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UNIVERSITE FELIX HOUPHOUET- BOIGNY



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**Florence Jessica Akosua KUMAH**

# Impact of Cocoa Cultivation on Soil Carbon Sequestration and Microbial Community under climate and land use changes in Ghana and Côte d'Ivoire

Public defence on 9<sup>th</sup> March 2024

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## THESE

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## **DEDICATION**

I dedicate this dissertation to my mother Gladys Akua Som and my lovely sister Peace Lilian Kumah of blessed memory. I also dedicate this work to my husband Mr. Albert Y. Fia and my children Kafui and Amenuveve for understanding and staying by me all this while.

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## ABBREVIATION AND ACRONYMS

<b>AEAs:</b>	Agric Extension Agents
<b>AMF:</b>	Arbuscular Mycorrhizal fungi
<b>BD:</b>	Bulk Density
<b>C:</b>	Carbon
<b>C/N:</b>	Carbon Nitrogen ratio
<b>CEOs:</b>	Chief Executive Officers
<b>CH<sub>4</sub>:</b>	Methane
<b>CO<sub>2</sub>:</b>	Carbon dioxide
<b>CSA:</b>	Climate Smart Agriculture
<b>DNA:</b>	Deoxyribonucleic Acid
<b>DOC:</b>	Dissolved Organic Carbon
<b>ELD:</b>	The Economics of Land Degradation
<b>FAO:</b>	Food and Agriculture Organization
<b>FAOSTAT:</b>	Food and Agriculture Organization Statistics
<b>GHGs:</b>	Green House Gases
<b>GSP:</b>	Global Soil Partnership
<b>GTC/yr:</b>	Giga Tone Carbon per year
<b>HRFZ:</b>	High Rainforest Zones
<b>IAA:</b>	Indole Acetic Acid
<b>ITPS:</b>	Intergovernmental Technical Panel on Soils
<b>IPCC:</b>	Intergovernmental Panel on Climate Change
<b>K:</b>	Potassium
<b>MBC:</b>	Microbial Biomass Carbon
<b>MBN:</b>	Microbial Biomass Nitrogen
<b>MNL:</b>	Multinomial Logit
<b>MoFA:</b>	Ministry of Food and Agriculture
<b>MyTIPS:</b>	Tropical mycology and Plants-soil fungi interaction
<b>MVA:</b>	Mean Vessel Area
<b>MVRD:</b>	Mean Vessel Radial Diameter
<b>MVTD:</b>	Mean Vessel Tangential Diameter
<b>N:</b>	Nitrogen
<b>NH<sub>4</sub><sup>+</sup>-N:</b>	Ammonium-nitrogen
<b>NO<sub>3</sub><sup>-</sup>-N:</b>	Nitrate-nitrogen

<b>N<sub>2</sub>O:</b>	Nitrous Oxide
<b>OTUs:</b>	Operational Taxonomy Unit stability
<b>P:</b>	Phosphorus
<b>PCA:</b>	Principal Component Analysis
<b>PCA:</b>	Plate Count Agar
<b>PCR:</b>	Polymerase Chain Reaction
<b>PDA:</b>	Potato Dextrose Agar
<b>PGP:</b>	Plant growth-promoting
<b>POXC:</b>	Permanganate Oxidizable Carbon
<b>PSPs:</b>	Permanent Sample Plots
<b>RWI:</b>	Ring-width index
<b>SDFZ:</b>	Semi-deciduous Forest Zones
<b>SOC:</b>	Soil Organic Carbon
<b>SOCD:</b>	Soil Organic Carbon Density
<b>SOM:</b>	Soil organic matter
<b>SRI:</b>	Soil Research Institute
<b>TN:</b>	Total Nitrogen
<b>TOC:</b>	Total Organic Carbon
<b>UN:</b>	United Nations
<b>UNCCD:</b>	United Nations Convention to Combat Desertification
<b>UNDP:</b>	United Nations Development Programme
<b>UNESCO:</b>	United Nations Educational, Scientific and Cultural Organization
<b>UNFCCC:</b>	The United Nations Framework Convention on Climate Change
<b>USD:</b>	United States Dollar
<b>UV:</b>	Ultraviolet
<b>VD:</b>	Vessel Density
<b>VN:</b>	Vessel Number
<b>WHC:</b>	Water Holding Capacity
<b>WMO:</b>	World Meteorological Organization

## ABSTRACT

Results of the present study provide relevant social and ecological insights on cocoa agroforestry system in West Africa. In general, cocoa land use tends to have major implication on soil properties due to unsustainable land conversion and management, and climate change, thereby making soils of these production systems function below their productive capacity and stability. Understanding how this cultivation system under climate change impact soil properties, and cocoa plant growth is crucial for sustainable soil management, climate change mitigation and conservation actions under climate and land use changes in Ghana and Côte d'Ivoire. Specifically, the study assessed farmers' perceptions and views of relevant stakeholders of how sustainable agroforestry should be designed to be able to achieve climate change mitigation and biodiversity conservation through the cocoa supply chain in Ghana and Côte d'Ivoire. Evaluated the impact of cocoa agroforestry management on soil physico-chemical properties and soil organic carbon sequestration. It has also characterized soil microbial population and communities common to the cocoa agroforestry farms in these countries. Finally, it has determined the growth rate and anatomical traits, and the climate-growth relationship of cocoa trees. To achieve these objectives, a face-to-face interview and semi-structured questionnaire were used to assess 201 (CI=100 and GH=101) farmers' perceptions of sustainable agroforestry, climate change mitigation and biodiversity conservation and how it can be achieved through the cocoa supply chain. Soil properties were analyzed from samples collected from the surface (0-15 cm) and subsurface (15-30 cm) soil depths of treatment plots from three stands of different aged cocoa agroforestry, designated as 5, 15 and 30 years old farms in Ghana and Côte d'Ivoire. Dendrochronological studies were used to investigate the anatomical growth responses of cocoa tree to climate. The results indicate that high proportion of the respondents (89 and 88 % from Côte d'Ivoire and Ghana respectively) were not very much aware of soil carbon and its management, agroforestry and biodiversity and lack knowledge of strategies through which they can be achieved on the cocoa farmers farm. Farmers were very much aware of the drivers of climate change. Further results show that soil organic carbon and microbial communities differed considerably between farms (5, 15 and 30 years old) and between sites. Generally, SOC, SOCD sequestration were higher in the cocoa agroforestry farms in Ghana than Côte d'Ivoire. The results further showed that 15 years old farm in both countries perform higher in terms of most of the soil properties measured. The results obtained indicate positive correlations between soil pH and soil nutrient and their interactions. Analysis of the anatomical characteristics of the wood of the cocoa tree revealed the formation of distinct growth rings. The results show irregular growth trends and anatomical vessel traits varied across farms. Climate has significant influence on the growth and anatomical characteristics of cocoa. The study shows that immediate calls for education and more training are needed on sustainable management practices within the cocoa agroforestry system, the reinforcement of soil system and restoration actions are crucial for achieving future agriculture and forest sustainability in Ghana and Côte d'Ivoire.

**Keywords:** Cocoa agroforestry; reforestation; microbial community; soil carbon sequestration; climate change mitigation; soil fertility, sustainable agriculture.

