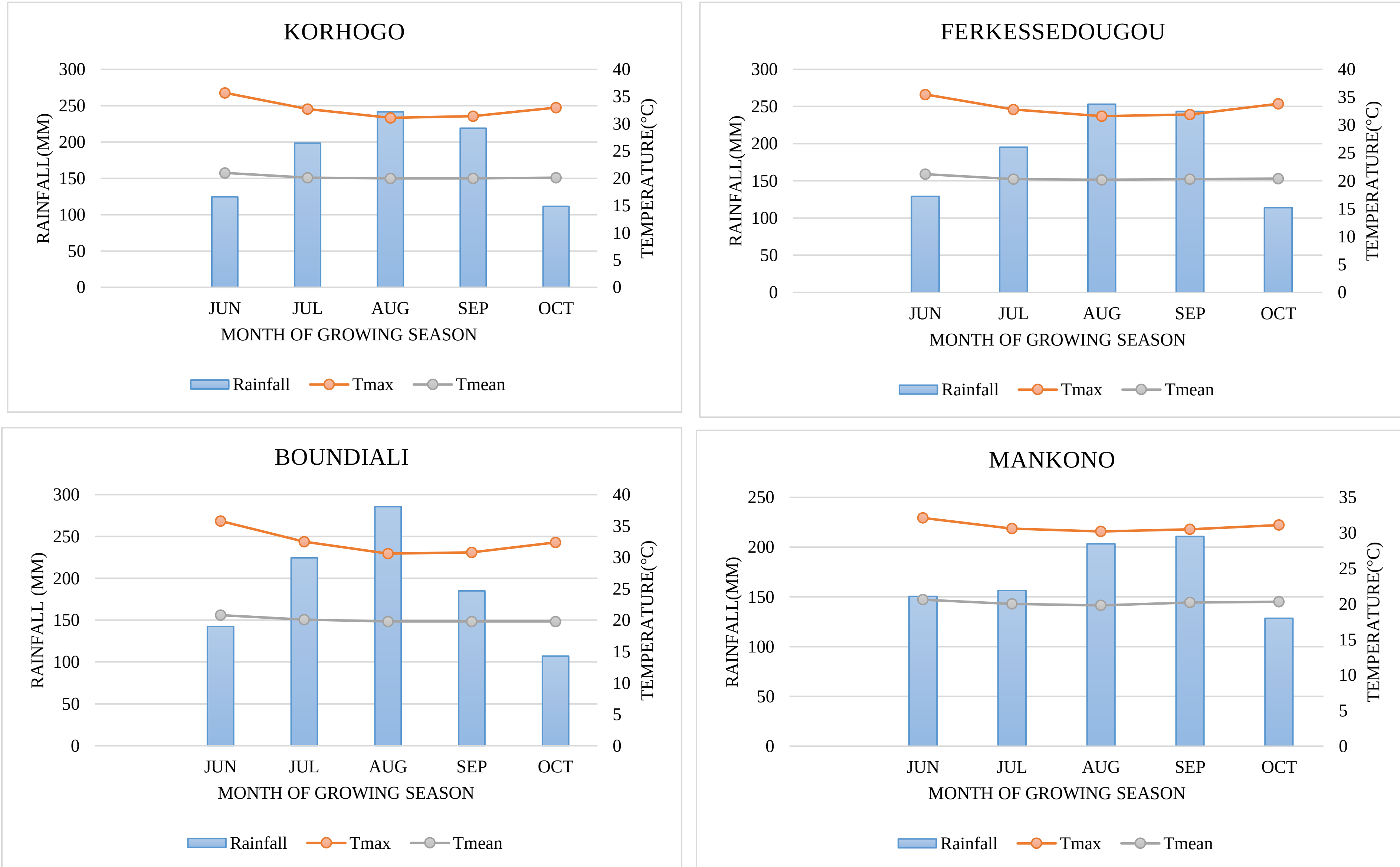


Figure 16. The trend of the rainfall, mean temperature, and maximum temperature during the growing satge (June-October) of cotton in the study area for the years 1980 to 2020

Table 11. Average of different soil physico-chemical characteristics used for suitability assessment

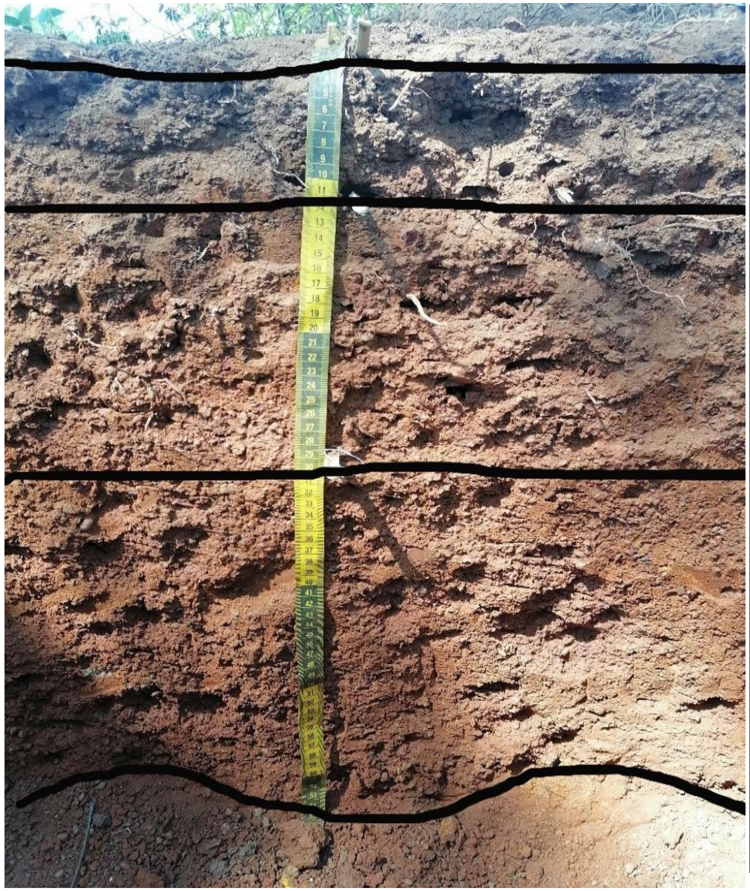
Area/ Villages	Slope (%)	Drainage	Flooding	Soil depth(cm)	Texture class	Coarse fragments (%)	Apparent CEC cmol⁺/kg	pH_{H20}	EC (dSm^{-1})	BS (%)	SBC cmol⁺/kg	OC (%)
KORHOGO												
Bafime	2-3	Moderate	F_0	65	SL	24.71	39.5	6.53	0.06	52	3.82	0.75
Larazourou	2-3	Moderate	F_0	100	SCL	24	32.16	6.49	0.06	62	4.97	0.82
FERKESSÉDOUGOU												
Largatonvo	2-3	Good	F_0	100	SCL	24.06	39.5	6.87	0.07	68	6.07	0.51
Tandokaha	2-3	Good	F_0	>20	LS	15	42.91	6.75	0.04	58	4.89	0.85
BOUNDIALI												
Ponondougou	2-3	Good	F_0	80	SCL	21	23.33	6.45	0.04	61	4.97	0.64
Zaguinansso	2-3	Moderate	F_0	110	SL	25	34.58	6.9	0.06	57	4.09	0.88
MANKONO												
Marandallah	2-3	Moderate	F_0	120	SCL	23.76	25.04	7.20	0.05	69	7.29	0.73
Marahoue	2-3	Moderate	F_0	95	SL	22.64	23.74	7.13	0.05	54	3.75	0.72

SBC: Sum of Basic Cations (cmol⁺/kg)

BS: Base Saturation (%)

CEC: Cation Exchange Capacity (%)

(a) Department KORHOGO /village: Bafime (Latitude:9° 28'8.59'' N; Longitude: 5° 33' 22.13 W)



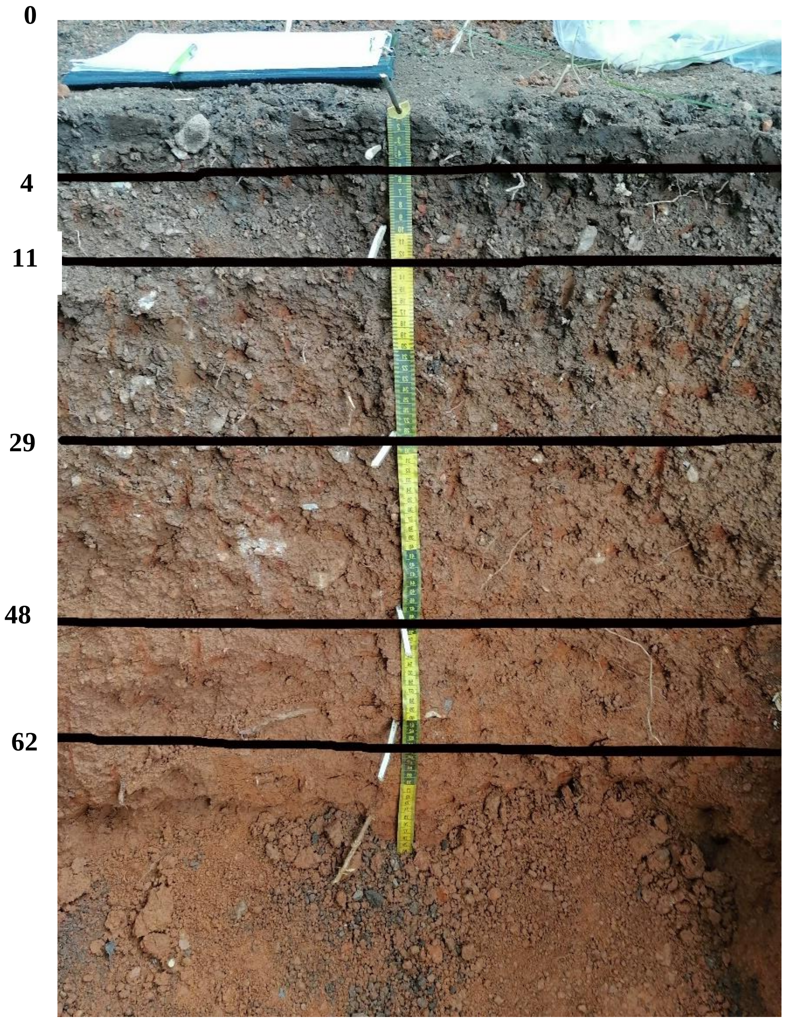
Depth (cm)	Morphological characteristics
0 - 2	Dry, humus-rich, red (5 YR 4/6), lumpy structure induced by coarse elements and roots, loamy sand texture (5-10 % clay), very porous, numerous roots (dm to mm) with preferential subhorizontal orientation, good internal drainage, 18.33 % of gravel content. Diffuse transition by color, more or less regular border.
2 - 11	Fresh, humus, yellowish red (5 YR 4/6), gritty structure induced by coarse elements and roots, loamy sand texture (10-15% clay), porous, coherent, many roots (mm) with preferential subhorizontal orientation, good internal drainage, 26 % of gravel content. Clear progressive transition.
11 - 29	Fresh, humus-bearing, yellowish-red (5 YR 4/6), gritty structure induced by coarse elements and roots, loamy sand texture (10-15 % clay), porous, coherent, many roots (mm) with preferential subhorizontal orientation, good internal drainage, 28 % of gravel content. Clear gradual transition through.
29-65	Fresh, not very humic, yellowish red (5 YR 5/6), general polyhedral subangular structure, sandy clay loam texture with medium sand (25-35 % clay), not very porous, coherent, a few rare roots (mm) with preferential subhorizontal orientation, 26 % of gravel content, medium internal drainage.

(b) Department KORHOGO /village: Larazourou (Latitude:9° 29’59.3’’ N; Longitude: 5° 55’ 7.17 W)

0
2
12
36
55

Depth (cm)	Morphological characteristics
0-2	Dry, humic, brown (7.5 YR 5/3), lumpy structure induced by coarse elements and roots, loamy sand texture, very porous, numerous roots (dm to mm) with preferential subhorizontal orientation, good internal drainage, 13 % of gravel content, diffuse transition by colour, more or less regular border.
2 - 12	Fresh, humic, brown (7.5 YR 5/4), gritty structure induced by coarse elements and roots, sandy clay loam texture, porous, coherent, numerous roots (mm) with preferential subhorizontal orientation, good internal drainage, 27 % of gravel content. Clear progressive transition.
12 - 36	Fresh, not very humic, brown (7.5 YR 5/8), gritty structure induced by coarse elements and roots, loamy sand texture (15-25 % clay), porous, coherent, some acini (mm) with preferential subhorizontal orientation, 47 % of gravel content, good internal drainage. Progressive transition.
36-55	Fresh, non-humic, brown (7.5 YR 5/6), alteration spot, dark red (2.5YR 3/6) polyhedral structure with subangular grumbling, sandy clay loam texture (20-35% clay), not very porous, coherent, some roots (mm) with preferential subhorizontal orientation, 23 % of gravel content, medium internal drainage. Progressive transition.
55 -100	Fresh, not humic, brown (7.5 YR 5/6), alteration spot (3.5YR 3/6), polyhedral structure with sub-angular grumbling, sandy-clay texture (45% clay), not very porous, coherent, some roots (mm) with preferential sub-horizontal orientation,10 % of gravel content, average internal drainage.

(c) <u>Department FERKESSÉDOUGOU /villages: Largatonvo (latitude: 9° 48' 52.53" N | Longitude: 5° 9' 29.07" W</u>



Depth (cm)	Morphological characteristics
0-4	Fresh, humus-bearing, very dark brown (7.5 YR 2.5/2), induced lumpy structure, loamy sand texture (10-15% clay), very porous, very numerous roots (dm to mm) with preferential subhorizontal orientation, good internal drainage, 4.2 % of gravel content. Diffuse transition.
4 - 11	Fresh, humus-bearing, dark brown (7.5 YR 3/4), subangular polyhedral structure induced by coarse elements, loamy sand texture (15-20% clay), porous, coherent, very numerous roots (mm) with preferential subhorizontal orientation, 22.42 % of gravel content, good internal drainage, gradual transition.
11 - 29	Fresh, low humus, bright brown (7.5 YR 4/6), subangular polyhedral structure induced by coarse elements, loamy sand texture (15-25% clay), very porous, coherent, numerous roots (mm) with preferential subhorizontal orientation, 44.46 % of gravel content, good internal drainage. Progressive transition.
29-48	Fresh, low humus, bright brown (7.5 YR 5/6), subangular polyhedral structure induced by coarse elements, sandy clay loam texture (25-35%), porous, coherent, numerous roots (mm) with preferential subhorizontal orientation, 38.66 % of gravel content, good internal drainage. Progressive transition.
48-62	Fresh, very little humus, bright brown (7.5 YR 6/8), polyhedral to lumpy structure, sandy-clay texture (35-45% clay), porous, coherent, some roots (mm) with preferential subhorizontal orientation, 25.13 % of gravel content, good inter-horizon drainage, diffuse transition.
62-100	Fresh, very little humus, bright brown (7.5 YR 5/8), subangular polyhedral structure, sandy-clay texture (35-45% clay), porous, coherent, few roots (mm) with preferential subhorizontal orientation, 9.66 % of gravel content. Medium internal drainage.