## RESUME

Les résultats de la présente étude fournissent des informations sociales et écologiques pertinentes sur le système agroforestier du cacaoyer en Afrique de l'Ouest. En général, l'utilisation des terres cacaoyères a tendance à avoir des implications majeures sur les propriétés des sols en raison de la conversion et de la gestion des terres non viables, et du changement climatique, ce qui fait que les sols de ces systèmes de production fonctionnent en dessous de leur capacité de production et de leur stabilité. Comprendre comment ces systèmes de culture sous le changement climatique ont un impact sur les propriétés du sol et la croissance des plants de cacao est crucial pour la gestion durable des sols et des terres et les actions de conservation dans le contexte des changements climatiques et d'utilisation des terres au Ghana et en Côte d'Ivoire. Plus précisément, l'étude a évalué les perceptions des agriculteurs et les points de vue des parties prenantes concernées sur la manière dont l'agroforesterie durable devrait être conçue pour être en mesure d'atténuer le changement climatique et de conserver la biodiversité à travers la chaîne d'approvisionnement du cacao au Ghana et en Côte d'Ivoire. Évaluation de l'impact de la gestion agroforestière du cacao sur les propriétés physico-chimiques des sols et la séquestration du carbone organique dans les sols. Il a également permis de caractériser les populations microbiennes et les communautés communes aux exploitations agroforestières cacaoyères de ces pays. Enfin, il a déterminé le taux de croissance et les caractéristiques anatomiques, ainsi que la relation climat-croissance du cacaoyer. Pour atteindre ces objectifs, un entretien en face à face et un questionnaire semi-structuré ont été utilisés pour évaluer les perceptions de 201 agriculteurs (IC = 100 et GH = 101) sur l'agroforesterie durable, l'atténuation du changement climatique et la conservation de la biodiversité et sur la manière dont cela peut être réalisé à travers la chaîne d'approvisionnement du cacao. Les propriétés du sol ont été analysées à partir d'échantillons prélevés à la profondeur du sol de surface (0 à 15 cm) et souterrain (15 à 30 cm) de parcelles de traitement provenant de trois peuplements d'agroforesterie cacaoyère d'âge différent, désignés comme fermes de 5, 15 et 30 ans au Ghana et en Côte d'Ivoire. Des études dendrochronologiques ont été utilisées pour étudier les réponses anatomiques de la croissance du cacaoyer au climat. Les résultats indiquent qu'une forte proportion des personnes interrogées (89 % et 88 % respectivement de Côte d'Ivoire et du Ghana) n'étaient pas très sensibilisées au carbone du sol et à sa gestion, à l'agroforesterie et à la biodiversité et qu'elles ne connaissaient pas les stratégies permettant d'y parvenir dans les exploitations des producteurs de cacao. Les agriculteurs étaient très conscients des facteurs du changement climatique. D'autres résultats montrent que le carbone organique du sol et les communautés microbiennes diffèrent considérablement d'une ferme à l'autre (5, 15 et 30 ans) et d'un site à l'autre. D'une manière générale, les séquestrations de SOC et de SOCD étaient plus élevées dans les exploitations agroforestières de cacao au Ghana qu'en Côte d'Ivoire. Les résultats ont en outre montré que les exploitations agricoles âgées de 15 ans dans les deux pays obtiennent de meilleurs résultats en termes de la plupart des propriétés du sol mesurées. Les résultats obtenus indiquent des corrélations positives entre le pH du sol et les éléments nutritifs du sol et leurs interactions. L'analyse des caractéristiques anatomiques du bois du cacaoyer a révélé la formation d'anneaux de croissance distincts. Les résultats montrent une tendance de croissance irrégulière et les caractéristiques anatomiques des vaisseaux varient d'une ferme à l'autre. Le climat a une influence significative sur la croissance et les caractéristiques

anatomiques du cacaoyer. L'étude montre que des appels immédiats à l'éducation et à davantage de formation sont nécessaires sur les pratiques de gestion durable au sein des systèmes agroforestiers cacaoyers, le renforcement du système des sols et les actions de restauration sont cruciaux pour parvenir à la durabilité future de l'agriculture et des forêts au Ghana et en Côte d'Ivoire.

**Mots-clés :** Agroforesterie cacaoyère ; reboisement ; communauté microbienne ; séquestration du carbone dans le sol ; atténuation du changement climatique ; fertilité des sols.

# CHAPTER I

## GENERAL INTRODUCTION

### 1. Soil degradation

Land degradation remains a global environmental issue in almost all terrestrial biomes and agroecologies. Loss of soil fertility and soil organic matter (SOM), and recurrent drought are results of severe land degradation. Data have shown that about 33 % of the global land area is hit by land degradation, with about 47 % of the degraded land being forest while cropland accounted for 18 % of global degraded land (Bai *et al.*, 2008; FAO, 2015; Nkonya *et al.*, 2016). A total of two billion people and 1.9 billion hectares of land are affected by land degradation (Naseer and Pandey, 2018). According to UNCCD (2019), annual land degradation has cost the global economy between 18-20 trillion USD. Land degradation has led to the reduction or loss in biological productivity making agricultural soil unsuitable for cultivation. Currently, agricultural soils are functioning below their productive capacity and stability. Though partly due to limited water availability, low agricultural productivity is immensely caused by soil degradation (Obalum *et al.*, 2012). Soil degradation and low soil fertility are already a big problem for global agriculture (Jones *et al.*, 2013) and are now in the wake of climate change. The world is unable to increase food production to meet the demand of the growing population due to poor soil functions. Soil functions include nutrient cycling, water dynamics, filtering and buffering, physical stability and support of plant systems and human structures, and promotion of biodiversity and habitat.

Sustaining soil fertility and reversing land degradation has become a global priority considering consequences for ecosystem services, such as loss of genetic resources, species and habitat loss, and carbon and other greenhouse emissions resulting from poor land use practices in production systems (Jones *et al.*, 2013). In view of this, many land-use practices have been proposed to achieve the objectives of land-based sustainable development goals (soil restoration). Aimed at restoring and improving soil fertility and productivity (Blaser *et al.*, 2013) while helping to mitigate the challenge posed by climate change by removing C from the atmosphere and storing it in stabilized form as soil organic carbon (SOC). Hence, agricultural sustainability should contribute to increased food production and positively impact on environmental goods and services.

## 1.1 Background

Soil is an important and often neglected element of the climate system. Soil is a part of the solutions to biodiversity loss, food insecurity and climate change. Soil and its biodiversity play a crucial role in human well-being and the well-being of all plants and land-based animals depends on the complex processes that take place in the soil. It is the second largest carbon sink after the ocean as far as the natural cycle of CO<sub>2</sub> is concerned (Faggian *et al.*, 2012). According to IPCC 1992, about 2500 Pg of carbon is stored in forest soils. Moreso, soil microorganisms such as bacteria, archaea, fungi, and protists play integral roles in terrestrial ecosystem functioning. In particular, fungi act as the main decomposers of organic material and regulators of the abundance of other organisms as, e.g., mutualists, pathogens or producers of antibiotics (Bahram *et al.*, 2018). Fungi are highly important biotic components of terrestrial ecosystems. Mycorrhizal fungi colonize the roots of plants and provide water and mineral nutrients to their hosts (Smith and Read, 2008). However, forests degradation and other land use practices to satisfy the human population's increasing demand for food and other livelihoods has resulted in the severe degradation of soils (FAO, 2015, Bai *et al.*, 2008; Naseer and Pandey, 2018), causing their stored carbon to be released back to the atmosphere making soil a net contributor of carbon to the atmosphere and decreasing the long-term ability of soils to provide humans with services including future food production and other ecosystem services (Gupta, 2019).