(d) <u>Department FERKESSÉDOUGOU /village: Tandokaha (Latitude: 9° 43' 39.94" N |Longitude: 5° 20' 9.0" W)</u>

0

3

14

21

Depth (cm)	Morphological characteristics
0-3	Fresh, humic, dark brown (10 YR 3/4), lumpy structure, fine sand texture (5-10% clay), porous, numerous roots (dm to mm) with preferential subhorizontal orientation, 2.67 % of gravel content, good internal drainage. Diffuse transition.
3 – 5/14	Fresh, humic, dark yellowish brown (10 YR 3/4), lumpy structure induced by coarse elements, loamy sand texture 10-15% clay), porous, coherent, numerous roots (mm) with preferential subhorizontal orientation, 2.26 % of gravel content, good internal drainage. Diffuse transition
5/14 – 8/21	Fresh, humic, dark yellowish brown (10 YR 3/4), gritty structure induced by gossamer elements, fine sand texture (5-10% clay), porous, coherent, few roots (mm) with preferential subhorizontal orientation, 40 % of gravel content, good internal drainage.
21 and over	Ferruginous Terrace

(e) Department BOUNDIALI /village: Ponondougou (Latitude: 9° 32' 38.15" N | Longitude: 6° 22' 30.13" W)

Depth (cm)	Morphological characteristics
0-2	Fresh, humic, very dark grey (10 YR 3/1), lumpy structure, loamy sand texture (10-15% clay), very porous, numerous roots (dm to mm) with preferential subhorizontal orientation, good internal drainage,4.6 % of gravel content, good internal drainage. Diffuse transition by colour.
2 - 7	Fresh, humic, dark yellowish brown (10 YR 3/6), gritty structure, loamy sand texture (10-20% clay), very porous, coherent, many roots (mm) with preferential subhorizontal orientation, good internal drainage,15 % of gravel content, good internal drainage. Clear progressive transition.
7 - 20	Fresh, not very humic, bright yellowish brown (10 YR 5/6), gritty structure with polyhedral debit, sandy-clay loam texture (20-25 % clay), porous, coherent, many roots (mm) with preferential subhorizontal orientation, good internal drainage, 16.1% of gravel content, good internal drainage. Progressive transition.
20-45	Fresh, low humus, brownish yellow (10 YR 6/8), (7.5YR/8) bright brown gritty structure with polyhedral debit, sandy clay loam texture (>35% clay), low porosity, coherent, many roots (mm) with preferential subhorizontal orientation, 25% of gravel content, good internal drainage. Medium internal drainage.
45-58	Fresh, non-humus, brownish yellow (10 YR 6/8), (7.5YR/8) bright brown gritty structure with polyhedral debit, sandy clay loam texture (>35% clay), poorly porous, coherent, many roots (mm) with preferential subhorizontal orientation, 46 % of gravel content, good internal drainage, poor internal drainage, abrupt transition.
58-80	Ferrous concretion

(f) Department BOUNDIALI /village: Zaguinasso (Latitude: 10° 4' 25.17" N |Longitude: 6° 23' 29.89"

Depth (cm)	Morphological characteristics
0-4	Fresh, very humic, dark reddish-brown (5 YR 3/3), lumpy to polyhedral structure, loamy sand texture (10-15 % clay), very porous, numerous roots (dm to mm) with preferential subhorizontal orientation, good internal drainage,11.19 % of gravel content, diffuse transition by color, more or less regular boundary.
4- 12	Fresh, humus-bearing, reddish-brown (5 YR 4/4), gritty structure with polyhedral debit, sandy loam texture (15-25 % clay), very porous, coherent, many roots (mm) with preferential subhorizontal orientation, 16 % of gravel content, good internal drainage, gradual transition.
12 - 38	Fresh, low humus, pink (5 YR 8/6), gritty structure due to coarse elements, sandy clay loam texture (25% clay), very porous, coherent, many roots (mm) with preferential subhorizontal orientation, good internal drainage,40 % of gravel content gradual transition.
38-54	Fresh, not very humic, yellowish red (5 YR 5/6), general polyhedral subangular structure, sandy clay texture (35 % clay), porous, coherent, some roots (mm) with preferential subhorizontal orientation, 32 % of gravel content, medium internal drainage, diffuse transition.
54-80	Fresh, not very humic, yellowish red (5 YR 5/6), (2.5YR 3/6) dark red, general subangular polyhedral structure, sandy-clay texture (35 % clay), not very porous, coherent, few roots (mm) with preferential subhorizontal orientation, 19.2 % of gravel content, medium internal drainage. Diffuse transition.
80-110	Fresh, non-humus, yellowish red (5 YR 5/8), (2.5YR 3/6) dark red, general subangular polyhedral structure, sandy-clay texture (45 % clay), not very porous, coherent, few roots (mm) with preferential subhorizontal orientation, 32 % of gravel, content medium internal drainage.

(g) Department MANKONO /village : Marandallah (Latitude : 8° 25' 21.33" N | Longitude : 5° 55' 4.98" W)

Depth (cm)	Morphological characteristics
0 - 10	Fresh, humic, dark greyish brown (2.5 YR 3/2), lumpy to polyhedral structure, loamy sand texture (10-15% clay), very porous, numerous roots (dm to mm) with preferential subhorizontal orientation, good internal drainage, 10 % of gravel content diffuse transition by colour, more or less regular boundary.
10 - 25	Fresh, low humus, dark olive-brown (2.5 YR 3/3), gritty to polyhedral structure, sandy-clay to medium sandy clay loam texture (20-25% clay), very porous, coherent, few roots (mm) with preferential subhorizontal orientation, 40 % of gravel content good internal drainage, 1% coarse elements, gradual transition.
25 - 41	Fresh, low humus, olive-brown (2.5 YR 4/6), general polyhedral structure with sub-angular debitage, sandy-clay loam texture (25-35% clay), porous, coherent, few roots (mm) with preferential subhorizontal orientation, 30% of gravel content medium internal drainage, gradual transition.
41-73	Fresh, low humus, light olive-brown (2.5 YR 4/6), general polyhedral structure with sub-angular debitage, sandy clay loam texture (25-35 % clay), porous, coherent, some rare acini (mm) with preferential subhorizontal orientation, 24 % of gravel content medium internal drainage. Diffuse transition.
73-120	Fresh, very low humus, olive-brown (2.5 YR 5/8), general polyhedral structure with sub-angular debitage, sandy clay loam texture (>35% clay), low porosity, coherent, few roots (mm) with preferential sub-horizontal orientation, 28 % of gravel content medium internal drainage.

(h). Department MANKONO (CIDT) /village : Marahoue (8° 7' 35.71" N | 6° 16' 0.22" W)

Depth (cm)	Morphological characteristics
0 - 11	Fresh, very humic, very dark red (2.5 YR 2.5/2), induced lumpy structure, fine sand texture (5% clay), very porous, numerous roots (dm to mm) with preferential subhorizontal orientation, 2 % of gravel content good internal drainage, gradual transition.
11 - 26	Fresh, low humus, dull red (2.5 YR 5/2), particulate structure, loamy sand texture, very porous, coherent, numerous roots (mm) with preferential subhorizontal orientation, good internal drainage, 17.32 % of gravel content, diffuse transition.
26 - 40	Fresh, not very humic, dull red (2.5 YR 5/3), particulate structure, sandy loam texture, very porous, coherent, numerous roots (mm) with preferential subhorizontal orientation, 31.41 % of gravel content good internal drainage, horizon, sharp transition.
40-64	Fresh, very little humus, reddish-yellow (7.5 YR 6/8), dark red (2.5 YR 4/8) subangular polyhedral structure, sandy clay loam texture (15-25% clay), not very porous, coherent, some roots (mm) with preferential subhorizontal orientation, 38 % of gravel content medium internal drainage, horizon, diffuse transition.
64-95	Fresh, very little humus, reddish-yellow (7.5 YR 6/8), dark red (2.5 YR 4/8) subangular polyhedral structure, sandy clay texture (>35% clay), not very porous, coherent, some roots (mm) with preferential subhorizontal orientation, 38 % of gravel content poor internal drainage.

Figure 17. Soil profile characteristics of the study area (a,b,c,d,e,f,g,h)

5.3.4. Climatic Suitability evaluation for cotton crop

To identify appropriate land use types, the study assessed the agro-climatic conditions including temperature (°C), relative humidity, and total rainfall during the growing season (mm). The results revealed that the agro-climatic conditions in the study area are moderately suitable (S2) for the chosen cotton varieties, as detailed in Table 12. The moderate suitability is due to the relative humidity that is very high in the studied departments in the study area. Tables 12 and 13 present a comprehensive overview of the climate and soil parameters in the research area, serving as the basis for evaluating the suitability of the land for cotton cultivation. However, the climate requirements for land suitability for cotton are suitable for cotton growing with the suitability class moderately suitable (S2). Although relative humidity is very high in the departments of the study area, this does not affect the climatic suitability for cotton cultivation, which remains moderately suitable (S2) for cotton crops. The examination shows that the soils in Larazourou, Largatonvo, Ponondougou, Bafime, Zaguinasso, Marandallah, and Marahoue villages are moderately suitable (S2) for growing cotton. However, the village of Tandokaha is only marginally suitable (S3) due to its texture and shallow soil. The fertility inadequacy can be remedied through the application of amendments and the adoption of improved agronomic and conservation practices.

Table 12. Determination of the climatic suitability class and the corresponding limitation level based on the evaluation of the number and degree of limitations (Table 7)

Area	RGS	RRS	TGS (°C)	TGSmax (˚C)	TRS (˚C)	RH	Max Limitation	Suitability class
Korhogo	0	0	1	1	1	3	L2	S2
Ferkéssédougou	0	0	1	1	1	3	L2	S2
Boundiali	0	0	1	1	1	3	L2	S2
Mankono	0	0	1	1	1	4	L2	S2

Table 13. Limitation classes of the soil characteristics for each of the eight soil profiles and soil suitability class based on the evaluation of the number and degree of limitations (Table 7)

Area/ Land characteristics	Bafime	Larazourou	Largatonvo	Tandokaha	Ponondougou	Zaguinasso	Marandallah	Marahoue
Topography								
Slope (%) (Manual tillage operation)	0	0	0	0	0	0	0	0
Drainage	2	2	0	0	0	2	2	2
Flooding	0	0	0	0	0	0	0	0
Soil characteristics								
Texture class	2	2	2	3	2	2	2	2
Coarse fragments (vol %)	2	2	2	1	2	2	2	2
Depth (cm)	2	1	1	4	1	0	0	1
Soil fertility								
CEC (soil) (cmol (p^+) $^{kg-1}$	0	0	0	0	1	0	1	1
SBC (cmol$^+$/kg)	2	1	1	1	1	2	2	0
BS (%)	1	1	1	1	1	1	1	1
O.C. (%)	1	0	2	0	1	1	1	1
ECe (dS m^{-1})	0	0	0	0	0	0	0	0
pH_{H2O}	0	0	0	0	0	0	1	1
Suitability class for dominant soil	**S2**	**S2**	**S2**	**S3**	**S2**	**S2**	**S2**	**S2**

5.4. Discussion

5.4.1. Climatic suitability for cotton crop

Climatic conditions are one of the main factors that interfere with cotton growing, as with all types of planting. It is crucial to give careful attention to comprehending the function of climate in this process. This research integrated with previous studies to identify the climate factors that could impact the suitability of cotton cultivation (Xiaoyu *et al.,* 2021). According to the findings, the climatic conditions in the northern region of the Savannah zone in Côte d'Ivoire meet the necessary levels of rainfall and temperature for successful cotton cultivation. The environmental factors related to temperature and precipitation play a crucial role in determining the climate suitability of cotton. Cotton is a crop that requires warm temperatures, and its growth and metabolism are adapted to high temperatures (Burke and Wanjura., 2010). Therefore, temperature has a significant impact on cotton yield and fiber quality (Luo *et al.,* 2014). According to CIRAD (2006), it is evident that the cotton plant needs a substantial amount of heat, ranging from 25 to 35°C for 150 days. According to Conaty *et al.,* (2012), the ideal temperature for the growth and development of cotton is 28°C. Cotton can be grown profitably in areas where rainfall is between 850 and 1100 mm during the growing phase. However, economic yields cannot be achieved in areas where rainfall is less than 500 mm. Thus, 500 mm of well-distributed rainfall is needed to achieve higher yields. During the harvest period, excessive rainfall, for more than two weeks, affects the opening of the fruits, as well as reducing the quality of the cotton fibre. This factor occurs because too much rain causes a great loss of waxes, which are fundamental in the spinning process. According to Zhang *et al.,* (2021), cotton is highly sensitive to water-logging stress, which can result in a decrease in the photosynthetic rate and significant crop failure or yield loss. The initial growth stage of cotton requires adequate rainfall, while it needs dry and sunny conditions after the flowering stage.

Even though the climate requirement (rainfall and temperature) is suitable for the cotton crop, the relative humidity is not the same, in the study area, this relative humidity is above the requirement for cotton growing. If there is too much moisture throughout the entire growth phase, it can negatively affect cotton yields by either hindering plant growth directly or creating conditions that promote disease and parasitism indirectly (Stern *et* *al.*, 2006). Additional experiments were conducted by the National Center for Agronomic Research (CNRA) on a monitoring site in Côte d'Ivoire to measure the influence of parasitism on cotton yield. According to Elodie *et al.*, (2008), the incidence of parasitism was observed to rise as one traveled from the Northwest to the South. Consequently, temperature and humidity could be the sole indicators in the majority of cases.

5.4.2. Land suitability for cotton crop

The analysis of the soil's potential fertility based on its organic carbon (OC) and soil bulk density (SBC) indicates that the majority of the soils have limitations in at least one of these properties. However, most soils have no limitations in soil pH_{H20}. According to Sehgal (1990), soils containing over 60 % clay content and coarse loamy/sandy soils with compact structures are considered crucial for successful cotton farming. The soil's physical properties are generally not a significant constraint except in areas where the clay content is very low. In the villages of Larazourou, Zaguinasso, Bafime, Largatonvo, Marandallah, Ponondougou, and Marahoue, the sand (80 %) is more than clay and silt, this is not favourable for the cotton crop because it is due to the availability of the clay with exchangeable cations Ca^{2+}, $Mg^{2+,}$ and K^{+} that the chemical richness of the soil is acquired. Sehgal (1991) recommends that for optimal cotton growth, it is ideal to have a soil depth ranging from 100 cm to 200 cm, as suggested by the FAO. On the other hand, a soil depth of less than 100 cm is not economically viable for achieving satisfactory cotton growth. The depth of the soils in the different villages of departments of the study area shows depths above 90 cm (Guessan *et al.*, 2015), except for the village of Tandokaha where the depths are below 90 cm.

Cotton is a crucial crop in northern Côte d'Ivoire and is grown under various soil conditions and on diverse landforms in the study region. The soil suitability for cotton cultivation was evaluated based on climate, soil relief, and soil site characteristics. The study revealed that a large portion of the study area is appropriate for growing cotton, and with the use of intensive farming techniques, the suitability can be increased. However, to improve the classification of suitability for cotton cultivation, efforts must be made to address limitations like erosion, fertility, and water availability through appropriate soil conservation and amelioration measures. However, certain restrictions such as soil depth, slope, and stoniness, which are permanent characteristics, may be challenging to rectify. The study indicates that only the soils in the villages of Larazourou, Largatonvo, Ponondougou, Bafime, Zaguinasso, Marandallah, and Marahoue were “moderately suitable” (S2) for cotton crops. However, soils in the village of Tandokaha, was ‘‘marginally suitable’’ (S3) for the cultivation of cotton due to low soil chemical properties and soil depth. Thus, utilizing a balanced mix of organic and inorganic fertilizers in these soils can achieve sustainable cotton yields while preserving soil fertility for future generations without any degradation.

5.4.3. Management options to improve soil fertility

The different villages in the study area need to improve their soil fertility, among them, some need a crucial improvement of soil fertility, mainly the villages of Marandallah, Zaguinasso, and Bafime for Sum of Exchangeable Bases (SBC), for soil organic carbon (OC) only the village of Largatonvo needs to improve soil on it. When low OC is the most limiting factor then farmers need to increase OC by returning crop residues, adding organic fertilizer like compost or manure, or growing additional cover crops that are incorporated into the soil, or adopting a cut-and-carry system where grasses in a fallow vegetation cut and carried to the cotton plots. To increase SBC, the fastest, most efficient, and most sustainable way is to add cations like Ca^{2+} and Mg^{2+} as ground rocks (e.g., limestone) or mineral fertliizers that contain these elements. The application of these fertilizers should be combined with increasing the OC content (management options to do this are already mentioned below). In terms of soil fertility management, it should be noted that enough technologies have been generated by research, but the results are poorly integrated into development (Lompo *et al.*, 2000).

These low chemical properties are mainly due to the poor management of cotton farming practices. Soil fertility can be further improved not only by the introduction of cover crops, which add organic matter to the soil, thus improving its structure, condition, and fertility but also by the introduction of green manures or leguminous crops between the spacing of two cotton plants (beans, groundnuts), which fix atmospheric nitrogen through the process of biological nitrogen fixation. Zhang *et al.*, (2013) found that the incorporation of leguminous green manure crops could enhance the levels of exchangeable Ca^{2+}, Mg^{+}, K^{+}, and CEC in the soil. Although chemical fertilisers can improve soil fertility, the increasing popularity of organic matter amendments suggests that biochar can produce promising outcomes in improving soil fertility, especially in tropical soils that are severely degraded.

In addition, Bama *et al.* (2017) state that improper tillage practices by cotton growers do not have a direct impact on plant growth; rather, they lead to a decrease in soil organic carbon levels and degradation of soil structure, which ultimately affects plant growth. Fallowing is also a method of soil fertility management to improve the chemical composition of the soil, however, this method is difficult to apply due to the lack of arable land for crops, which leads cotton farmers to reuse cotton plots every year. Cerri *et al.* (2007) propose that the adoption of various management strategies, including the cultivation of new crop varieties with deep root systems, the effective utilization of organic amendments like compost and manure, the implementation of improved crop rotations, the enhancement of internal drainage systems, and appropriate fertilization practices, can potentially lead to an augmentation in Soil Organic Carbon (SOC) reservoirs. The integrated management approach to cotton cultivation combines the principles of organic and conventional agriculture. This fusion dominates in the domain of managing soil productivity.

5.4.5. Management options to improve soil drainage

The soils of Larazourou, Zaguinasso, Bafime, Largatonvo, Marandallah, Ponondougou, and Marahoue were “moderately suitable” (S2), while that of Tandokaha, were ‘‘marginally suitable’’ (S3); however, they are not very well drained as their texture in the subsoil contains more clay than the topsoil. The importance of clay is well known in the clay-humus complex, however, a strong and abrupt increase of clay content with soil depth below can be a problem for drainage and cause water logging. Soils with high clay content have higher water-holding capacity compared to sandy soils, as they have a sticky texture and poor drainage. Although it is not feasible to modify the soil texture, which is determined by the percentage of clay, the soil structure, which refers to the organization of soil particles, can be enhanced. The only solution would be to build artificial drainage systems (subsoil pipes) which would be too expensive. Therefore, improving internal drainage is economically not feasible in this case.

5.5. Conclusion and Recommendations

According to this study, most of the soils in the Northern zone of Côte d'Ivoire that support cotton crops are only moderately or marginally suitable due to soil fertility constraints, such as low soil organic carbon and soil biological activity, and some physical limitations such as soil depth, texture, and drainage. The soils that are the least suitable have at least three moderate limitations, and only one village has a severe limitation. To increase cotton yields, it is necessary to establish good soil fertility management by applying both chemical and biological fertilizers and adopting farming practices that increase soil organic matter content. Before applying fertilizers, it is essential to conduct site-specific soil fertility surveys, including soil and leaf sampling and test analysis, due to the diversity of these soils. Moreover, there is an urgent need to establish a fertilizer recommendation system for sustainable cotton production in the Cote d'Ivoire cotton basin. In order to ensure effective land management, it is necessary to adapt the existing land-use pattern according to its suitability classes and implement appropriate land management strategies. Additionally, it is advisable to introduce alternative income-generating activities to support impoverished farmers who depend on vulnerable land, thereby alleviating the strain on the land and creating opportunities for the revitalization and recovery of the cotton region.

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CHAPTER 6: MODELLING LAND USE AND LAND COVER IN THE CÔTE D 'IVOIRE COTTON BASINS

Abstract

The environmental consequences of alterations in land use and land cover (LULC) have been widely recognised. Evaluating the changes in LULC is a valuable approach to comprehending the history of land usage, predicting the nature of the changes, and identifying the underlying factors and trends responsible for these changes. The aim of this study was to evaluate the transformations in land use and land cover (LULC) within the cotton basins of Côte d'Ivoire, examining both historical and projected changes and analysing their correlation with variations in soil fertility. To achieve this, Landsat images were scrutinised to analyse the patterns of land use and land cover (LULC) during the years 1998, 2009, and 2020. To forecast the anticipated alterations in LULC for the years 2035 and 2063, the TerrSet Geospatial Monitoring and Modeling System, in combination with the CA-Markov chain, was integrated with the Random Forest classification system accessible in QGIS. The study found that there were significant changes in LULC patterns over time. In general, from 1998 to 2020, there was a reduction in forestland and Savannah in the four departments of the study area. The share of forestland and Savannah in the departments decreased by -11.09 % and -21.56 % respectively at Korhogo, -14.09 % and -1.78 % at Ferkessedougou, -0.33 % and -14.8 % at Boundiali, and -6.9 % and -31.33 % respectively at Mankono, while water body, cropland, and settlement/bare land increased. From 1998 to 2035, the results revealed that the share of cropland and, settlement/bear with the departments land could continue to increase by 4.54 % and 28.2 %, respectively at Korhogo, 5.34 %, and 10.45 % at Ferkessedougou, 14.95 %, and 0.01 % at Boundiali, and 1.12 %, and 37.04 % in the department of Mankono. From 1998 to 2063, the results revealed that the share of cropland and, settlement/bear with the department's land could continue to increase. Soil fertility quality has generally decreased due to the improper application of soil conservation and management practices during the conversion of natural forests into various land uses. To uphold agricultural productivity in the cotton basin, it is crucial to adopt an integrated approach to land resource management. Forest areas are expected to be primarily converted into agricultural land, driving LULC change in the cotton basin of Côte d'Ivoire. To ensure the responsible use of agricultural land and effective management of forest conversion, it is necessary to implement suitable measures such as afforestation, protected lands, and agroforestry practices.

Keywords: LULC change, Random Forest, Markov chain, TerrSet, cotton, Soil fertility

6.1. Introduction

Soil, which is the predominant loose surface material covering land, is composed of both inorganic particles and organic matter. As the structural foundation for agriculture, it supplies plants with water and essential nutrients. Soils possess diverse chemical and physical properties, which result from a combination of leaching, weathering, and microbial activity processes. These processes create distinct soil types that have unique advantages and disadvantages for agricultural purposes. Soil degradation caused by human activities, resulting from modifications in land utilisation, negatively impacts soil functionality and fertility. The transformation of natural forests into agricultural and grazing areas stands out as a significant contributor to changes in the chemical, physical, and biological properties of the soil. The land is recognised as a crucial natural asset in the nation. Land degradation arises from a range of factors, including land clearance, inadequate agricultural methods, excessive grazing, unsuitable irrigation practices, urban expansion, commercial development, pollution from industrial waste, as well as mineral, sand, and stone extraction (Eni, 2012). Land degradation commonly arises from reduced soil fertility, which is caused by intensive land management practices, inadequate soil conservation measures, and unfavourable climatic conditions (Mosier *et al.*, 2021). Land degradation is a critical concern that poses a risk to worldwide food production. The primary drivers of land degradation encompass agricultural practices, changes in land utilisation, deforestation, the utilization of agricultural machinery and chemicals, and modifications in hydrological systems (Khresat *et al.*, 2008). In this context, continued land degradation poses an additional risk to the environmental sustainability of agriculture by accelerating the depletion of soil carbon (C), nitrogen (N), and phosphorus (P). The loss of these essential nutrients from agricultural systems leads to land that cannot produce nutrient-rich food for human consumption (FAO, 2019). Furthermore, intensifying land management to restore lost fertility can create a negative feedback loop, which further exacerbates the problem (Mosier *et al.*, 2021).

Land use and land cover (LULC) changes are intricate, non-linear interactions between humans and nature that involve complex processes resulting from substantial land surface conversions. Over the last 300 years, the global trajectory of LULC change has been characterised by the expansion of agricultural land and the decline of forests (FAO, 2020). According to the authors (Kolb *et al*., 2013), changes in land use and land cover (LULC) are linked to the conversion of forested areas to agricultural land, urbanization, and deforestation. Population growth in Africa has been identified as a key factor driving changes in land use and land cover (LULCC), particularly through the expansion of agriculture (Leta *et al.*, 2021). According to Winkler *et al.* (2021), approximately 30 % of the world's land has changed between 1960 and 2019, with a net loss of forest area of 0.8 million km^2 and a global expansion of agriculture by 1.0 million km^2. In West Africa, Barnieh *et al.* (2020) found that between 1975 and 2013, there was a significant conversion of Savannah, open forest, and woodland to crop production and urban areas, resulting in a 33 % loss of forest cover and a 47 % increase in bare land areas over four decades (CILSS, 2016).

Côte d'Ivoire is facing a significant ecological issue related to land degradation, which involves the deterioration of vegetation cover, soil quality, and nutrient depletion, as identified by Kouassi *et al.* (2021). Human activities can lead to various forms of soil degradation, such as the physical displacement of soil material and the deterioration of soil quality, as pointed out by AL-Awadhi (2013). Unsound agricultural practices frequently result in the loss of soil fertility due to the decrease of soil biodiversity and organic matter. Continuous utilization of degraded lands for agriculture necessitates an ongoing increase in management interventions to facilitate the production of high-yielding food. Studies conducted in the Northern part of Côte d'Ivoire in recent years have observed an increase in cultivated land areas (Tiebre *et al.*, 2020; Cisse *et al.*, 2021; Adam *et al.*, 2021). Nonetheless, limited studies have aimed to evaluate the historical and future changes in land use and land cover (LULC) across the entire cotton basin that contributes to the economy in this region. During the last decades, the cultivated lands were significantly extended in Côte d’Ivoire (Combaz, 2020). Techniques used in the past to restore soil fertility have almost been abandoned and lands are continuously cropped without any fertilization plan. Degraded and marginal lands with severe agricultural limitations due to unsustainable management practices, inadequate soil conservation, and climate change are often abandoned but can still be used for agriculture. However, continuous agriculture on such land may necessitate greater use of external inputs like fertilizers and herbicides, which could worsen soil degradation and hinder nutrient retention and recycling (Mosier *et al.*, 2021).

Expanding agricultural land is a leading cause of land degradation in the Savannah region of Côte d'Ivoire, according to Dugué *et al.* (2003). The Northern region of Côte d'Ivoire mainly relies on cotton as its primary cash crop. However, the production of seed cotton has witnessed a significant decline in the past twenty years, as noted by Bassett (2017). Cotton is often indicated to contribute more to natural resource degradation than any other crop (Traore *et al.*, 2007). Few results are available on the effect of the expansion of cotton area on land degradation. Hence, the objective of this investigation was to evaluate the degradation of land in the cotton-growing region of Côte d'Ivoire. To be specific, this study aimed to evaluate the extent of land use/cover change within the cotton basin area of Côte d'Ivoire and to examine the historical trends of such changes, which can provide insights into the future changes in land use/cover for 2035 and 2063. The prediction of future land use and land cover (LULC) was conducted using the Markov model integrated within the TerrSet geospatial monitoring and modeling system. By analysing the changes in land use and land cover in the cotton basin of Northern Côte d'Ivoire, including historical dynamics and future predictions, it is possible to gain insights into the vulnerability of these areas to land degradation caused by the expansion of cotton production, as well as similar environments. Three (3) contrasting periods: 1998, 2009, and 2020 were used to produce two maps. These years were chosen because 1998 corresponds to the beginning of the expansion of cotton cultivation in the study area, 2020 period corresponds to the peak in cotton production in the area. The 2009 period is the middle years among the two contrasting periods to check for significant differences between them. The maps generated during these three time periods were sufficient for understanding the main changes that occurred within a 22-year timeframe.

Land cover refers to the surface characteristics of the Earth's immediate top layer, which includes natural features like vegetation, water bodies, ice, and sand surfaces, and man-made features like urban areas. On the other hand, land use pertains to the activities carried out by humans within a specific area of land, with regard to their utilization, or management practices have effects on the land cover (Ellis *et al.*, 2010). According to

Vincent *et al*. (2013), modifying land cover can affect the variety of possible land uses in a particular location, whereas changing land use can bring about a physical transformation in land cover. The alteration in land use and the cover has the potential to affect the quantity and quality of biomass that is returned to the soil, water, and energy budgets; and also result in changes in soil and atmospheric temperatures, which in turn may impact the stocks of Soil Organic Carbon (SOC), according to Cerri *et al.* (2007). To illustrate, changing land use from forests to agricultural systems reduces the amount of Soil Organic Carbon (SOC) stored (Angelo *et al.*, 2021). Incorporating crop residues into the soil and adding nitrogen and phosphorus fertilizers may be a useful strategy to improve agricultural yields and potentially boost soil organic carbon levels.

Cropland is defined as an area of land used for growing crops, including both annual and perennial crops, as well as areas that are temporarily left uncultivated or used for grazing. The conversion of natural ecosystems to agricultural land use is the main source of greenhouse gas emissions in history, which is associated with the loss of biomass and carbon in both above and below ground biomas (FAO, 2020). It can be challenging to map the changes in Soil Organic Carbon (SOC) in agricultural fields due to various factors, such as soil properties being continuously altered by both natural and human-related factors such as climate and land management practices (Grunwald, 2009).

6.2. Materials and methods

6.2.1. Data collection and analysis

- **Images data collection**

The satellite images used were acquired at the same period of the year to reduce angle problems related to differences in solar angles, phenological changes in vegetation, and differences in soil moisture. Therefore, the collection comprises twelve Landsat sensor scenes, which include Landsat Thematic Mapper (TM), Landsat Enhanced Thematic Mapper (ETM), and Operational Land Imager (OLI) images (Path 197, Row 53 and 54) in 1998, 2009, and 2020 for each of the four departments (Korhogo, Ferkessedougou, Boundiali, and Mankono). All images of the study area (Figure 18) with a cloud cover of less than 10 % were obtained by downloading twelve images from the USGS website (USGS, http://www.glovis.usgs.gov/). Afterward, ENVI software was used for thematic analysis, classifying the images into five distinct land use and cover types: forest land, Savannah land, cropland, bare soil/settlements, and water bodies as shown in Table 15. The ArcGIS 10.8 software was used for digital image processing and mapping respectively as shown in the flowchart (Figure 19).

- **Fieldwork and data collection**

Based on the land use of the study area and the integration of certain data such as localities, tracks, bodies of water, and locality boundaries, 140 points were identified to be visited. These represented the different types of ecosystems present on the study sites. The geographical coordinates of the points were recorded and integrated into the GPS using ArcGIS software in preparation for the field mission. An initial field mission was carried out to visit and verify the selected points. In the field, meticulous observation of the different types of land use found on the site was carried out. The land use was described, and the coordinates of the sites visited were recorded. In short, this mission provided an opportunity to visit, describe and collect data for image classification, in the first instance, and to validate the latter based on control points collected in the field in the second instance.