Agricultural land use, such as cocoa cultivation, has led to vast forest degradation in the tropics in search of livelihoods, particularly in West Africa. FAOSTAT (2016) reveals that over 10 million hectares (ha) of land in the tropical regions of the world are used for cocoa production, with 83 % of cocoa grown in Africa and the remaining percentage in Asia and America. According to Gockowski *et al.* (2004), West Africa cocoa cropping systems cover between 5 - 6 million hectares of the moist tropics of Côte d'Ivoire, Ghana, Nigeria and Cameroon, and in Ghana and Côte d'Ivoire alone, the cultivated cocoa area occupies approximately 3.69 Mha in Côte d'Ivoire and approximately 2.15 Mha in Ghana (Abu *et al.*, 2021). Cocoa farmers in Ghana and Côte d'Ivoire, were encouraged to practice full-sun cocoa production primarily due to new hybrid varieties which involve complete clearance of the forest (Asase *et al.*, 2009; Ruf and Zadi, 1998) to maximize yield basically in short-terms. However, this practice is associated with deforestation and forest degradation (Ruf and Zadi, 1998). Cocoa farming becomes a destructive circle in these areas as farmers exhaust the soil and cut further into the forest to obtain fresh land in the search for fertile soil. It has been estimated that global soil organic

carbon loss could reach 212 Gt, and further decline in biodiversity by 10 % by the year 2050 due to unsustainable land management and land conversion (UNCCD, 2019). Unsustainable land use has also been noted to affect the soil nutrient cycle of agroecosystems (Sun *et al.*, 2017).

Changes in precipitation and rising temperature coupled with unsustainable land use is challenging and threatening the future of humanity (Haden *et al.*, 2012; IPCC, 2014). The agricultural sector is most sensitive to these climatic conditions which affect agricultural production and farming communities (IPCC, 2014). Increasing temperature will impact additional global climatic factors such as precipitation and evapo-transpiration patterns (IPCC, 2013). The fulfilment of temperature will have crucial consequences on the climate sensitive ecosystems such as forests and rural agricultural landscapes of the world (Warren *et al.*, 2011; Kayranli *et al.*, 2009). By 2080, moisture is predicted to be inadequate for profitable cocoa production in Ghana if the current trend of cultivation is maintained (Schroth *et al.*, 2016). The increase of dry season temperatures will limit the growth of cocoa trees due to decreasing water availability (Schroth *et al.*, 2016). Läderach *et al.* (2013) has predicted the future climatic suitability for cocoa farming of Ghana and Côte d'Ivoire and noticed that longer dry seasons will strongly affect cocoa yields in Côte d'Ivoire and Ghana.

Hence, agroforestry practice has been identified as one of the most important tools to restore agricultural soils and fulfill sustainable land use and livelihood objectives and mitigate the adverse effect of climate change (Mosquera-Losada *et al.*, 2018). Agroforestry is a system whereby a deliberate attempt is made to integrate and manage both forest and agricultural resources on the same landscape. Agroforestry systems is advocated as interesting and effective option to reduce forest loss, restore degraded soils, conserve biodiversity, and provide an important source of income for local populations (Nair, 1993). This intermediary land use system is important for sustainable forestry and agriculture (Hao *et al.*, 2002). Agroforestry systems occur in all tropical regions and can be based on many different tree crop species, including the cocoa agroforestry system. Cocoa agroforestry offer real opportunities to conserve biodiversity compared with other agricultural systems (Rolim and Chiarello 2004)

**Knowledge gap** Several works has been done in the domain of cocoa plantation/agroforestry system in the west Africa sub-region, including Cameroon (Sonwa *et al.*, 2007; Bisseleua, Herve and Vidal, 2007; Zapfack *et al.*, 2002) Nigeria (Oke and Odebiyi, 2007) and Ghana and Côte d'Ivoire (Ruf and Zadi 1998; Attua, 2003; Osei-Bonsu, Ameyaw and Tetteh, 2003; Ofori-Frimpong, Asase & Mason, 2005, Asare, 2005; Smith *et al.*, 2014; Tandoh *et al.*, 2015; Dawoe

*et al.*, 2016; Ladreach *et al.*, 2013; Kyereh, 2017; Abdulai *et al.*, 2018; Kouassi *et al.*, 2021). Most of these studies focused on the aboveground system neglecting the unseen below-ground communities and the soil system and by comparing cocoa agroforestry to cocoa monocultures, forestland and secondary forest in the West Africa sub-regions.

Comparing the performance of cocoa agroforestry system at farm level is rare. However, at farm level farmers' activities differ with the implications for increasing SOC storage or emitting CO<sub>2</sub> to the atmosphere. Under a changing climate, it is thus important to evaluate land use systems at farm level for soil management actions at the Ghana and Cote d'Ivoire level. Hence, appropriate research is thus needed to confirm the positive effect of cocoa agroforestry on soil with a particular focus on soil carbon sequestration, microbial population and communities, cocoa growth and ways in which sustainable cocoa agroforestry system can be achieved. Therefore, the main objective of this study was to provide social and ecological insights of cocoa agroforestry on soil properties as prerequisite for a sustainable agricultural and forest management through the cocoa supply chain in Ghana and Côte d'Ivoire.

## **1.2 General research question**

How is cocoa agroforestry management impacting soil properties (microbial biodiversity and carbon sequestration) in the context of climate change in fulfilling sustainable land use, conservation and livelihood objectives?

## **1.3 This study wants to answer the following questions**

- How do farmers perceive cocoa agroforestry, soil carbon management, climate change mitigation and biodiversity conservation and how can sustainable agroforestry be achieved?
- What impact do cocoa agroforestry management practice have on soil carbon sequestration and soil nutrient concentration?
- What soil microbial biodiversity is associated with cocoa agroforestry system in Ghana and Côte d'Ivoire?
- How does the growth of *Theobroma cacao* trees respond to environmental changes in this system?

## **1.4 General objective**

To provide social and ecological insights of cocoa agroforestry on soil properties as prerequisite for a sustainable agricultural and forest management through the cocoa supply chain in Ghana and Côte d'Ivoire.

## **1.5 Specific Objectives**

- a.** Examine cocoa farmers and stakeholders' perceptions of sustainable cocoa agroforestry system through the cocoa supply chain.

- b.** Determine the amount of soil carbon sequestered and soil nutrient concentration of cocoa agroforestry system.
- c.** Characterize soil microbial communities common to this cultivation system.
- d.** Assess the radial growth and anatomical response of *Theobroma cacao* to climate change.

### **1.6 Justification**

Soils of cocoa production systems in Ghana and Côte d'Ivoire are functioning below their productive capacity and stability which is a major threat to food security, biodiversity conservation and climate change mitigation (Somarriba *et al.*, 2013). There is a need for increased knowledge in research and understanding among stakeholders for sustainable solutions through the cocoa supply chain.

### **Research hypotheses**

#### **Main research hypothesis**

Sustainable cocoa agroforestry system in Ghana and Côte d'Ivoire can only be achieved through adequate training and education and sustainable soil management at farm level.

#### **Specific research hypothesis**

- Smallholder farmers are knowledgeable of cocoa agroforestry, biodiversity and its benefits.
- Local farmers are aware of the causes of climate change and its impacts on crop production.
- Smallholder cocoa farmers have adopted agroforestry practice under climate change, but farm management differ, this may have implications for soil carbon storage, microbial population and diversity, and soil nutrient availability.
- Management and climatic variables have significant influence on cocoa tree growth in the two countries.