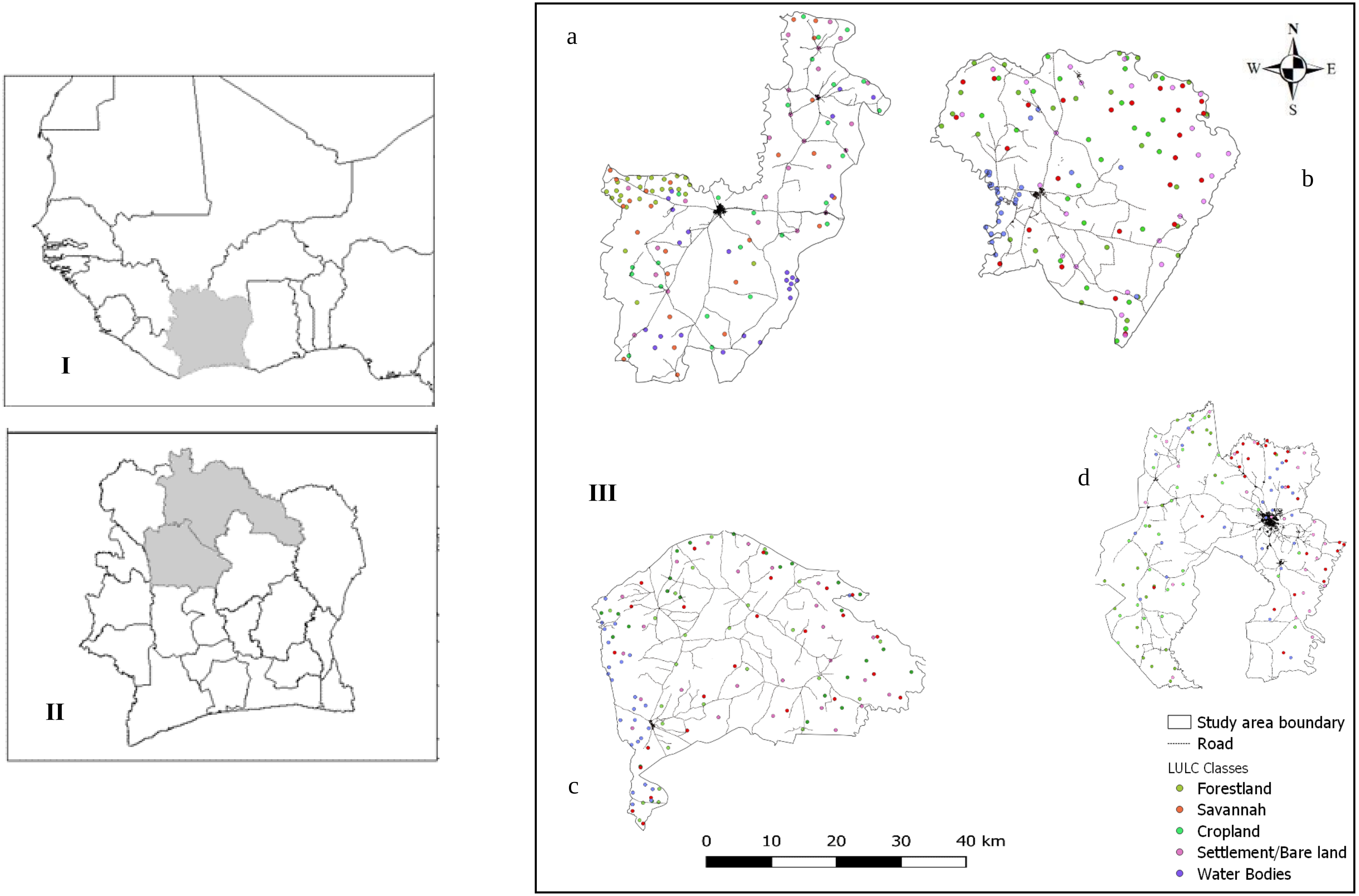

Figure 18. Study area (a) Boundiali, (b) Ferkessedougou, (c) Mankon, and (d) Korhogo (d) with ground truth point for each LULCC

I: Africa map; **II:** Cote d'Ivoire map; **III**: Departments of the study area

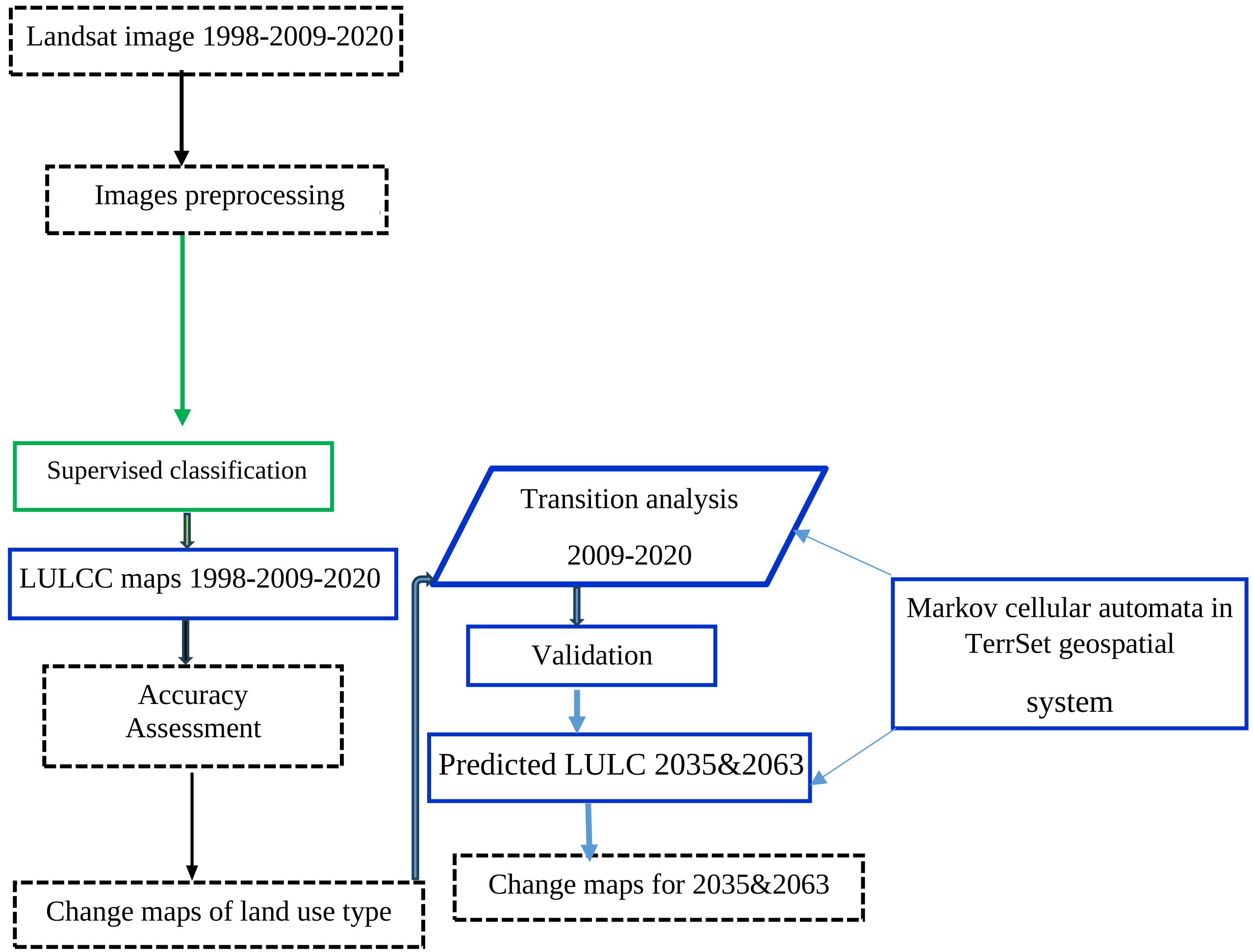

Figure 19. Methodology flowchart of the study

Table 14. Characteristics of Landsat satellite images

Sensors	Acquisition data	Spatial resolution (m)	Sources
Landsat OLI	15/02/2020	30	
Landsat ETM$^+$	09/02 / 2009	30	http://www.glovis.usgs.gov/
Landsat TM	25/02/1998	30	

TM: Landsat Thematic Mapper, ETM$^+$: Landsat Enhanced Thematic Mapper Plus, OLI: Landsat 8 Operational Land Imager

Table 15. Definition of the land use/land cover

LULC Classes	**Description**
Forest land	An area dominated by trees, community, and public forest reserves
Cropland	Agriculture lands, the area under cultivation, farmland
Savannah	Areas made up of trees from 8 to 15 meters high at two levels, low crown density, scattered shrubs, and grasses
Settlement/Bare land	Areas with no vegetation cover, built-up areas, roads, infrastructures
Water bodies	Lakes, streams, reservoirs, rivers

Source : (FAO, 2009)

6.2.2. Image classification and accuracy assessment

A maximum likelihood decision was used to perform supervised classification for each satellite image of 1998, 2009, and 2020, with the collected training data as a basis. The supervised classification was validated by producing and analysing confusion matrices to assess the overall performance of the processing, as well as the land cover classes in terms of overall accuracy and the Kappa coefficient. The various land use and land cover categories were identified through the use of ground truth points, which were selected from gathering field data and Google Earth and employed in the Random Forest (RF) supervised classification method. RF is a robust ensemble classifier that employs multiple trees to prevent the effects of noise and overfitting, and it can accurately process large, high-dimensional datasets (Shetty, 2019). Additionally, RF is the most effective classifier for soil (Forkuor *et al.*, 2017) and LULC mapping (Thiam *et al.*, 2022; Yangouliba *et al.*, 2022). The pre-processing functions are operations that are typically required before performing the main analysis and retrieval of the information. Pre-processing operations are divided into radiometric corrections and geometric corrections. Radiometric corrections include, but are not limited to, data correction due to sensor irregularities, sensor or atmospheric noises, and data conversion so that they can accurately represent the reflected or emitted radiation measured by the sensor. Geometric corrections include correction for geometric distortions due to variations in the Earth-sensor geometry, and the transformation of data into true coordinates (latitude and longitude) on the Earth's surface (Atilio,2018).

To ensure the correctness of the classified image, it is essential to conduct an accuracy assessment. The accuracy assessment helps to evaluate the extent to which the classified image represents the ground truth. It is important to assess the classification accuracy as land use maps obtained from image classification are prone to some errors. This assessment provides a level of assurance in the accuracy of the results and the subsequent change detection process (Samal *et al.*, 2015). To evaluate the accuracy of the classification, the classified map was compared to the ground truth data. For 1998, 2009, and 2020, the reference points were collected from the field survey conducted by using GPS, original Landsat images, interviews, and previous reports. Only some of the points collected during the 2020 field mission were used to process the historical images (1998 and 2009). Invariant points are points that have not changed land use during the period of data analysis (1998-2020). In simpler terms, these are areas that have remained stable. The maps obtained are validated by the production and analysis of confusion matrices. Like the 2020 map, the two historical images are imported into ArcGIS software for vectorisation.

The Kappa coefficient was calculated following Equation (3) as described by Jenness *et al.*, (2005). According to Pontius, (2000) and; Mishra *et al*.,(2016), when interpreting the kappa coefficient, a value less than 0.4 indicates weak agreement, a value between 0.4 and 0.8 indicates moderate agreement and a value greater than 0.8 indicates strong agreement.

$$K = \frac{\sum_{i=1}^{r} x_{ii} - \sum_{i=1}^{r} (x_{i} + x_{x+1})}{N^2 - \sum_{i=1}^{r} (x_{ii} X x_{+1})} \quad (3)$$

The kappa table displays the categories of the classified result map layer along the vertical axis and the reference map layer categories along the horizontal axis. Each panel can contain up to five categories (or nine in wide format) across the top. The last column in the final panel displays the total number of each row for each column. All categories of the map layer along the vertical axis are present in each panel. Each column represents true classes, and each row represents the classifier's predictions. The matrix is square, and all correct classifications are located along the upper-left to lower-right diagonal. The sum of all rows in a column is shown at the bottom of each column.

where;

r = number of rows and columns in the error matrix,

N = total number of observations (pixels),

Xii = observation in row i and column i,

Xi+ = marginal total of row i, and X+i = marginal total of column i

A Kappa coefficient equal to 1 means perfect agreement whereas a value close

to zero means that the agreement is no better than would be expected by chance.

The LULC maps for the years 1998, 2009, and 2020 were also evaluated using a confusion matrix, which provides information on the causes of misclassification for a given LULC class (Liu *et al.*, 2020).

6.2.3. Analysis of Land Use Land Cover Change

Nadoushan *et al.* (2012) used the classified maps from 1998, 2009, and 2020, as well as the predicted LULC map for 2035, to analyse the changes that occurred and to illustrate the resulting patterns. The changes in LULC during each study period were evaluated by analysing the numerical values obtained from the classified images. To identify the pattern of change, cross-tabulation was conducted to compare the classified images from consecutive periods. To determine the number of changes in the different land use/land cover (LULC) categories between the periods, the change percentage (Leta *et al.*, 2021) and the rate of change were computed (Temesgen *et al.*, 2014) for each category. Equations (4) and (5) were used for this purpose.

$$\text{Percent of change} = \frac{A_Y - A_X}{A_X} 100 \quad (4) \qquad \text{Rate of change} = \frac{A_Y - A_X}{T} \quad (5)$$

The rate of change for each LULC category is determined using the following formula: ΔA = (Ay - Ax) / T, where ΔA represents the change in LULC area (in hectares), Ay represents the LULC area (in hectares) of a later land cover image, Ax represents the LULC area (in hectares) of an earlier land cover image, and T represents the time interval (in years) between Ax and Ay.

6.2.4. LULC Change Prediction and Validation, using Markov cellular automata in TerrSet geospatial system

The LCM (Land Change Modeler) function of the TerrSet Geospatial Monitoring and Modeling System (TGMMS) software was employed to forecast the future land use and land cover (LULC) for a specific year by utilizing the classified satellite images from previous periods. The combination of Cellular Automata and Markov Chain enables the simulation of changes in LULC over both space and time. The Markov Chain enables analysis of the temporal dynamic of LULC using the transitional probability (Table 16), whereas Cellular Automata examine the spatial dynamics using a neighborhood filter.

Table 16. Transition probability matrix for the simulation in 2020

a: Korhogo

LULC	Forest	Savannah	Cropland	Settlement/ Bare land	Water
Forest	0.96	0	0.0014	0.03	0
Savannah	0	0.82	0.0035	0.17	0
Cropland	0	0	1	0	0
Settlement/Bare land	0	0	0	1	0
Water	0	0	0.034	0	0.9

b: Ferkessedougou

LULC	Forest	Savannah	Cropland	Settlement/ Bare land	Water
Forest	0.59	0.32	0.49	0.27	0
Savannah	0	0.93	0.28	0.32	0
Cropland	0	0	1	0	0
Settlement/Bare land	0	0.48	0.35	0.48	0
Water	0	0	0	0	1

c: Boundiali

LULC	Forest	Savannah	Cropland	Settlement/ Bare land	Water
Forest	0.62	0.24	0.04	0.08	0.001
Savannah	0.16	0.42	0.1	0.3	0.0003
Cropland	0.01	0.01	0.9	0.003	0
Settlement/Bare land	0.28	0.34	0.001	0.36	0.006
Water	0.01	0.002	0.07	0.52	0.37

d: Mankono

LULC	Forest	Savannah	Cropland	Settlement/ Bare land	Water
Forest	0.82	0.11	0.05	0.006	0.0002
Savannah	1	0.84	0.008	0.04	0.0004
Cropland	0.74	0.05	0.76	0.1	0
Settlement/Bare land	0.01	0.08	0.05	0.85	0.035
Water	0.03	0.63	0.063	0.07	0.31

The CA-Markov model applies the cellular lattice, cellular state, and transition rule to imitate the quantity and spatial patterns of LULC changes over time, and it is believed to yield superior simulation outcomes compared to alternative models (Aburas *et al.,* 2021). According to Arsanjani *et al.*, (2013), the CA-Markov model's Cellular Automata (CA) can identify alterations in regions by examining the closest region that exhibits a modification. The CA-Markov model's Cellular Automata (CA) has the ability to detect changes in specific regions by analysing the closest region that has undergone a transformation, as stated by Arsanjani *et al.* (2013). The CA-Markov model, which can anticipate future land cover and land use images by merging the Multi-Criteria Analysis (MCA) and CA models, can be accessed through the TerrSet software. The study examined the changes in Land Use and Land Cover (LULC) trends during 1998, 2009, and 2020, in the cotton basin of Côte d'Ivoire, in order to forecast future years. To simulate the LULC of 2020, the images of the first observation year 1998, and the images of the second observation year 2009 were considered in the TerrSet model with a difference of 11 years between them. The Markov Chain Model was used to simulate the next 11 years, with a focus on 2020, and to predict future LULC, which is a common approach in many studies (Koko *et al.,* 2020; Yangouliba *et al.,* 2022). The "VALIDATE" module was employed to compare the simulated LULC map of 2020 with the actual LULC of 2020. This module uses the Kappa index, a metric that assesses the level of agreement or disagreement between the simulated and actual maps, ranging from -1 to 1 (Pontius, 2000). Once the model was validated, the same drivers and parameters, in addition to the changes identified in LULC between 1998 and 2020, were utilised to predict the future LULC of 2035 and 2063.