### **Outline of the dissertation**

This research used an interdisciplinary approach, combining social surveys, soil fertility, soil carbon management and sequestration and soil microbial population and communities. Cocoa tree growth relationship with climate change: Dendrochronological studies and biodiversity informatics to understand how cocoa land use in the context of climate change impact soil properties and cocoa growth in Ghana and Côte d'Ivoire and it further developed policy for sustainable cocoa agroforestry management which will contribute to soil carbon sequestration, climate change mitigation, biodiversity conservation and profitable cocoa production in West Africa. Besides the introduction, conclusion, suggestions and perspectives, this work is

subdivided into four parts. The first part is about generalities on the study area and definition of some concepts. The second part deals with the materials and methods. The third part presents the results and finally, the fourth part deals with discussion of the results.

## CHAPTER II

### LITERATURE REVIEW

This chapter reviewed relevant literature on the impact of cocoa cultivation, cocoa agroforestry technologies on soil carbon sequestration and microbial community under climate and land-use changes. The review highlights the following: Cocoa cultivation, soil degradation, level of agroforestry adoption in the cocoa production chain, soil carbon management practices, SOC density and microbial biomass and diversity, and climate change.

#### **2. Cocoa cultivation in Ghana and Côte d'Ivoire**

In west Africa, particularly in the leading producing countries, cocoa is the main cash crop and the chief agricultural export crop. Côte d'Ivoire and Ghana are the leading and largest producer and exporter of cocoa in the world (FAO, 2017; ICCO, 2006). Cocoa production in these countries occurs mainly in the country's forested areas, in Ghana: Brong-Ahafo, Ashanti, Central, Western, Eastern, and Volta Regions and Côte d'Ivoire, it is centralized in the southern and towards northern part of the country (Cocobod, 2018; Tondoh *et al.*, 2015; Asase *et al.*, 2009) where annual rainfall ranges between 1200 and 2000mm. However, the cocoa growing regions have different characteristics in terms of soil type, age of (both farmer and farm) and variety of trees, which can affect the productivity of the system (Asase *et al.*, 2009; Asare *et al.*, 2014).

Cocoa Cultivation has been done under shade regimes that have evolved over the decades (Rainforest Alliance, 2018). The relatively dense forest that characterized the initial cultivation of cocoa in Ghana and Côte d'Ivoire, maintained the natural ecosystem suitable for cocoa growth. This system conserved to some extent many ecosystem functions and the remnant biodiversity of the original forest. These include generating and maintaining soils, storing and cycling essential nutrients, water related services such as maintenance by hydrological cycles and prevention of floods, water quality improvement, maintaining biodiversity, carbon sequestration, and regulating climate (Ruf, and Zadi, 1998; Schroth, *et al.*, 2004). This practice was the case of early cocoa cultivation in West Africa particularly in Ghana and Côte d'Ivoire, where farmers started the indigenous farming system growing cocoa crop under forest trees until the introduction of new hybrids to maximize yield to satisfy the increasing demand of chocolate industry and the farmers' livelihood (Tondoh *et al.*, 2015; Smith *et al.*, 2014; Rainforest Alliance, 2018).

Cocoa production turns out to be a destructive and a leading cause of forest degradation (Ruf and Varlet, 20017), soil degradation, biodiversity loss, pollution of water bodies and soil carbon

and other greenhouse gas emission. Cocoa agroforestry is considered as one of the potential adaptation strategies, contributing to food production, and resilience to climate change impacts (Somarriba and Lopez-Samson, 2018; Pattanayak *et al.*, 2003). Research has revealed major implications for cocoa cultivation under climate change (Ladreach *et al.*, 2013). Therefore, suggest the promotion of cocoa agroforestry system that maintains or improves the carbon content or carbon rich soil and stabilize the climate.

## **2.1 Conversion of sustainable cocoa to unsustainable intensified production system**

Cocoa cultivation using traditional agroforestry techniques has dwindled following the introduction of sun-tolerant hybrid cocoa (UNDP, 2011). In the past, low-shade or no-shade was recommended for hybrid cocoa, resulting in a highly unsustainable production system (Rice and Greenberg, 2000). The weakness of the zero-shade system was masked by the short-term yield increases driven by initially fertile forest soils. However, yields soon declined as forest soils were depleted of major nutrients. The practice of using zero shade production systems needs to be reversed.

### **2.1.1 Unsustainable land management practices and resource use**

The use of slash and burn techniques have led to reduced soil fertility through elevated nutrient release, loss of soil structure and stability, and lack of natural forest mulching that reduces soil and water loss from erosion and poor water infiltration and retention in the soil (Dawoe *et al.*, 2016). Near abandonment of traditional cocoa agroforestry systems in favor of zero shade cultivation methods has also resulted in widespread land degradation in the cocoa growing areas (UNDP, 2011; Ruf, and Zadi, 1998).

### **2.1.2 Cocoa and Climate change in Ghana and Côte d'Ivoire**

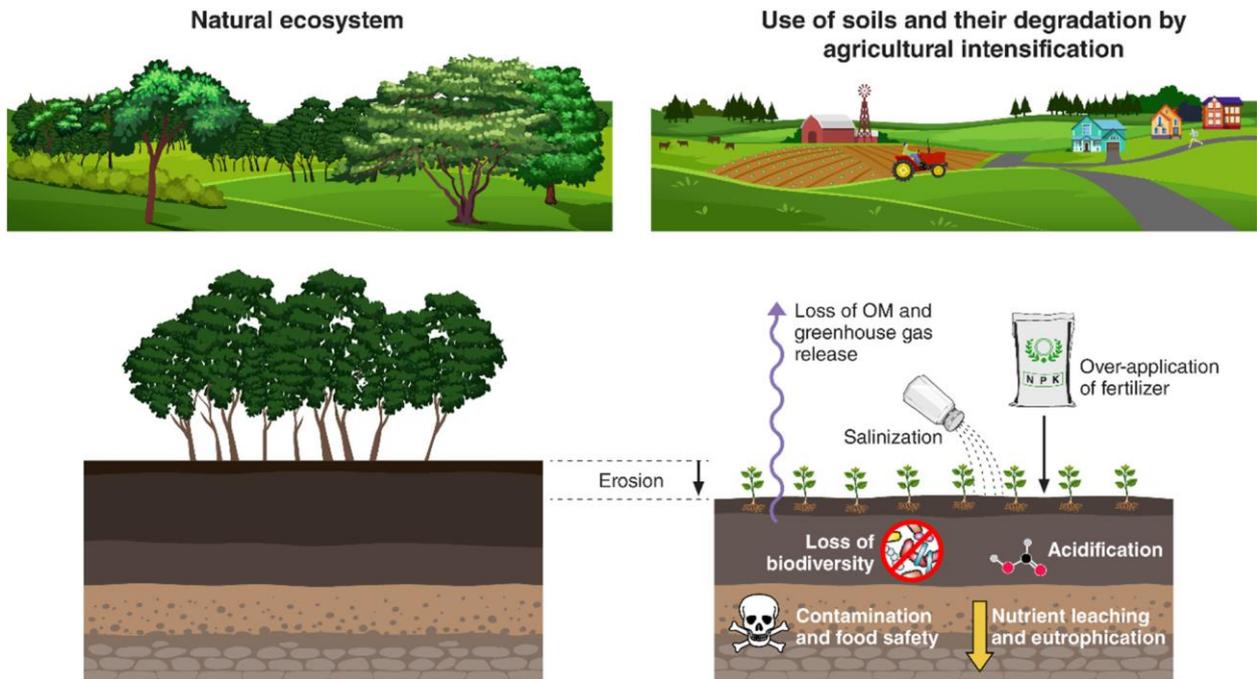
Most farmers perceive climate change in terms of changes in rainfall pattern and temperature. Projected rainfall for the semi-deciduous forest zone (SDFZ) and high rainforest zones (HRFZ) of Ghana indicates a decline in rainfall by 2 %, 11 % and 19 % in the years 2020, 2050 and 2080 respectively in the SDFZ and 3 %, 12 % and 20 % in the HRFZ. The predicted drop in cocoa yield will be 14 % and 28 % for 2020 and 2050 respectively (Ladreach *et al.*, 2013). By 2080, moisture is predicted to be inadequate for profitable cocoa production in Ghana if the current trend of cultivation is maintained. In Côte d'Ivoire, a noticeable part of the central-western region, the western coast and some northern areas in the eastern region will decrease in suitability by 2050 due to climate change (Schroth *et al.*, 2016).