6.3. Results

6.3.1. Accuracy Assessment of the Classified Images

The accuracy of the LULC change analysis was evaluated by creating a confusion or error matrix for each LULC category within the 1998, 2009, and 2020 classified maps. The evaluation involved using various metrics, including overall accuracy, kappa statistics, and producer's and user's accuracy.

Korhogo

Table 17 displays the confusion matrix statistics for the LULC maps of 1998, 2009, and 2020. The classification outcomes exhibit a total precision of 93 %, 90 %, and 93 % for the respective years, alongside Kappa coefficients of 0.89, 0.86, and 0.87.

Ferkessedougou

Table 18 displays the confusion matrix statistics for the LULC maps of 1998, 2009, and 2020. The classification outcomes exhibit a total precision of 76 %, 91%, and 89 % for the respective years, alongside Kappa coefficients of 0.60, 0.85, and 0.85.

Boundiali

Table 19 presents the confusion matrix statistics for the LULC maps of 1998, 2009, and 2020. The classification results indicate a total precision of 76 %, 89 %, and 85 % for the corresponding years, along with Kappa coefficients of 0.70, 0.84, and 0.85.

Mankono

The classification outcomes for 1998, 2009, and 2020 LULC maps are presented in Table 20, displaying the confusion matrix statistics. The accuracy rates for the three maps are high, at 96 %, 95 %, and 91 % respectively, and their corresponding Kappa coefficients are 0.93, 0.92, and 0.87.

Table 17. Confusion matrix of the LULC classification at Korhogo for 1998,2009, and 2020

LULCC 1998	**Forest**	**Savannah**	**Cropland**	**Settlement/ Bare land**	**Water**
Forest	**93.96**	6	22.71	0.13	0
Savannah	4.4	**92.26**	2.76	5.34	0.08
Cropland	0.07	0.12	**74.16**	0	0.01
Settlement/Bare land	0.32	1.3	0.36	**93.49**	0.1
Water	1.25	0.31	0	1.04	**99.81**
Total	100	100	100	100	100

LULCC 2009	**Forest**	**Savannah**	**Cropland**	**Settlement/ Bare land**	**Water**
Forest	**94.74**	2.68	2.16	0.2	0
Savannah	0.44	**94.54**	2.13	4.74	0
Cropland	0.01	0.29	**90.9**	5.47	0
Settlement/Bare land	0	1.43	0.29	**85.29**	0
Water	4.82	1.07	4.52	4.3	**100**
Total	100	100	100	100	100

LULCC 2020	**Forest**	**Savannah**	**Cropland**	**Settlement/ Bare land**	**Water**
Forest	**88**	0.64	0.35	0.01	0
Savannah	11.63	**92.92**	8.31	2.96	0
Cropland	0	0.44	**91.09**	0	0
Settlement/Bare land	0.36	6	0.25	**97.02**	4.1
Water	0	0	0	0.01	**95.9**
Total	100	100	100	100	100

the bold values represent the percentage of fitted pixels for each row while the non-bold represent the percentage of confusion with the other LULC classes represented in the corresponding column.

Table 18. Confusion matrix of the LULC classification at Ferkessedougou for 1998.2009, and 2020

LULCC 1998	**Forest**	**Savannah**	**Cropland**	**Settlement/ Bare land**	**Water**
Forest	**72.59**	11.12	12.36	1.72	0
Savannah	21.7	**82.64**	70.93	22.95	31.1
Cropland	5.69	2.28	**16.16**	0.05	0
Settlement/Bare land	0.02	3.95	0.55	**75.23**	0.04
Water	0	0.01	0.01	0.05	68.86
Total	100	100	100	100	**100**

LULCC 2009	**Forest**	**Savannah**	**Cropland**	**Settlement/ Bare land**	**Water**
Forest	**90.14**	2.16	0.87	1.33	0
Savannah	7.85	**94.93**	5.37	14.91	0
Cropland	0.25	0	**71.66**	0.03	0
Settlement/Bare land	1.76	2.9	22.1	**83.73**	0
Water	0	0	0	0	**100**
Total	100	100	100	100	100

LULCC 2020	**Forest**	**Savannah**	**Cropland**	**Settlement/ Bare land**	**Water**
Forest	**91.96**	1.31	3.7	1.44	0
Savannah	6.1	**98.07**	31.05	8.81	0.06
Cropland	0.65	0	**57.46**	0	0
Settlement/Bare land	1.28	0.62	7.79	**89.75**	2.28
Water	0	0	0	0	**97.66**
Total	100	100	100	100	100

The bold values represent the percentage of fitted pixels for each row while the non-bold represent the percentage of confusion with the other LULC classes represented in the corresponding column

Table 19. Confusion matrix classification at Boundiali for 1998,2009, and 2020

LULCC 1998	Forest	Savannah	Cropland	Settlement/ Bare land	Water
Forest	**77.76**	36.73	1.15	0	11.98
Savannah	11.57	**56.62**	0.3	0	0.01
Cropland	9.71	5.3	**94.77**	6.4	0.11
Settlement/Bare land	0	0	3.64	**93.6**	0
Water	0.96	1.35	0.15	0	**87.9**
Total	100	100	100	100	100

LULCC 2009	Forest	Savannah	Cropland	Settlement/ Bare land	Water
Forest	**84.35**	2.03	18.48	2.67	4.46
Savannah	9.29	**95.78**	5.4	2.24	0
Cropland	5.44	1.71	**74.93**	5.09	0
Settlement/Bare land	0.91	0.48	1.19	**96.01**	0.47
Water	0	0	0	0	**95.07**
Total	100	100	100	100	100

LULCC 2020	Forest	Savannah	Cropland	Settlement/ Bare land	Water
Forest	**74.98**	1.68	0.25	0.23	7.41
Savannah	9.88	**89.55**	3.24	2.6	32.51
Cropland	13.7	8.07	**96.14**	10.97	19.26
Settlement/Bare land	1.43	0.67	0.38	**86.18**	1.04
Water	0.02	0.03	0	0.01	**39.78**
Total	100	100	100	100	100

the bold values represent the percentage of fitted pixels for each row while the non-bold represent the percentage of confusion with the other LULC classes represented in the corresponding column

Table 20. Confusion matrix of the LULCC classification at Mankono for 1998,2009, and 2020

LULCC 1998	**Forest**	**Savannah**	**Cropland**	**Settlement/ Bare land**	**Water**
Forest	**98**	0.19	5.4	0	0.22
Savannah	1.3	**97.77**	10.58	2.22	2.13
Cropland	0.09	0.41	**83.82**	0.16	0.04
Settlement/Bare land	0	0.33	0.06	**96.74**	0.03
Water	0.61	1.3	0.13	0.88	**97.57**
Total	100	100	100	100	100

LULCC 2009	**Forest**	**Savannah**	**Cropland**	**Settlement/ Bare land**	**Water**
Forest	**98.48**	4.02	1.47	0.03	0
Savannah	0	**95.72**	0	10.88	16.12
Cropland	1.51	0.01	**98.52**	0	0
Settlement/Bare land	0	0.16	0	**89.07**	0
Water	0	0.09	0	0.01	**83.88**
Total	100	100	100	100	100

LULCC 2020	**Forest**	**Savannah**	**Cropland**	**Settlement/ Bare land**	**Water**
Forest	**98.11**	0.59	1.04	0.15	0.16
Savannah	1.68	**92.64**	2.49	14.66	0.02
Cropland	0.19	0.26	**96.47**	0.77	0
Settlement/Bare land	0	6.46	0	**84.38**	0
Water	0.02	0.06	0	0.05	**99.81**
Total	100	100	100	100	100

the bold values represent the percentage of fitted pixels for each row while the non-bold represent the percentage of confusion with the other LULC classes represented in the corresponding column

6.3.2. Land use and land cover maps in 1998, 2009, and 2020

Figure 20 displays the LULC maps of the Côte d'Ivoire cotton basin's four departments (Korhogo, Ferkessedougou, Boundiali, and Mankono) for 1998, 2009, and 2020, while Table 21 presents the alterations that occurred in land use and land cover.

Korhogo

Back in 1998, the primary land cover in Korhogo department was Savannah (60.58 %) and settlement/bare land (19.11 %), with forestland, cropland, and water body accounting for 17.72 %, 2.43 %, and 0.14 % respectively. The same order was maintained in 2009, with Savannah covering 49.92 %, followed by settlement/bare land (30.24 %), forestland (17 %), cropland (2.66 %), and water body (0.14 %). Cropland and water body remained the least represented LULC categories, similar to 1998. However, in 2020, settlement emerged as the dominant land cover in the cotton basin, covering 47.23 %, followed by Savannah (39 %), cropland (6.95 %), and forestland (6.63 %). Over the years, natural vegetation has given way to anthropogenic land uses, including cropland and settlement/bare land.

Ferkessedougou

The primary land cover in Ferkessedougou department in 1998 was Savannah (58.08 %) and forestland (27 %), with settlement/bare land, cropland, and water body accounting for 14.24 %, 0.26 %, and 0.32 %, respectively. The same order was maintained in 2009, with Savannah covering 70.39 %, followed by settlement/bare land (9.48 %), forestland (16 %), cropland (3.72 %), and water body (0.31 %). Cropland and water body remained the least represented LULC categories, similar to 1998. However, in 2020, Savannah still dominated the cotton basin's land cover in Ferkessedougou department, covering 56.32 %, followed by settlement/bare land (24.7 %), forestland (13 %), and cropland (5.6 %). Over the years, natural vegetation has given way to anthropogenic land uses, including cropland and settlement/bare land.

Boundiali

The main land cover in Boundiali department in 1998 was forestland (48.21 %) and Savannah (29.21 %), with settlement/bare land, cropland, and water body accounting for 21.48 %, 0.64 %, and 0.43 %, respectively. In 2009, Savannah became the dominant land cover (34.97 %), followed by forestland (32.12 %), settlement/bare land (25.49 %), cropland (7.05 %), and water body (0.34 %). Cropland and water body remained the least represented LULC categories, as in 1998. However, in 2020, Savannah still dominated the cotton basin's land cover in Boundiali department, covering 33.36 %, followed by forestland (28.88 %), settlement/bare land (21.49 %), and cropland (15.56 %). Over the years, natural vegetation has been replaced by anthropogenic land uses, including cropland and settlement/bare land.

Mankono

In 1998, the main land cover types in the department of Mankono were Savannah (71.58 %) and forestland (13.18 %), while settlement/bare land, cropland, and water body covered 9.49 %, 5.53 %, and 0.20 % of the area, respectively. By 2009, the order remained the same, with Savannah covering 63.47 % and forestland covering 18.66 %, followed by settlement/bare land (11.74 %), cropland (6 %), and water body (0.13 %). Cropland and water body remained the least represented LULC, as in 1998. Settlement/bare land dominated the land cover in 2020 (46.5 %), followed by Savannah (40.25 %), cropland (6.6 %), and forestland (6.4 %), indicating that natural vegetation has been replaced by anthropogenic land uses (cropland and settlement/bare land) over time.

6.3.3. Changes in land use and land cover between 1998 and 2009, 2009 and 2020, and 1998 and 2020

Korhogo

From 1998 to 2020, changes in LULC units resulted in both losses and gains. In the first eleven years (1998-2009), the savannah (-17.5 %) and forestland (-0.70 %) decreased, while settlement/bare land and cropland increased by 11.13 % and 0.24 %, respectively. Between 2009 and 2020, there was a decrease in forestland (-10.38 %) and Savannah (-10.88 %), but an increase in settlement/bare land (17 %) and cropland (4.28 %). In the last 22 years, there has been an overall increase in settlement/bare land (28 %) and cropland (4.5 %). These increases are believed to have come at the expense of Savannah and forestland, which decreased by -21.5 % and -11 %, respectively, from 1998 to 2020 (as shown in Table 21).

Ferkessedougou

During the initial period of eleven years (1998-2009), forestland (-11.01 %) and settlement/bare land (-4.74 %) experienced a decrease in LULC, while Savannah and cropland increased by 12.35 % and 3.44 %, respectively. Subsequently, from 2009 to 2020, the share of forestland and savannah underwent a decrease of -3.08 % and -14.1 %, respectively, while settlement/bare land, cropland, and water bodies showed an increase of 15.22 %, 1.9 %, and 0.08 %, respectively. Overall, in the past 22 years, settlement/bare land (10.5 %) and cropland (5.34 %) have increased. These increases were likely due to the decline of forestland (-14.09 %) and Savannah (-1.78 %) from 1998 to 2020, according to Table 21.

Boundiali

From 1998 to 2020, changes were observed in the land cover and land use (LULC) units. During the first 11 years (1998-2009), savannah (-13.24 %), forestland (-2.91 %), and water bodies (-0.09 %) decreased, while cropland and settlement/bare land increased by 6.41 % and 4.01 %, respectively. From 2009 to 2020, the share of forestland, Savannah, and settlement/bare land decreased by -3.23 %, -1.61 %, and -4 %, respectively, while cropland and water bodies increased by 8.49 % and 0.35 %, respectively. Overall, over the last 22 years, there was an increase in cropland (14.9 %) and settlement/bare land (0.01 %). These increases may have been at the expense of Savannah and forestland, which decreased by -14.8 % and -0.33 %, respectively, from 1998 to 2020, as shown in Table 21.

Mankono

Between 1998 and 2009, the land use and land cover (LULC) categories that saw a decrease were Savannah (-8.11 %) and water bodies (-0.1%), whereas forestland, settlement/bare land, and cropland increased by 5.47 %, 2.24 %, and 0.46 % respectively. Between 2009 and 2020, there was a decrease in forestland and savannah by -12.24 % and -23.22 % respectively, while an increase of 34.75 %, 0.63 %, and 0.1 % was observed for settlement/bare land, cropland, and water bodies. In summary, over the last 22 years, there has been an increase in settlement/bare land (37 %) and cropland (1.09 %), while Savannah and forestland decreased by -31.33 % and -6.76 %, respectively (as shown in Table 21).