## 2.2 Soil degradation through the cocoa production chain

Rapid population growth is the root cause of agriculture expansion and forest resource degradation in Ghana and Côte d'Ivoire (Schroth *et al.*, 2016; Asare *et al.*, 2014; Ruf and Zadi 1998). The situation is aggravated when farmers respond to growing pressure to expand primary commodity export and thus enlarge the areas on which cash crops are grown (Smith, 2014). Large landowners and small farmers who own their land do not protect the quality of their land and soil. This activity has led to the depletion of soils, caused nutrient loss, water pollution, decreased biodiversity (Kopittke *et al.*, 2019) (Fig. 1) and contributed to climate change (Sánchez *et al.*, 2016). The introduction of hybrid cocoa with its need for high inputs of fertilizers, pesticides and fungicides, and its low-to-no-shade cultivation methods has left an unsustainable cocoa production system in its wake (Abdulai *et al.*, 2018). To meet the future crop demands of 9.8 billion people without causing any significant change in existing cropped land areas, predictions show that, an increase in land use of 1000 M ha<sup>-1</sup> with a tripling of international trade is required by 2050 on a global scale (Pastor *et al.*, 2019). Presently, it is estimated that, over 33 % of soils are moderately to highly degraded due to erosion, contamination, salinization, acidification and compaction through the conversion of forest to agricultural land-uses and that 52 % of agricultural land is already moderately to severely affected by soil degradation (FAO and ITPS, 2015; GSP, 2017).

FAO (2015) defines soil degradation “*as a change in the soil health status resulting in a diminished capacity of the ecosystem to provide goods and services for its beneficiaries. Degraded soils have a health status such that they do not provide the normal goods and services of the particular soil in its ecosystem*”.

To this effect, it is projected that 12 % of global food productivity could potentially reduce over the next 25 years by land degradation (ELD, 2015). Also, the widespread use of pesticides in agricultural production results in marked decreases in yield losses (Oerke, 2006) and are perhaps necessary if sufficient food is to be produced for the growing human population (FAO and ITPS, 2017). However, conservation agriculture (Climate Smart Agriculture CSA) practices such as no tillage, planting of trees on farm in order to reduce the rate at which soil organic matter is lost from soil, will increase soil organic carbon content, increase water infiltration and storage and reduce erosion in crop production systems (Somasundaram *et al.*, 2017).



**Fig. 1.** Impact of agricultural intensification on soils, including degradation by loss of soil organic matter, loss of biodiversity and the release of greenhouse gases to the atmosphere, over-application of fertilizers, erosion, soil contamination, acidification, salinization, and loss of soil genetic diversity (Kopittke, *et al.*, 2019).

### 2.2.1 Soil fertility and productivity

Soils are the most complex and diverse ecosystem that provides humanity with over 98.8 % of its food. In addition to this capacity, soil can provide extensively other services such as carbon storage and greenhouse gas regulation, flood control, filtering of nutrients, and support for infrastructure (Dominati *et al.*, 2014; Kopittke *et al.*, 2019). Soil fertility is not just important to sustainable agriculture, but it is also a key consideration in poverty alleviation and the improvement of livelihoods of resource poor farmers (Heger *et al.*, 2018). It has been found that, over 97.5 % of human food needs come from the land while less than 2.5 % comes from aquatic systems when measured in calories consumed (Brevik, 2009). This shows that food supply to meet our demand will have to come from the terrestrial environment making soil critically important to food security. Soil processes and properties have been altered due to changes in global temperature and precipitation patterns (Meehl *et al.*, 2007; Trenberth *et al.*, 2007).

Soil productivity is integral to agricultural growth, food security and support of the livelihoods of the resource-poor farmers (IPCC, 2019). Soil degradation, therefore, threatens food security, as it reduces yield, forces farmers to use more inputs, and may eventually lead to soil abandonment. Conserving soil depth and soil fertility can contribute to growth by sustaining the resource base for crop cultivation. It is imperative that we examine how increasing pressure

placed on soil for provisioning services is already resulting in their unsustainable degradation. Such degradation reduces the long-term ability of soils to provide the complex multitude of services upon which humanity depends (Kopittke *et al.*, 2019). Other threats, such as climate change, further contribute to the increased pressure on soils.

### **Key priority of soils**

- ✓ The sustainable management of soils can contribute to healthy soils and thus to food-secure world and to stable and sustainable use of ecosystems.
- ✓ Sustainability of soils is key to addressing the pressure of a growing population.
- ✓ Good soil management is of high economic and social importance, and thus includes soils management particularly for its contribution towards growth, biodiversity, sustainable agriculture and food security, which in turn are key to eradicating poverty (UN, 2013).

José Graziano da Silva, FAO Director-General, declared that “*The multiple roles of soils often go unnoticed. Soils don’t have a voice, and few people speak out for them. They are our silent ally in food production.*”

## **2.3 Level of agroforestry adoption in the cocoa production chain**

### **2.3.1 Concept and practice of agroforestry systems**

Possibly agroforestry is an old agricultural practice implemented in Africa, Asia, Europe, and Tropical America, and has been in the system for long under the subsistence farming conditions (Nair, 1993; 2012; Nair and Kumar, 2006). Therefore, practicing agroforestry in this recent does not mean it is a new concept. Agriculture modernization, and scientific land use scenarios has however, brought changes to these indigenous forms of growing trees and crops or animals together. Although the modern agriculture land use simply production of preferred species of crops in monoculture crop stands coupled with the use agrochemicals has been helpful in gaining significant food production and mitigate large scale hunger in some regions in the world. A practice in response to the growing food demand of the increasing population in the world (FAO, 2006). Nonetheless, the conversion of forests to agricultural lands and its intensification had negative feedback on the soils, as most of our tropical soils could not withstand the impact of these high-input technologies. Forest degradation to provide food and fuelwood for human well-being, increases desertification, loss of biodiversity, soil erosion and salinity, and water pollution and has become a grave concern (FAO, 2006; Pimentel *et al.*, 1997).

To counteract the aforementioned problems, it has become more necessary to fall back on the old practice, which is sustainable and socially acceptable, a system that can provide ecological,

economic and social friendly environment is the best. In this wise, integrating trees on farms and agricultural landscape would help to diversify and sustain production for enhanced economic, environmental and social benefits (World Agroforestry Centre, 2008; Atangana *et al.*, 2014). Based on this concept, agroforestry is defined by many authors as deliberate planting of tree species incorporated with crops or animals by farmers on the same land management unit while also allowing trees naturally growing on croplands for mutual benefits (Bene *et al.*, 1977; Combe and Budowski, 1979; Charles *et al.*, 2013) or agroforestry is a resilient practice where farmers retain trees and plant other woody perennials in association with crops as well as livestock in agricultural fields to benefit from the resultant ecological and economic interactions (Lungdgren and Raintree, 1982; MackDicken and Vergara, 1990; Nair, 1993). Agroforestry is now being seen as an alternative way to achieve rural development worldwide, focused on species-richness, low input agricultural techniques including a diverse array of new indigenous tree crops, rather than on high input monocultures with only a small set of staple food crops (Garrity, 2004). This alternative was put in line as a way of addressing challenges associated with deforestation, land degradation, unsustainable cropping practices, loss of biodiversity, increasing impact of climate change and rising hunger, poverty and malnutrition.