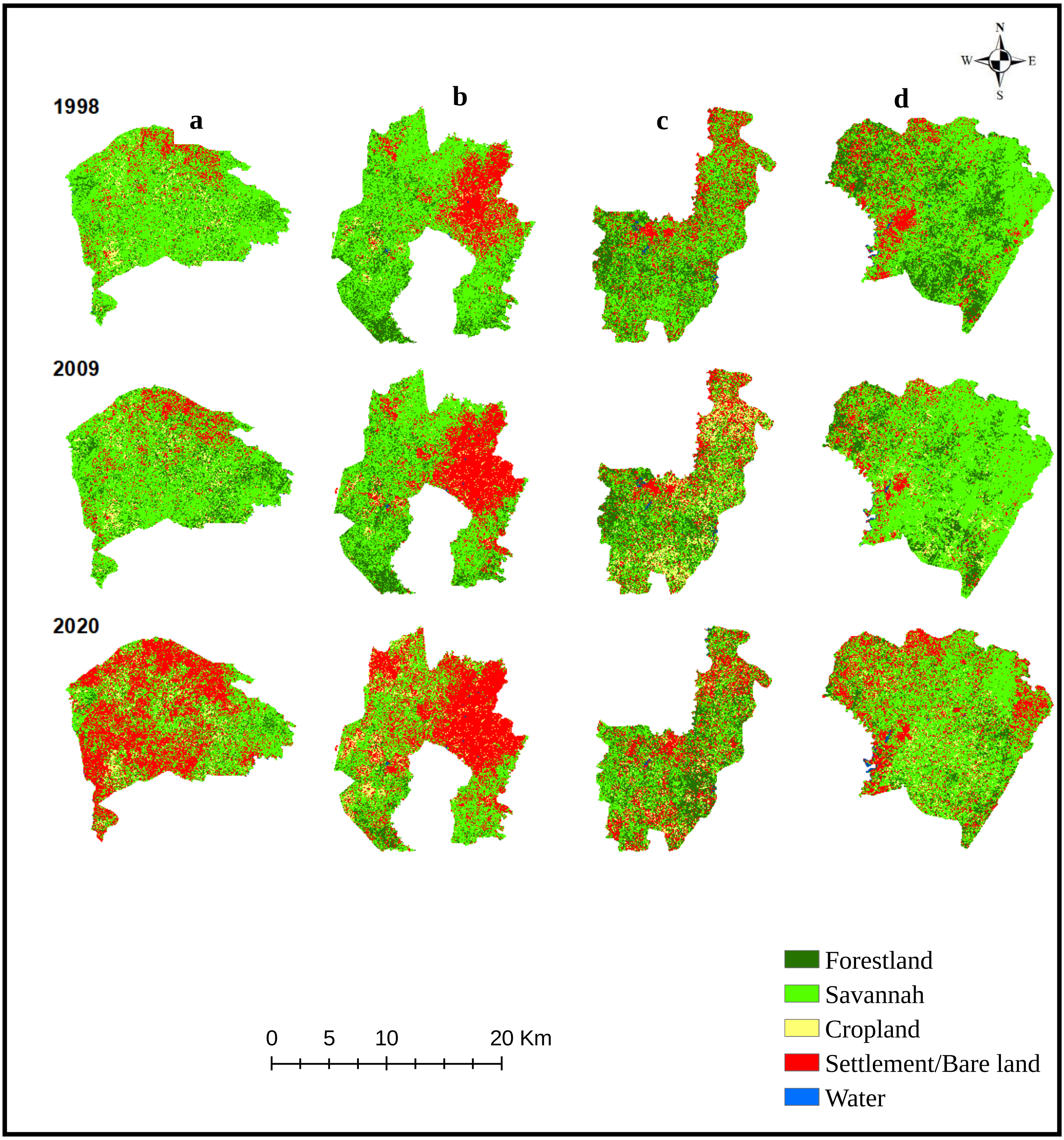

Figure 20. Land use land cover maps of (a) Mankono, (b) Korhogo, (c) Ferkessedougou, and (d) Boundiali departments from 1998 to 2020

Table 21. The area coverage of LULCC percent, rate of changes in the cotton basin of Cote d'Ivoire between 1998,2009, and 2020

Korhogo

	Area						Change								
	1998		**2009**		**2020**		**1998-2009**			**2009-2020**			**1998-2020**		
LULCC Types	Ha	%	Ha	%	Ha	%	Ha	%	Rate of change (ha/Year)	Ha	%	Rate of change (ha/year)	Ha	%	Rate of change (ha/year)
Forest	126269.01	17.72	121220.28	17.03	47251.71	6.63	-5048.73	-0.70	-458.97	-73968.57	-10.38	-6.724.4	-79017.3	-11.09	-3592
Savannah	431576.82	60.6	355681.8	49.92	278071.38	39.04	-75895.02	-17.58	-6899.54	-77610.42	-10.88	7055.4	-153505	-21.56	-6977
Cropland	17333.46	2.43	19009.26	2.67	49517.01	6.95	1675.8	0.24	152.34	30507.75	4.28	2773.4	32183.55	4.52	1463
Settlement	136178.64	19.11	215450.1	30.24	336521.34	47.24	79271.46	11.13	7206.49	121071.24	17	11006.4	200342.7	28.13	9106
Water	1024.02	0.14	1020.51	0.14	1020.51	0.14	-3.51		-0.32	0	0	0	-3.51	0	-0.16
Total	**712381.95**	**100**	**712381.95**	**100**	**712391.95**	**100**									

Ferkessedougou

	Area						Change								
	1998		**2009**		**2020**		**1998-2009**			**2009-2020**			**1998-2020**		
LULCC Types	Ha	%	Ha	%	Ha	%	Ha	%	Rate of change (ha/Year)	Ha	%	Rate of change (ha/year)	Ha	%	Rate of change (ha/year)
Forest	107763.75	27.09	63956.52	16.08	51583.59	13	-43807.2	-11.01	-3982.48	-12372.9	-3.08	-1124.81	-56180	-14.09	-2553.6
Savannah	231069.87	58.08	280014.21	70.4	224045.91	56.3	48944.34	12.35	4449.48	-55968.3	-14.1	-559.683	-7023	-1.78	-319.3
Cropland	1033.29	0.26	14818.68	3.7	22281.57	5.6	13785.39	3.44	1253.21	7462.89	1.9	678.44	21248	5.34	965.8
Settlement	56655.09	14.24	37732.59	9.5	98285.31	24.7	18922.5	-4.74	-1720.23	60552.72	15.22	1.60	41630	10.46	1892.3
Water	1267.2	0.32	1267.2	0.32	1591.2	0.40	0	0	0	324	0.08	1.85	324	0.08	14.72
Total	**397789.2**	**100**	**397789.2**	**100**	**397787.2**	**100**									

Boundiali

	Area						Change								
	1998		**2009**		**2020**		**1998-2009**			**2009-2020**			**1998-2020**		
LULCC Types	Ha	%	Ha	%	Ha	%	Ha	%	Rate of change (ha/Year)	Ha	%	Rate of change (ha/year)	Ha	%	Rate of change (ha/year)
Forest	126846.9	29.21	139465.44	32.12	125410.68	28.88	12618.54	-2.91	3034.6	-14058.8	-3.24	-1277	-1436.2	-0.33	-65
Savannah	209361.69	48.21	151859.52	34.97	144851.13	33.36	-57502.2	-13.24	-4494.2	-7008.39	-1.61	-637	-64510.6	-14.8	-2932
Cropland	2801.79	0.64	30648.33	7.05	67545.99	15.56	27846.54	6.41	256.56	36897.66	8.49	33.54	64744.2	14.9	2943
Settlement	93285.81	21.48	93349.5	21.49	110709.36	25.49	17423.55	4.01	1246.1	-17359.8	-4	-1578	63.72	0.01	2.89
Water	1896.03	0.43	1509.75	0.34	3034.89	0.69	-386.36	-0.09	-0.08	15.25	0.35	4138	1138.86	0.26	0.01
Total	**434192.2**	**100**	**434192.2**	**100**	**434192.2**	**100**									

Mankono

	Area						Change								
	1998		**2009**		**2020**		**1998-2009**			**2009-2020**			**1998-2020**		
LULCC Types	Ha	%	Ha	%	Ha	%	Ha	%	Rate of change (ha/Year)	Ha	%	Rate of change (ha/year)	Ha	%	Rate of change (ha/year)
Forest	80350.65	13.2	113731.74	18.7	39125.43	6.4	33381.09	5.5	3034.6	-74606.3	-12.3	-6782.4	-41225.2	-6.9	-1874
Savannah	436272.75	71.6	386837.1	63.5	245318.49	40.3	-49435.7	-8.11	-4494.2	-141519	-23.2	-12865.3	-190954	-31.33	-8679
Cropland	33705.54	5.5	36527.7	6	40376.7	6.6	2822.22	0.5	256.56	3848.94	0.6	349.9	6671.16	1.09	303
Settlement	57867.21	9.5	71574.3	11.8	283375.53	46.5	13707.09	2.3	1246.1	211801.2	34.75	19254.6	225508.3	37	10250
Water	1238.4	0.2	788.31	0.1	1238.4	0.2	-450.09	-0.1	-40.9	459.09	0.1	40.91	0	0	
Total	**609434.6**	**100**	**609459.2**	**100**	**609434.6**	**100**									

The Percentage and rate of change were calculated using Equations (4) and (5), respectively

6.3.3. Validation of the Model

In order to determine the quality of the predicted land cover map, 2020 simulated and classified maps were compared using the VALIDATE tool in TerrSet software. This evaluation is important to assess the accuracy of the predicted map. The overall accuracy of the model was evaluated using Kno, while Klocality was used to assess the model's ability to correctly identify locations, as explained by Sibanda *et al.,* (2021). The Kappa coefficient was calculated with the following criteria: a value of <0 indicates an agreement level lower than chance, 0.01-0.40 represents a poor agreement, 0.41-0.60 signifies moderate agreement, 0.61-0.80 indicates substantial agreement, while 0.81-1.00 shows almost perfect agreement. As stated by Philip *et al.*,(2022) and Mukherjee *et al.,* (2009), the statistics determine how well the model predictions correspond with actual data and account for chance accuracy. If the Kappa coefficient falls below 0.5, it indicates a lack of agreement. Once satisfactory Kappa values were obtained, the CA-Markov model was utilised to simulate the land use/land cover change (LULCC) maps for the years 2035 and 2063. Philip *et al.*,(2022) and; Nath *et al.*,(2020) reported that the Clark Lab's LCM module of TerrSet was used to evaluate the model's results. Additionally, the Kno index, a standard Kappa agreement index, was utilised to determine the overall accuracy of the CA-Markov model's predictions. The $K_{location}$ index was used to validate the simulation's ability to predict locations. The results of these agreement indices were presented in Table 22, and the average value was approximately 0.74, indicating that the actual and simulated LULC categories had a similarity of more than 70 %. This information was also reported by Nath and colleagues in 2020. Table 22 presented the results of the K_{no}, K_{index}, $K_{locality}$, and $K_{standard}$ indices, indicating that the model was able to generate the expected LULC for 2020 with slight variations from the actual map. However, the model tended to overestimate the areas of bare land/built-up, shrubland, and woodland, while underestimating the extent of water bodies and cropland.

Table 22. The k-index values of the simulated LULCC map of 2020 in the study area

Index (Korhogo)	Value
Kno	0.83
Klocation	0.96
KlocationStrata	0.96
Kstandard	0.80

Index (Ferkessedougou)	Value
Kno	0.99
Klocation	1
KlocationStrata	0.99
Kstandard	1

Index (Boundiali)	Value
Kno	0.99
Klocation	0.99
KlocationStrata	0.99
Kstandard	0.99

Index (Mankono)	Value
Kno	0.70
Klocation	0.84
KlocationStrata	0.84
Kstandard	0.61

6.3.4. Future LULC Prediction

The purpose of this study was to achieve a more sustainable world in alignment with the United Nations' 2030 Agenda and the African Union's Agenda 2063. This agenda aims to foster a prosperous Africa through structural economic transformation, promoting sustainable resource use, production, and consumption, as well as addressing climate change. In order to forecast future changes in land use and land cover (LULC) by 2035 and 2063, the transition probabilities matrix was utilized to analyze the likely percentage of change during the periods of 1998-2035 and 1998-2063. The LULC Change Model (LCM), employing the Markov chain, provides insights into both the magnitude and spatial distribution of changes, as depicted in Figures 21 and 22. Additionally, Tables 23-26 and Tables 27-30 present information regarding area coverage, percentages, and rates of change.

Table 23. The area coverage of LULCC percent, and rate of changes between 1998 and 2035 at Korhogo

	Area				Change	
	1998		**2035**		**1998-2035**	
LULCC Types	Ha	%	Ha	%	Ha	%
Forest	126269.01	17.72	46589.49	6.53	-79679.5	-11.19
Savannah	431576.82	60.6	278071.38	39.03	-153505	-21.57
Cropland	17333.46	2.43	49664.25	6.97	32330.79	4.54
Settlement	136178.64	19.11	337036.86	47.31	515.52	28.2
Water	1024.02	0.14	1020.51	0.14	-3.52	0
Total	**712381.95**	**100**	**712383**	**100**		

Table 24. The average of LULCC percent, and rate of changes between 1998 and 2035 at Ferkessedougou

	Area				Change	
	1998		**2035**		**1998-2035**	
LULCC Types	Ha	%	Ha	%	Ha	%
Forest	107763.8	27.09	51631.11	12.97	-56132.6	-14.12
Savannah	231069.9	58.08	224062.83	56.31	-7007.04	-1.77
Cropland	1033.29	0.26	22308.75	5.60	21275.46	5.34
Settlement	56665.09	14.24	98258.13	24.69	41603.04	10.45
Water	1267.2	0.32	1591.2	0.4	324	0.08
Total	**397787.6**	**100**	**397787.6**	**100**		

Table 25. The area coverage of LULC percent and rate of change between 1998 and 2035 at Boundiali

	Area				Change	
	1998		**2035**		**1998-2035**	
LULCC Types	Ha	%	Ha	%	Ha	%
Forest	126846.9	29.21	125410.68	28.88	-1436.22	-0.33
Savannah	209361.7	48.21	144666.09	33.31	-64695.6	-14.19
Cropland	2801.79	0.64	67733.37	15.59	64931.58	14.95
Settlement	93285.81	21.48	93349.53	21.49	63.72	0.01
Water	1896.03	0.43	3032.55	0.69	1136.52	0.26
Total	**434192.2**	**100**	**434192.2**	**100**		

Table 26. The area coverage of LULC percent and rate of change between 1998 and 2035 at Mankono

	Area				Change	
	1998		**2035**		**1998-2035**	
LULCC Types	Ha	%	Ha	%	Ha	%
Forest	80350.65	13.2	38955.33	6.39	-41395.3	-6.81
Savannah	436272.8	71.6	245201.58	40.23	-191071	-31.37
Cropland	33705.54	5.5	40377.33	6.62	6671.79	1.12
Settlement	57857.21	9.5	283662.54	46.54	225795.3	37.04
Water	1238.4	0.20	1238.4	0.20	0	0
Total	**609434.6**	**100**	**609434.6**	**100**		

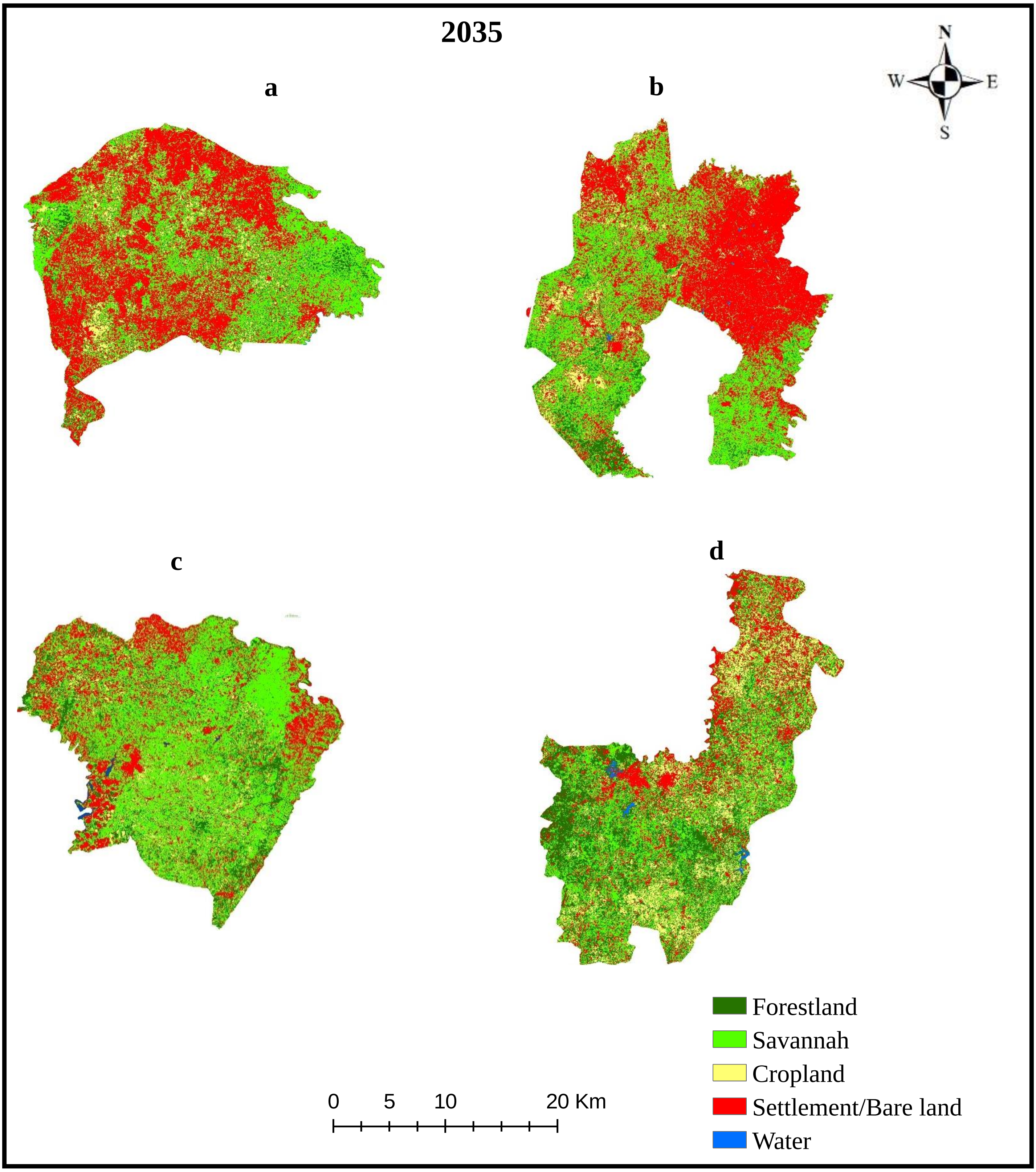

Figure 21. Projected LULC maps (2035) (a) Mankono, (b) Korhogo, (c) Ferkessedougou, and (d) Boundiali