### **2.3.2 Classification of Agroforestry systems**

Agroforestry was classified based on numerous criteria according to Nair (1993); MackDicken and Vergara (1990); Torquebiau *et al.* (2002), on the following as:

1. Structural basis refers to the composition of the components, including a spatial mixture of the woody component, vertical stratification of the component mix and temporal arrangement of the different components.
2. The functional components refer to the key function of the system, played mainly by the woody components that can be productive: in the production of fodder, food, fuelwood, or for protection such as windbreaks, shelterbelt, soil and water conservation or for medicinal purpose.
3. Ecological: this aspect concerns the environmental condition and ecological suitability of the system, on the assumption that certain types of systems can be more suitable for certain ecological conditions. Thus, agroforestry systems can be designed for arid and semi-arid lands, tropical high-lands and tropical humid lands as well.
4. Lastly, socio-economic basis refers to the level of inputs of management (whether low input or high input) or the intensity or scale of management and commercial goals e.g. (subsistence, intermediate or commercial).

Based on these components Nair (1985); Nair, Young (1989), identified four major types of agroforestry systems namely: - **Agrosilvicultural** which comprises of crops and trees including shrubs/vines/ trees and trees; - **Silvopastoral** this system composes of trees with pasture and livestock; - **Agrosilvopastoral** constitute of crops with trees, pasture and/ or animals; Apiculture with trees and aquasilviculture are other forms of agroforestry systems but there is a lack of term to describe them better however, they interact economically and ecologically with other land-use components.

### **2.3.3 Role of Agroforestry systems**

The main idea behind the practice of agroforestry is that trees are an indispensable part of natural ecosystems, so their presence in agricultural systems provides a variety of benefits to agricultural soil, other plant species and overall biodiversity, a tool for mitigating climate change, and diversified farmers' income. In sub-Sahara Africa, Franzel and Scherr (2002) and Pattanayak *et al.* (2003), have reported the potential of agroforestry practice in increasing farmers' incomes and solving difficult environmental challenges and increase in overall farm output.

### **2.3.4 Description of cocoa agroforestry systems**

Cocoa is a primary cash crop that is typically grown in many countries in the world including some West Africa countries (Asare *et al.*, 2014; Arevalo-Gardini *et al.*, 2015; Abou Rajabet *et al.*, 2016). Cocoa originates from understory of western Amazonia (Clay, 2004), and it is a shade-loving crop that can be cultivated under forest trees in a humid environment than other crops (Gockowski and Sonwa, 2011). Cocoa agroforestry system ranges from no shade system, simple system possibly with few associated tree species, semi-complex with few productive shade species (e.g., cocoa with fruit trees, banana, and timber trees) to complex system which is forest-like system (Somarriba and Lopez-Samson, 2018; Greenberg, 2000; Beer *et al.*, 1998).

**Traditional agroforestry system:** this system involves shaded cocoa plantations that manipulate the native forest ecosystem. In this case cocoa is grown under the canopy of the original forest trees (Wade *et al.*, 2012; Nair, 1985)

**Complex cocoa agroforestry system:** an agroforestry system with at least 50 shade trees per hectare, it involves a more advanced stage of manipulation of the native forest, and cocoa is grown along with different useful plant species, forming a sophisticated system of managing native and exotic species. This system resembles a natural forest and offers maximum vegetation and architectural complexity and the highest useful tree diversity (Nair, 1985; Nair and Kumar, 2006).

**Semi-complex system:** this system contains at least 15 trees per hectare and is exclusively for commercial purposes which involves the complete clearance of the natural forest ecosystem, thereby growing different shade species that seem appropriate to coca cultivation (Ruf and Zadi, 1998). Shaded tree species that make up this cultivation system are mostly leguminous species with intention of adding nitrogen to the soil or useful economic species for timber production and fuelwood such as *Erythrina Spp*, *Castilla elastica* and *Cedrela odorata* or fruit crops like citrus, avocado, mango, palm trees, and other food crops such as banana are grown in this system.

**Simple agroforestry system:** this system simply describes a cocoa plantation with one other species introduced into the plantation system. It could be leguminous species to provide shade and nitrogen need of the cocoa crop (Young, 1989; Nair, 1985). This system is purely modern and cannot do away with fertilizer application. The system focuses on high yield for market purposes.

**The no-shade cocoa agroforestry system** is exclusively market oriented. The system has no shaded trees and involves complete clearance of forest tree species or slash and burn system (Pattanayak *et al.*, 2003; Charles *et al.*, 2013). These cocoa plantations require high amounts of chemical inputs such as fertilizer and pesticides to keep the production alive and involve a high labour force throughout the cropping years (Somarriba and López Sampson 2018). However, this system provides the highest yield among all the systems outlined. So, farmers are always tempted to go into this cultivation system with the view of getting higher yield every year until the soil is depleted of its nutrient capacity which is highly not ecologically or environmentally acceptable (Kumar *et al.*, 2019).

If maximizing the value of provisioning services in agricultural systems turns to diminish or modify the ecological services provided by unmanaged forests, then the need to employ appropriate management is key to improving the ability of agroecosystems to provide a broad range of ecosystem services to humanity.

### **2.3.5 Ecological importance of cocoa agroforestry systems (supporting and regulating services)**

Agroforestry systems are deliberately designed and managed to maximize positive interactions between agriculture and the environment. Regardless of the fact that cocoa is cultivated at the expense of forests, its successful management plays a crucial ecological role. According to Negawo and Beyene (2017), the significant differences in these roles play by cocoa agroforestry in delivering ecological services depends on the cocoa agroforestry systems in

place, and whether it is a simple (two-species) system, a semi-complex or a highly complex system resembling natural forest.

Several studies (Kohler *et al.*, 2009; van Straaten *et al.*, 2010; Philpott and Bichier, 2012; Lasco *et al.*, 2014; Rahn *et al.*, 2014) have shown the role of agroforestry in the improvement of water quality in agricultural landscape, and conserve a range of diverse life forms, reduce non-point source pollution, prevent runoff, air quality, protect crops, enhance climate conditions as well as providing shade for living organisms, provide additional habitat for wildlife, and provide conducive habitation human being.

In addition to the above roles played by agroforestry, it also plays an important role in soil conservation. Agroforestry trees protect the soil through the litter layer and the leaf canopy thereby reducing runoff and erosion losses, reducing soil temperature and moisture variation, and improving and maintaining soil physical and biological properties (Rao *et al.*, 1998) agroforestry is believed to increase soil organic carbon via litter fall and increase land productivity (Murthy *et al.*, 2013; Saha *et al.*, 2010; Young, 1989). Similarly, Wade *et al.* (2012) confirmed that traditional cocoa farms have higher carbon storage and species richness than intensive cocoa farms. Thus, cocoa agroforestry system contributes to climate change mitigation and adaptation through carbon sequestration both in soil and plant biomass (Kumar *et al.*, 2019; Justine *et al.*, 2019; Andrade *et al.*, 2018; Ehrenbergerova *et al.*, 2016; Jose and Bardhan *et al.*, 2012)

Cocoa tree itself can capture carbon from the atmosphere for its food production therefore, a successfully managed cocoa agroforestry system would be of higher advantage of solving many environmental, ecological, and socio-economic challenges posed by it.