Table 27. The area coverage of LULCC percent, and rate of changes between 1998 and 2063 at Korhogo

	Area				Change	
	1998		**2063**		**1998-2063**	
LULCC Types	Ha	%	Ha	%	Ha	%
Forest	126269.01	17.72	45167.90	6.34	-81101.1	-11.38
Savannah	431576.82	60.6	279303.40	39.20	-152273	-21.4
Cropland	17333.46	2.43	48663.48	6.83	31330.02	4.4
Settlement	136178.64	19.11	338189.65	47.47	202011	28.36
Water	1024.02	0.14	1013.91	0.14	-10.11	0
Total	**712381.95**	**100**	**712338.35**	**100**		

Table 28. The area coverage of LULCC percent, and rate of changes between 1998 and 2063 at Ferkessedougou

	Area				Change	
	1998		**2063**		**1998-2063**	
LULCC Types	Ha	%	Ha	%	Ha	%
Forest	107763.8	27.09	50482.15	12.68	-57281.7	-14.41
Savannah	231069.9	58.08	226920.70	57.03	-4149.2	-1.05
Cropland	1033.29	0.26	21690.24	5.45	20656.95	5.19
Settlement	56665.09	14.24	97151.90	24.41	40486.81	10.17
Water	1267.2	0.32	1597.63	0.4	330.43	0.08
Total	**397787.6**	**100**	**397842.6**	**100**		

Table 29. The area coverage of LULCC percent, and rate of changes between 1998 and 2063 at Boundiali

	Area				Change	
	1998		**2063**		**1998-2063**	
LULCC Types	Ha	%	Ha	%	Ha	%
Forest	126846.9	29.21	126238.33	29.07	-608.57	-0.14
Savannah	209361.7	48.21	143315.20	33	-66046.5	-15.21
Cropland	2801.79	0.64	68022.97	15.6	65221.18	14.96
Settlement	93285.81	21.48	93646.70	21.6	360.89	0.12
Water	1896.03	0.43	2934.6	0.67	1038.57	0.24
Total	**434192.2**	**100**	**434157.8**	**100**		

Table 30. The area coverage of LULCC percent, and rate of changes between 1998 and 2063 at Mankono

	Area				**Change**	
	1998		**2063**		**1998-2063**	
LULCC Types	Ha	%	Ha	%	Ha	%
Forest	80350.65	13.2	38013.22	6.23	-42337.4	-6.97
Savannah	436272.8	71.6	246286.06	40.40	-189997	-31.2
Cropland	33705.54	5.5	40117.95	6.58	6412.41	1.08
Settlement	57857.21	9.5	283891.24	46.57	226034	37.07
Water	1238.4	0.20	1190.06	0.19	0	0
Total	**609434.6**	**100**	**609498.5**	**100**		

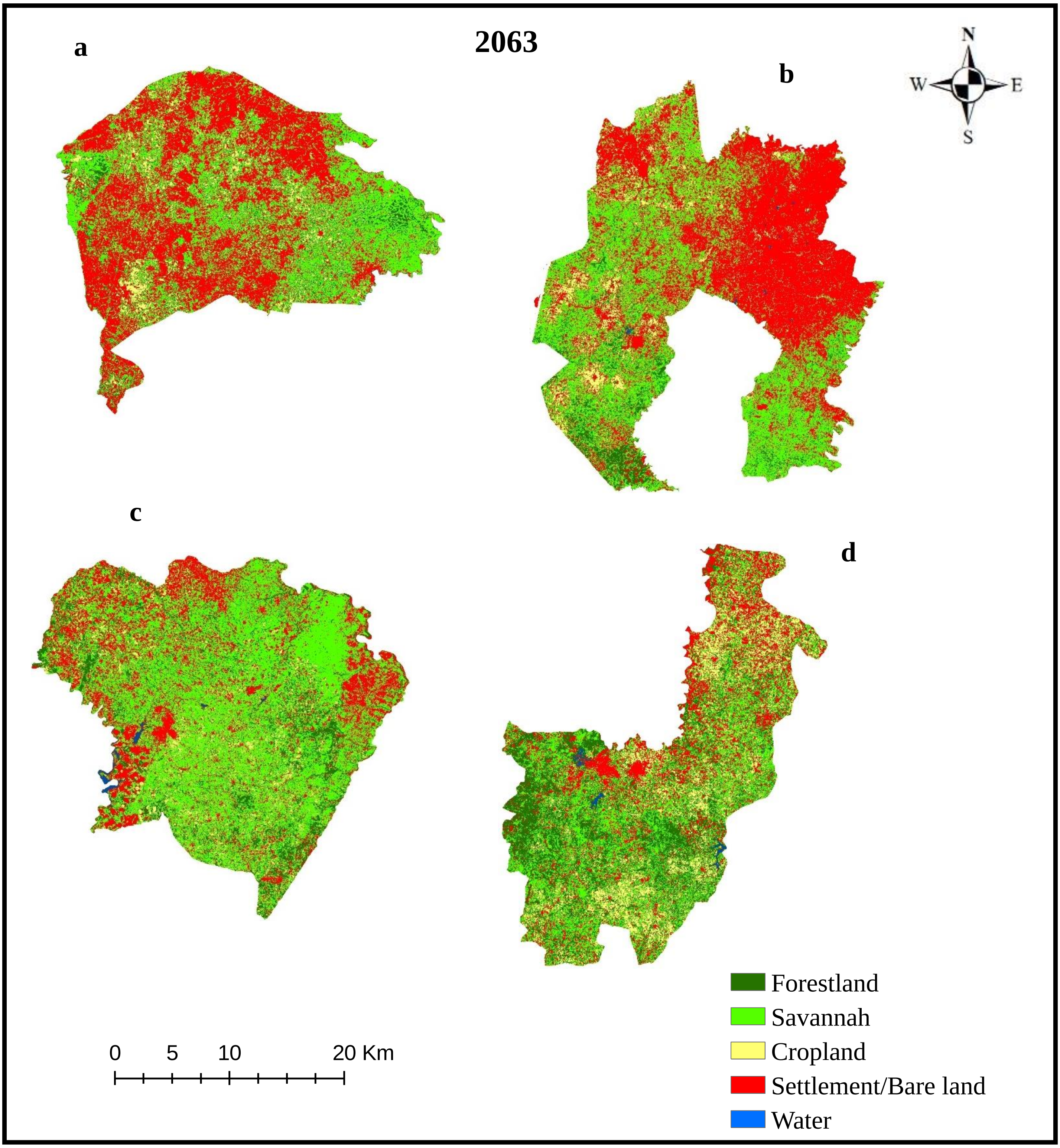

Figure 22. Projected LULC maps (2063) (a) Mankono, (b) Korhogo, (c) Ferkessedougou, and (d) Boundiali

6.4. Discussions

6.4.1. Accuracy Assessment of the Classified Image and historical LULC dynamics

By analysing satellite images captured at various times, the research investigated the alterations in land use and land cover within the Côte d'Ivoire cotton basins. To ascertain the accuracy of the pixel classification into the appropriate land cover classes, evaluating accuracy was deemed a crucial aspect of the classification process. The investigation conducted in the study area established five principal land cover types: Forestland, Savannah, Cropland, Settlement/Bare land, and water body. Savannah and Settlement/Bare land were identified as the predominant categories, with Savannah being the most prevalent from 1998 to 2020. The assessment of accuracy produced outstanding results, except for the cropland in Ferkessedougou for all the years under investigation, as well as the cropland in Korhogo in 2009. In terms of overall accuracy, the findings of the study are similar to those of Tadese *et al.,* (2020), who reported a satisfactory overall accuracy rate of 86.6 % and 87.1% respectively. According to Kindu *et al.,* (2013), the Kappa statistics in the investigation demonstrated a substantial agreement between the recently classified image and the actual image, with accuracy falling within an acceptable range for further analysis of land use and land cover change detection. The classification accuracy for all the LULC was found to be good. The classification of cropland in Ferkessedougou and some other districts showed poor performance, which could be due to sample selection errors. The misclassification rates were higher in 2020 than in 2009 and 1998, as shown in the confusion matrices, with cropland often being misidentified as natural vegetation and Savannah. This could be attributed to selective trees in the croplands, which are preserved due to their ecological benefits. This finding is consistent with Larbi *et al.,* (2019) who noted confusion between cropland and grassland classification due to the presence of grasses and trees in harvested croplands. On the contrary, in 2020, there was a notable reduction in Savannah and forestland, which were transformed into other land use and land cover types in all four departments of the study area. Similar studies conducted in other parts of Northern Côte d'Ivoire also reported the loss of forests to crops, with cotton crops covering up to 25 % of the crop area in the department of Korhogo (Bassettet, 2017).

The study revealed a persistent decline in forestland and Savannah and a consistent rise in settlement/bare land and cropland in the cotton basin of Côte d'Ivoire over the years. Within the last two decades, approximately half of the forest and savannah had been transformed into anthropogenic land use. The accelerated transformation could be linked to the fast growth in population. The findings indicated a rise in the demand for farmlands, settlements, fuel wood, and construction materials due to an increase in population pressure on land resources. More than 70 % of the study area's total population resides in rural areas, where households depend heavily on land resources for their livelihoods. This, in turn, has led to the expansion of shrubs, forests, and grasslands into farmlands. Furthermore, deforestation has accelerated as a result of household energy demands and the need for additional income. The results indicate that population expansion is a significant factor driving the land use and land cover changes in the Côte d'Ivoire cotton basins. These observations are consistent with the findings of Yangouliba *et al.,* (2022), who reported a comparable trend of expansion in cropland, bare land, and settlement areas, and a decrease in natural vegetation in the Nakambe River Basin of West Africa.

6.4.2. Future LULC dynamics and their implications for land degradation

Land use and land cover change (LULC) refer to both human and natural alterations of the land surface (Tolessa *et al.,* 2019). The conversion of natural vegetation to cultivated land is having a substantial impact on the natural surroundings. The expansion of cultivated land poses a significant risk to soil fertility, leading to land degradation (Moges *et al.,* 2019). The study predicted the future LULC map of the Côte d'Ivoire cotton basin for 2035 and 2063, and it indicated a significant increase in settlement/bare land and cropland and a decline in natural vegetation from 1998 to 2035 in three of the four departments. The progressive loss of vegetation reveals how natural lands will continually be replaced by man-made structures and cropland in the future. The rise in farmland can be attributed to the variety of changes that were permitted within the Markov Chain algorithm used to calculate the land use and land cover (LULC) for the years 2035 and 2063. According to Vanwalleghem *et al.,* (2017), there has been a rise in the conversion of natural vegetation to agricultural land and urban areas, along with an increase in agricultural activities. Philip *et al.,* (2022); Sonam *et al.,* (2021) and Hussien *et al.*, (2022) forecasted a rise in cropland and settlement, which is consistent with the findings of this study. In Côte d'Ivoire, the soil's fertility could be influenced by the outcomes of upcoming changes in land use and land cover. According to Tellen *et al.*, (2018), the process of transforming natural forests or Savannah into agricultural land leads to a decrease in various elements such as organic carbon, total nitrogen, available phosphorus, pH, cation exchange capacity, and exchangeable bases. Villarino *et al.*, (2019) suggest that agricultural production can be enhanced by expanding the cropland area or improving productivity per unit area. However, when natural cover areas are converted into crop production agriculture, the overall provision of SOC-mediated ecosystem services decreases. According to Hayicho *et al.*, (2019), changes in land use and land cover (LULC) caused by human activities have a significant impact on the alteration of soil organic carbon (SOC). Fantaw *et al.*, (2006) state that the lower SOC content in cultivated land could be due to the significantly higher rates of erosion and decomposition processes occurring in these areas compared to forest and grazing lands. As a result, the SOC content in cultivated land was found to be substantially lower than in other types of land. According to Ashagrie (2007), the concentration of nutrients, including SOC, is low in the cotton basins of Côte d'Ivoire. When the soil in this area is used for agricultural production, SOM undergoes rapid decomposition due to various factors, such as changes in soil structure caused by disruption of soil aggregates, alteration in aeration, and water content. Villarino *et al.* (2019) state that the conversion of forestland or natural vegetation into cropland results in a net reduction in SOC. This was also observed in the Côte d'Ivoire cotton basin. The land-use change had significant effects on topsoil chemical properties (Bato *et al.*, 2020). The authors also noted that the transition from natural forests to cotton crops brought about significant alterations to the nutrient content of the topsoil. To mitigate the negative consequences of unplanned development and changes in natural land cover, adopting appropriate land management strategies is crucial.

6.5. Conclusion and Recommendations

This study aimed to investigate the changes in land use and land cover (LULC) patterns in the Côte d'Ivoire cotton basins between 1998 and 2035 and 1998 and 2063. To achieve this, remote sensing, GIS, and a Markov Chain of LCM model were employed to analyse the spatiotemporal dynamics of LULC and forecast future changes. The accuracy of the model was verified by comparing its results with the LULC of 2020. The study's findings revealed that the forestland and Savannah areas underwent a continual decline, whereas cropland and settlement/bare land expanded continuously from 1998 to 2020. Based on the predicted LULC, it is anticipated that the declining trend in forestland and Savannah areas while expanding cropland and settlement/bare land would persist in the future. This trend can lead to decreased soil fertility, land degradation, and a decline in SOC. The observed LULC changes are primarily attributed to the increasing population, rising demand for natural resources, and the expansion of cultivated and settlement areas in the Côte d'Ivoire cotton basins. To prevent these adverse effects, policymakers and local communities should adopt sustainable land use planning and management practices, implement tree planting initiatives, employ soil and water conservation measures, and consider alternative livelihood strategies.

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CHAPTER 7: SYNTHESIS, CONCLUSION, AND RECOMMENDATIONS

This chapter summarises the main findings related to the research questions, general conclusions, and recommendations obtained from the previous chapters.

GENERAL CONCLUSION

1. The study in Côte d'Ivoire's cotton basin area explored local cotton farmers' perceptions and adaptations to climate change. Farmers recognized that changing rainfall patterns, temperature, and wind speed had a significant impact on cotton productivity, with irregular and insufficient rainfall being a major challenge. Interestingly, farmers' perceptions did not align completely with historical weather records, highlighting the need for objective information to guide adaptation strategies. To address these challenges, cotton farmers in the region have adopted various adaptation strategies, such as using climate-resistant cotton varieties, intercropping, and applying organic manure.
2. A significant improvement in exchangeable cations and base saturation was observed between 2013 and 2021. This indicates a gradual shift towards more sustainable crop and soil management practices, including the frequent application of organic amendments in addition to chemical fertilisers.
3. The study also emphasized the importance of soil physicochemical parameters for sustainable cotton productivity management. Most soils in the study area were degraded and less suitable for cotton cultivation, showing deficiencies in mineral elements and limitations in Cation Exchange Capacity (CEC) and soil erosion buffer (SEB).
4. Additionally, the study investigated land use and land cover (LULC) patterns in the cotton basin using remote sensing, GIS, and a Markov Chain of Land Change Modeler. The findings showed a continuous decline in forestland and Savannah areas, accompanied by the expansion of cropland and settlement/bare land from 1998 to 2020. These trends could lead to a decline in soil fertility, land degradation and a reduction in soil organic carbon in 2035 and 2063.