### **2.3.6 Socio-economic importance of cocoa agroforestry systems**

Cocoa plays an important role in the economy of countries involved in its production. It also plays a significant economic role for small farmers (Ruf, 2011). Cocoa as a cash crop, it can provide income for farmers to purchase other food sources (Bentley *et al.*, 2004, Belsky and Siebert, 2003). Cocoa is one of the world's most popular beverages.

Cocoa agroforestry plays a major role in food production in two ways; directly by providing edible food products such as fruits, and indirectly by supporting food production through soil enhancement that support agriculture (Buresh and Tian, 1998). A large number of fruits producing trees are an integral part of agroforestry systems and have important cultural and economic value for farmers (Jose and Gordon, 2007). They also contribute significantly to food and nutritional security in farmers' households. Studies (Schroth *et al.*, 2004; Pinard *et al.*,

2014) have shown the importance of agroforestry in medicine, particularly in Africa, where over 80% of the population depend on medicinal plants for their medical needs, and about two-thirds of the species from this medicine are derived from trees. Other socio-economic values obtained from agroforestry tree species grown or left on the farm are use as fodder, fuelwood, timber (Yasin *et al.*, 2019; Willis, 2015; Ruf, 2011; Chandrashekara, 2009) as well as income generation from trees such as *Cola nitidae* and *Garcinia kola* (Agwu *et al.*, 2018)

#### **2.4 Carbon sequestration processes**

The primary source of carbon is from plant materials obtained through the capturing of atmospheric carbon dioxide (CO<sub>2</sub>) by a process called photosynthesis. Carbon is in two forms; organic and inorganic (Monger *et al.*, 2015). The organic carbon content of soil is a key indicator of the soil' health and a variable that indicates the functioning of many ecosystem processes such as nutrient and waste cycling, water storage and biodiversity. While CO<sub>2</sub> (carbon dioxide) and CH<sub>4</sub> (methane) are the main carbon-based atmospheric gases, autotrophic organisms (mainly plants), as well as photo- and chemo-autotrophic microbes synthesize atmospheric CO<sub>2</sub> into organic material. Dead organic material (mainly in the form of plant residues and exudates) is incorporated into the soil by soil fauna, leading to carbon inputs into the soil through organic material transformation by heterotrophic microorganisms. According to Von Lützow *et al.* 2006; Paul 2014, this organic material transformation process results in a complex biogeochemical mixture of plant litter compounds and microbial decomposition products in various stages of decomposition that can be associated with soil minerals and occluded within aggregates, enabling SOC persistence in soil for decades, centuries or even millennia (Schmidt *et al.*, 2011). CO<sub>2</sub> is emitted back into the atmosphere when soil organic matter (SOM) is decomposed (or mineralized) by microorganisms especially when the soil is exposed through deforestation. Carbon loss can also be caused by root exudates such as oxalic acid, which liberate organic compounds from protective mineral associations (Keiluweit *et al.*, 2015). Finally, carbon is also partly exported from soils to rivers and oceans as dissolved organic carbon (DOC) or as part of erosion material (Zhao *et al.*, 2017; Keiluweit *et al.*, 2015). Factors controlling the decomposition of organic matter in soil include soil temperature, quantity of organic matter and water content (mainly determined by climatic conditions) which greatly influence soil C storage through their effect on microbial activity. The microbial community's composition (e.g., the bacteria: fungi ratio) may also influence the preferential decomposition of certain compounds (Zach *et al.*, 2006).

### **Soil carbon sequestration**

There is a growing body of evidence supporting the hypothesis that the earth's climate is rapidly changing in response to continued inputs of CO<sub>2</sub> and other greenhouse gases (GHGs) to the atmosphere resulting from human activities (IPCC, 2007). While a suite of GHGs exist (e.g., N<sub>2</sub>O, CH<sub>4</sub>), CO<sub>2</sub> has the largest effect on global climate due to enormous increases from the preindustrial era to today. Atmospheric CO<sub>2</sub> concentrations have risen from approximately 280 parts per million (ppm) prior to 1850, to 381.2 ppm in 2006 (WMO, 2006), with a current annual increase of 0.88 ppm (3.5 GT C/yr) (IPCC, 2007). Approximately two-thirds of the total increase in atmospheric CO<sub>2</sub> is a result of the burning of fossil fuels, with the remainder coming from SOC loss due to land use change (Lal, 2004), such as the clearing of forests and the cultivation of land for food production. Although historical losses of soil organic matter associated with agricultural production are significant, soil type, climate and land use influence the potential for SOC storage (Lal, 2018). The impact of climate change on SOC stocks is very variable according to the region and soil type; however, rising temperatures and increased frequency of extreme events are likely to lead to increased SOC losses. Soil organic carbon sequestration is currently defined as the process of transferring CO<sub>2</sub> from the atmosphere into the soil through plants, plant residues, and other organic solids that are stored or retained as part of the soil organic matter (humus) (Lal, 2015).

In principle, the amount of SOC stored in a given soil depends on the equilibrium between the amount of C entering the soil and the amount of C leaving the soil as carbon-based respiration gases resulting from microbial mineralization and, to a lesser extent, leaching from the soil as dissolved organic carbon (DOC). A report by FAO and ITPS (2015), shows that C can also be lost or gained through soil erosion or deposition, leading to the redistribution of soil C at local, landscape and regional scales. Levels of SOC storage are therefore mainly controlled by managing the amount and type of organic residues that enter the soil (i.e., the input of organic C to the soil system) and minimizing the soil C losses.

### **2.5 Microbes in soil fertility**

Microorganisms decompose organic matter, detoxifying the toxic substance, fixing the nitrogen, transformation of nitrogen, phosphorous, potassium and other secondary and micronutrients are the major biochemical activities performed by microbes in soil (Brady and Weil, 2012). Low populations of microorganisms are mostly found in compact soil, soil with low organic matter percentage and on deeper strata of soil.

The agriculturally beneficial microorganisms are plant growth promoting N-fixing cyanobacteria, rhizobacteria, mycorrhiza, plant disease suppressive beneficial bacteria, stress

tolerance entophytes and bio-degrading microbes. Study shows that count of Azotobacter, Azospirillum, Rhizobium, cyanobacteria, phosphorus and potassium solubilizing microorganisms and mycorrhizae are high under no tillage or minimum tillage soil (Bhardwaj *et al.*, 2014). Bacteria are the important soil microorganism responsible for many enzymatic transformations like nitrification, ammonification etc. Azospirillum is micro aerobics that fixes the nitrogen in association with roots of grasses. Inoculation of Azospirillum to grass crops have positive hormonal effect on roots and plant growth (Dastager *et al.*, 2010; Ogbo, 2010). Rhizobium alone in symbiotic association with legume fixes about 50-200 kg of N<sub>2</sub> per hectare. Nonsymbiotic association of Azobacter, Clostridium fixes about 5-20 kg N/ha/yr's and various species of blue green algae fixes about 10-50 kg N/ha/yr's (Brady and Weil, 2012; Dastager *et al.*, 2010). Two fungi Aspergillus fumigatus and A. niger isolated from decaying cassava peels were found to convert cassava wastes to phosphate bio-fertilizers (Ogbo, 2010).

Nitrifying bacteria of the genus Nitrosamines produce nitrite ions from the oxidation of ammonia. Bacteria of the genus Nitrobacter and a few other genera can oxidize nitrites to nitrates. Nitrogen fixers such as Clostridium pasteurianum are obligate anaerobes, they convert atmospheric nitrogen in ammonia and fix in soil.