RECOMMENDATIONS

Recommendations for Policy (Côte d’Ivoire Government and NGO)

i. Farmers should be encouraged to use crop varieties with a shorter maturity that can withstand drought and high temperatures.

ii. increased stakeholder awareness of the importance of climate-smart agriculture such as developing resilience against climate change effect which is considered significant in the cotton basin of Côte d'Ivoire.

iii. Popularise strategies to improve the use of organic manure to improve soil fertility.

iv. Farmers should be encouraged to leave more trees on their farmland to compensate for the loss of forests and to practice fallowing techniques and intercropping.

v. Agroforestry practices that involve retention or planting of large canopy trees in cotton plantations should be promoted for biodiversity conservation and carbon stock enhancement.

vi. Decision-making and policy should emphasise the promotion of intensive rather than extensive farming.

Recommendations for Future Research

Due to the constraint of resources and time, some issues are still unanswered in this research. These issues are presented below for future research:

i. Further research should consider the carbon pools of the different land use and land cover classes provided by the study to estimate and map carbon as well as carbon dioxide emissions and removals from land use and land cover changes.

ii. Conduct long-term experiments to evaluate the impacts of climate variability and land use/land cover change on soil fertility. This will help to understand how soil fertility responds to changes in climate and land use over a longer period, providing more accurate predictions for future changes.

iii. Develop models to simulate the impacts of climate variability and land use/land cover change on soil fertility. This will provide a useful tool for predicting how soil fertility will respond to changes in climate and land use, and help to inform land management decisions.

iv. Investigate the impacts of climate variability and land use/land cover change on soil microbiomes. Soil microbes play an important role in soil fertility, and understanding how changes in climate and land use affect them can help us to predict changes in soil fertility

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APPENDICES

Appendices 1: Attestation of communication and publication

ATTESTATION DE PARTICIPATION

Décernée à

KONE ISMAIL

pour avoir participé à la

5ème ÉDITION DES JOURNÉES DES SCIENCES GÉOLOGIQUES « JSG 2022 »

du 09 au 10 mars 2022 à l'Université Félix Houphouët-Boigny, Abidjan (Côte d'Ivoire) sur le thème:

« Contribution des sciences géologiques à l'économie »

Titre de la communication: Local perception of cotton farmers and détermination of favourable cotton growing areas in a context of climate change : Northern cotton basin of Côte d'Ivoire

Type de communication: Orale

Abidjan le 10 mars 2022

Le Doyen

Pr SORO Nagnin

Building Stronger Universities
III Project in Collaboration with its **Danish Partners**

CERTIFICATE OF PARTICIPATION

PRESENTED TO

Ismail Kone

for submitting an Abstract and delivering an **Oral Presentation** at the BSU III International Conference on Climate Change Resilience, Adaptation & Sustainable Rural Transformation held from 4th & 5th October, 2022 at KNUST, Kumasi, Ghana

Prof. Robert C. Abaidoo
BSU III Coordinator, KNUST

Prof. Torsten Rodel Berg
BSU III Coordinator, Aarhus University, Denmark

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Local Cotton Farmers' Perceptions of Climate Change Events and Adaptations Strategies in Cotton Basin of Cote d'Ivoire

Ismail Kone Wilson Agyei Agyare Thomas Gaiser Nat Owusu-Prempeh Konan-Kan Hippolyte Kouadio
Emmanuel NGoran Kouadio William Amponsah

Abstract

Climate change represents a major potential threat to the viability of rural households' livelihoods in sub-Saharan Africa. This study focused on the perceptions of climate change and adaptation strategies of local cotton farmers in Côte d'Ivoire, identified as particularly vulnerable to climate change. A survey was conducted among 355 smallholder farmers distributed in four departments of the cotton basin of Côte d'Ivoire (Korhogo, Boundiali, Ferkessédougou and Mankono). Using changes in weather pattern as indicators of climate change, the results showed that majority of respondents believe climate change is evident in the study area and has negative effects on their livelihoods. Respondents reported an increase in temperature and decrease in rainfall amount in Korhogo and Boundiali departments, which were consistent with the climate data. The main coping strategies implemented by the farmers were shifting of planting dates and timing of cultural activities, adopting new crop varieties, ploughing before planting, diversifying crops and making specific sacrifices to divine powers depending on the type of belief of the farmer. The farmers' adoption of adaptation strategy depended on their perception of climate change and the available coping strategy. Lack of sufficient knowledge and government support were the major constraints that hindered cotton farmers to adapt effectively, leading to low cotton productivity in the study area. Therefore, policy implications will be crucial to help farmers make better adaptation choices in the face of climate change.

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Assessment of soil fertility status in cotton-based cropping systems in Cote d'Ivoire

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Appendices 2: Farmer's household survey questionnaire evaluation of the adaptation options used by local cotton farmers to cope with climate change

This research survey questionnaire is designed for academic purposes to assess the perception of on-farm adaptation strategies. You are assured of the confidentiality of any view expressed concerning this research. I, therefore, appeal to you to provide information as possible for a relevant result. Thank you for your cooperation.

Survey on Perceptions and Adaptations of Cotton Producers in the Face of Climate Change

Geographic coordinate: Latitude............................ Longitude.................…............

Date of investigation................................... Time: Survey start time ....

QUESTIONNAIRE ADDRESSED TO THE LOCAL COTTON FARMERS (write in lower case. No capitalization in the form)

		codes
Department		
Cotton company		
Zone		
Section		
Village		

IDENTIFICATION
Name and surnames of the investigator:.........
Name and surnames of the respondent:................
Producer's sitracot code: ....

I. SOCIO-DEMOGRAPHIC CHARACTERISTICS OF THE HOUSEHOLD		
Gender of respondent	Male Woman	1 2
Age of the respondent (age absolutely, do not put the year)	……………………………………………………………………..	
What is your marital status	Married/in a relationship Bachelor Widower (Ve) Divorced	1 2 3 4
What is your level of education	None Primary Secondary Upper Koranic school	1 2 3 4 5
Ethnic group	…………………………………………………………………	
What is your status in the zone?	Indigenous Immigrant Non-native	1 2 3
Size of households surveyed	Number of women (If male and married) Number of children Other family members	……… ……… ………

	Household size:	………
Respondent's relationship (If the head of household is absent) with the head of household	Head of household Wife Child Brother Nephew Other to be specified	1 2 3 4 5 6
Are you a member of a cotton cooperative?	Yes Not	1 2
If yes, the name of the co-op	………………………………………………………………………	

How do you access to land?	Inheritance Don Purchase Location Loan Sharecropping Gage	1 2 3 4 5 6 7
Do you use a workforce?	Yes No	1 2
If so, what kind of workforce do you use?	Family Employee Mutual aid	1 2 3
If so, what is the number of this workforce by type?	Family Employee Mutual aid	……… ……… ……….
How important is cotton among your main crops?		1 2 3 4 5 6 7
How important is cashew nut among your main crops?		1 2 3 4 5 6 7
How important is rice among your main crops?		1 2 3 4 5 6 7
How important is Maize among your main crops?		1 2 3 4 5 6 7
How important is millet among your main crops?		1 2

		3 4 5 6 7

What are the elements of nature that show the arrival of rain or the dry season? Justify your answer.		
Do these aforementioned elements still exist?		
How do you assess the number of rainy days in recent years?	Increase Decrease No change	1 2 3
If Augmentation, when do they occur? Circles the months	January -February -March- April- May- June-July-August-September- October- November- December	
If Decline, when do they occur? Circles the months	January -February -March- April- May- June-July-August-September- October- November- December	
What is your assessment of the temperature in your area in recent years?	Increase Decrease No change	1 2 3
If Augmentation, when do they occur?	January -February -March- April- May- June-July-August-September- October- November- December	
If Decline, when do they occur?	January -February -March- April- May- June-July-August-September- October- November- December	
In your community, winds tend to be:	Louder Less strong No change	1 2 3
If stronger, at what times do they intervene?	January -February -March- April- May- June-July-August-September- October- November- December	
If stronger, at what times do they intervene?	January -February -March- April- May- June-July-August-September- October- November- December	
In your opinion, what are the causes of climate change in your area?	Deforestation Bushfires Violation of the prohibitions of tradition Others to be specified.....................	1 2 3 4
Have you noticed any consequences of climate change on cotton production in your area?	Yes No	1 2
If so, how?	Decline in production Disruption of the crop calendar Soil depletion Insect pest blooms Increase in herbs Other to be specified	1 2 3 4 5 6
If the crop calendar is disruptive, at what time of year do you do the Soil Preparation for the Soil?		
If the crop schedule is disruptive, at what time of year do you make pre-emergence herbicides for the cotton?		
If the crop calendar is disrupted, at what time of year do you do the Reseeding for the cotton?		
If the cultural calendar is disruptive, at what time of year do you do the Demarriage for the Coronate?		

If the crop schedule is disruptive, at what time of year do you make the post-emergence herbicide for the cotton?		
If the cultural calendar is disruptive, at what time of year do you do the First weeding for the cotton?		
If the crop calendar is disrupted, at what time of year do you do Second weeding for the cotton?		
If the crop calendar is disrupted, at what time of year do you apply NPK fertilizer for the cotton?		
If the crop calendar is disruptive, at what time of year do you apply urea to the cotton?		
If the crop schedule is disruptive, at what time of year do you make pre-emergence herbicides for the cotton?		
If the crop calendar is disruptive, at what time of year do you carry out Insecticide Treatments for the Cotton?		
If the crop calendar is disruptive, at what time of year do you harvest cotton?		
If production drops, what are you doing to increase your production		
If depletion, soil depletion, what are you doing to increase		
IV. PERCEPTION ON SOIL FERTILITY MANAGEMENT		
How do you find the soil quality of your cotton field?	Good for cotton cultivation Poor	1 2
In case the soil is tired or poor, how do you know that the fertility of your soil is declining?	Decreased yield Change in soil colour Difficult to plough Absence of dominant vegetation Others to be specified	1 2 3 4 5

Justify your answer	…………………………………………………	
In case the soil is poor, how is the cotton tree doing?	Cotton does not produce well Cotton does not grow well Cotton is stunted Cotton does not grow well	1 2 3 4
In case the soil is poor, what do you think are the causes?	Expansion of livestock farming Illegal logging Others to be specified...............................	1 2 3 4
In case the soil is poor, what do you do to make it fertile?	Burning plots Fallow practice Intercropping of legumes Use of fertilizers Mulching	1 2 3 4 5
In your opinion, can mulching increase soil fertility?	Yes Not	1 2
If so, how?	……………………………………………………..	
In your opinion, can the burning of plots increase soil fertility?	Yes Not	
If so, how?	…………………………………………………………..	
In your opinion, can fallow increase soil fertility?	Yes Not	1 2
If so, how?	………………………………………………………	
Are legumes used in cotton intercropping?	Yes Not	1 2
Justify your answer	……………………………………………………..	

What fertilizer formulation do you use?	Foliar fertilizer Solid fertilizer	1 2
How many days after emergence do you apply NPK fertilizer ?		…… …….
How many days after emergence do you apply urea fertilizer ?		
How much do you apply fertilizer per hectare?		…… …… ……
At what dose do you apply NPK fertilizer (bag) per hectare?		
At what dose do you apply urea fertilizer (bag) per hectare?		
How much do you apply foliar fertilizer (litre) per hectare?		
How do you apply the fertilizer you use?	Shutter Slash Closed seat	1 2 3
Apart from mineral fertilizer, bring other types of fertilizer	Yes Not	1 2
If so, which ones?	Compost Manure Crop residues Other to be specified	1 2 3 4
V. PERCEPTION OF LAND USE		
How has vegetation cover changed in your area over the past 30 years?	Increase Intact Decrease	1 2 3
If decreasing, how do you feel about the level of degradation of the last 30 years?	Weak Medium High	1 2 3
How land use affects soil fertility	Through chemical fertilizers Through water erosion Inappropriate cultural practices Other to be specified	1 2 3 4
Justify your answer	………………………………………………………………	
How do you weed your plot	Cattle plough Tractor Gave Machete Herbicides	1 2 3 4 5
Do you combine cotton with other crops in your field?	Yes Not	1 2
If so, what are these crops?	Food crops Anacardes	1 2
Why do you make the association?	………………………………………………………………	
If cashew nuts, does this association have an impact on cotton?	Yes Not	1 2
Justify your answer	……………………………………………………	
VI. IDENTIFICATION OF ACCOMMODATION MEASURES		
What tools do you no longer use?	……………………………………………………………….	
What new tools are you using now	……………………………………………………………..	

In the face of climate change, have you changed your cotton varieties?	Yes Not	1 2
If so, do these varieties give good yields?	Yes Not	1 2
If so, do these new varieties adapt to the climate?	Yes Not	1 2
If so, with these new varieties, how many tons do you produce per hectare?	…………………………………………………………..	
With climate change, what types of cotton varieties do you prefer	Early Average Late	1 2 3
Justify your answer	………………………………………………………..	
Faced with climate variability, have you increased or decreased the area?	Yes Not	1 2
Have you changed your technical itinerary to:	Choice of plot Cultivation technique Other	1 2 3
Justify your answer.	………………………………………………………	
With climate variability, have you changed the sowing period?	Yes Not	1 2
Justify your answer		
If so, in what decade do you currently sow cotton?	D1 D2 D3 D4	1 2 3 4
With climate change, do you practice semi-dry?	Yes Not	1 2
Justify your answer		
Do you use plant protection products?	Yes Not	1 2
If so, which ones and why?	…………………………………………………………..	
Has this climatic context pushed you towards other cultures?	Yes No	1 2
Do you grow other crops in combination or rotation with cotton?	Yes Not	1 2
If so, why?	……………………………………………………….	
In your opinion, are there other coping strategies?	Yes Not	1 2
If so, which ones?	…………………………………………………………	
In the face of climate change, what would you like us to do to improve your cotton production?		
Respondent contact		

End time ....

Thank you for your availability and attention

Appendix 3: Location of various soil sites samples in the cotton basin zone of Côte d'Ivoire that was used in the study

DEPARTMENT	VILLAGES	LATITUDES	LONGITUDES
Korhogo	TAWARA	9.718724	-5.67181
Korhogo	LATAHA	9.580858	-5.599016
Korhogo	BAFIME	9.453642	-5.569199
Korhogo	KAKLOKAHA	9.476977	-5.504861
Korhogo	SAMBALAKAHA	9.392883	-5.580668
Korhogo	GBALOHO	9.491487	-5.71627
Korhogo	LARAZOUROU	9.498599	-5.916522
Korhogo	FORO	9.406223	-5.735742
Ferkéssedougou	PARAWALAKAHA	9.589201	-5.1391
Ferkéssedougou	LASSOLOGO	9.582522	-5.09584
Ferkéssedougou	DEKOKAHA	9.673034	-5.172654
Ferkéssedougou	MOMIRASSO	9.712598	-5.17261
Ferkéssedougou	LARGATONVO	9.814898	-5.159701
Ferkéssedougou	TIEPKE	9.678053	-5.307038
Ferkéssedougou	TANDO KAHA	9.726664	-5.335686
Ferkéssedougou	MAMADOUVOGO	9.616411	-5.309422
Boundiali	PONONDOUGOU	9.544162	-6.366228
Boundiali	KPAFONON	9.708097	-6.491886
Boundiali	KOLIA	9.708029	-6.492189
Boundiali	BOYO	9.993195	-6.365541
Boundiali	ZAGUINANSSO	10.07554	-6.390862
Mankono	MARAHOUE	8.125549	-6.26741
Mankono	MADIAN	8.152533	-6.114385

Appendices 4: Illustrations

- **Fieldwork**

- **Survey**

- **Laboratory analysis**