Acid products of bacterial fermentation convert insoluble phosphates into soluble phosphates which are now utilized by plants for growth. Vascular carbuncular mycorrhiza in association with plant roots converts insoluble phosphate into soluble one. Bacteria such as Thiobacillus ferrooxidans and iron bacteria of the genus Gallionella are capable of oxidizing ferrous (Fe<sup>2+</sup>) iron into ferric (Fe<sup>3+</sup>) iron (Hertage *et al.*, 1999). Soil flora and fauna play a great role in improving the soil texture, nutrient and crop productivity. Bacteria on decomposing plant tissue secretes polysaccharides and other organic glue. Sticky sugar-protein called glomalin secreted by mycorrhizae possesses cementing properties which helps to hold the soil particles together. Also, decomposition of organic components by the bacteria increases the soil porosity which increases the infiltration capacity, thus protects the soil from erosion (Watson and Kelsey, 2006; Stier, 2000).

## **2.6 Impact of land use and climate variables on soil microbes**

Land use type had a strong driving effect on microbial community diversity (Wang *et al.*, 2019). Land use change is currently one of the most important environmental changes and can alter soil environmental factors, nutrient conditions, and biological interactions, thereby affecting microbial communities (Engelhardt *et al.*, 2018). Studies have reported that the conversion of woodland to pasture or farmland could lead to a reduction in the abundance and diversity of some microbial communities; this shift may be related to nutrient cycling because

soil microorganisms and their activities play an important role in soil formation, organic matter decomposition, nitrogen fixation and other soil processes (Merloti *et al.*, 2019). Human activities, especially agricultural management, have an evident effect on the composition of vegetation, the levels of soil water and heat, and the mineralization of soil organic matter, leading to structural changes in the soil fungal community that can lead to the emergence of diversity and new species (Arévalo-Gardini *et al.*, 2020).

On the other hand, temperature and water table levels influence pathways of greenhouse gas emissions and rates of organic matter decomposition (Happell and Chanton, 1993; Conrad, 1996). According to Zhou *et al.* (2002), soil water content may determine microbial community structure and free water connecting soil particles would influence the diversity patterns by controlling nutrient availability and cell movement. Rewetting dried soils does not necessarily return the microbial community to its previous status. The activity of the microbes can decline and there can be a change in community structure and population after soil drying and rewetting (Wildman, 2016). A high moisture content is found to decrease the rate of organic matter decomposition due to low oxygen supply and low soil moisture decreases microbial population and activity, reducing the diffusion of soluble substrates (Schjonning *et al.*, 2003; Pabst *et al.*, 2016; Zhao *et al.*, 2017).

#### **Individual climate variables responsible for changes in soil processes**

Though climate is considered a slow process involving small changes in temperature and precipitation over a long period of time; however, these changes in climate influence the various soil processes, particularly those related to soil fertility (addition, loss, transformation, and translocation).

**Additions:** consist of materials being deposited on the soil from above as well as materials moving in from below with rising groundwater. **Losses:** are obvious, erosion is a major form of soil loss. Erosion can be the slow process of dust being blown away, the rapid, largescale process of a landslide moving materials off a slope, or anything in between.

**Translocations:** are similar to losses in that they involve the movement of materials. Translocation differs in that the material is not removed from the soil; instead, it moves from one location to another (e.g., leaching of nutrient elements).

**Transformation:** leaf litter that is added to the soil is eventually decomposed. This decomposition is a transformation process. Rocks weathering to soil is also a transformation process. The effect of climate change on soils is mainly expected through alteration in soil moisture conditions and an increase in temperature and CO<sub>2</sub> levels. Global climate change is

expected to have variable effects on soil processes and properties important for restoring soil fertility and productivity (IPCC, 2019).

However, while it is known that climate change and land use changes have negative impacts on soil biodiversity and function, the impacts of the management practices in the cocoa production system under climate change on microbial community and soil carbon sequestration is largely unknown in Ghana and Côte d'Ivoire.

## **2.7 Tropical wood anatomy and dendrochronology**

Wood and bark in stems, branches and roots of trees, shrubs and herbs contain information about their genetic origin, the formation time and environmental conditions. These organisms can potentially be used as proxies for reconstructing past environmental conditions. Due to seasonal changes, trees usually form annual growth rings that can be used to study variability in climate. This discipline is called dendrochronology. Dendrochronological methods are used to reconstruct past climate in dendroclimatology, whereas in dendroecology to study the impact of disturbances such as insects, pests or avalanches (Fritts, 1971). In the tropics, studies have proven the existence of annual rings in tree species from arid (Fichtler *et al.*, 2004, 2017; Gebrekirstos *et al.*, 2008; Gebrekirstos *et al.*, 2014) to humid zones (Trouet *et al.*, 2010). However, the complexity of tree ring formation in dry tropical environments is exacerbated by three features of tree growth behaviour (Wils *et al.*, 2011): first, tree rings are often discontinuous along the circumference of the tree (partial rings), which requires the obtaining of multiple cores per tree or even stem discs (Worbes, 2002); second, the response to environmental conditions tends to vary strongly between species and individual trees, depending on variability in, e.g. Wood anatomical structure, habitat, nutrient availability, rooting depth and growth history (Cherubini *et al.*, 2003); third, and most profoundly, many trees do not experience true dormancy (no cambial activity), but rather varying degrees of quiescence (reduced cambial activity), in which the (highly variable) degree of quiescence determines ring distinctness (Cherubini *et al.*, 2003; De Luis *et al.*, 2007). These techniques are based on the measurement of the structural characteristics of tree rings or wood anatomy. For instance, ring width, wood density and vessel size reflect differences from one ring to another. Tree rings have been widely used for reconstructing past climatic conditions and events, and tree ring records can provide information about the reaction of trees to past environmental stress and disturbances. Cocoa's vulnerability towards climate change based on climate projections for the 2050 under the Intergovernmental Panel on Climate Change (IPCC) intermediate emissions scenario RCP 6.0, was thoroughly analyzed for the West African cocoa belt by Schroth *et al.* (2016). They found that temperature as the limiting factor for cocoa shade

trees has an essential influence on cacao trees' survival. They modelled the climatic suitability areas for cocoa and projected it in the year 2050 using variables like maximum temperature, total rainfall and intensity of dry season.

Dendroanatomical approaches have often targeted on the objective of quantifying the association between climate and tree ring growth and wood anatomical parameters with a time scales and resolutions, dendroanatomy approach for analyzing xylem-cell features along dated tree-ring series, offers a longer-term perspective on wood formation processes (Fonti *et al.*, 2010). Xylem anatomical features are determined by both external climate and internal physiological adaptation (Fonti *et al.*, 2010; 2013; Carrer *et al.*, 2014). Vessels are constructed of highly specialized cells in the wood that developed features that allow the efficient and reliable transport of water (Tyree and Zimmerman, 2002; Sperry, 2003). Dendroanatomy studies have shown that many tree species from tropical regions characterized by one severe dry season per year form annual rings with anatomical structures similar to growth rings of temperate tree species. Any contribution to understanding the reaction of cacao trees towards climate change can be of great value since cocoa (*Theobroma cacao* L.), is one of the most important perennial crops in the world (Fig. 2).



**Figure 2.** World cocoa production. Source: icco.org

## CHAPTER III

### MATERIALS AND METHODS

The study involved four main activities namely, (1) Field survey/interview (2) Soil and cocoa stem disc sampling, (3) laboratory analysis and (4) Data analysis.

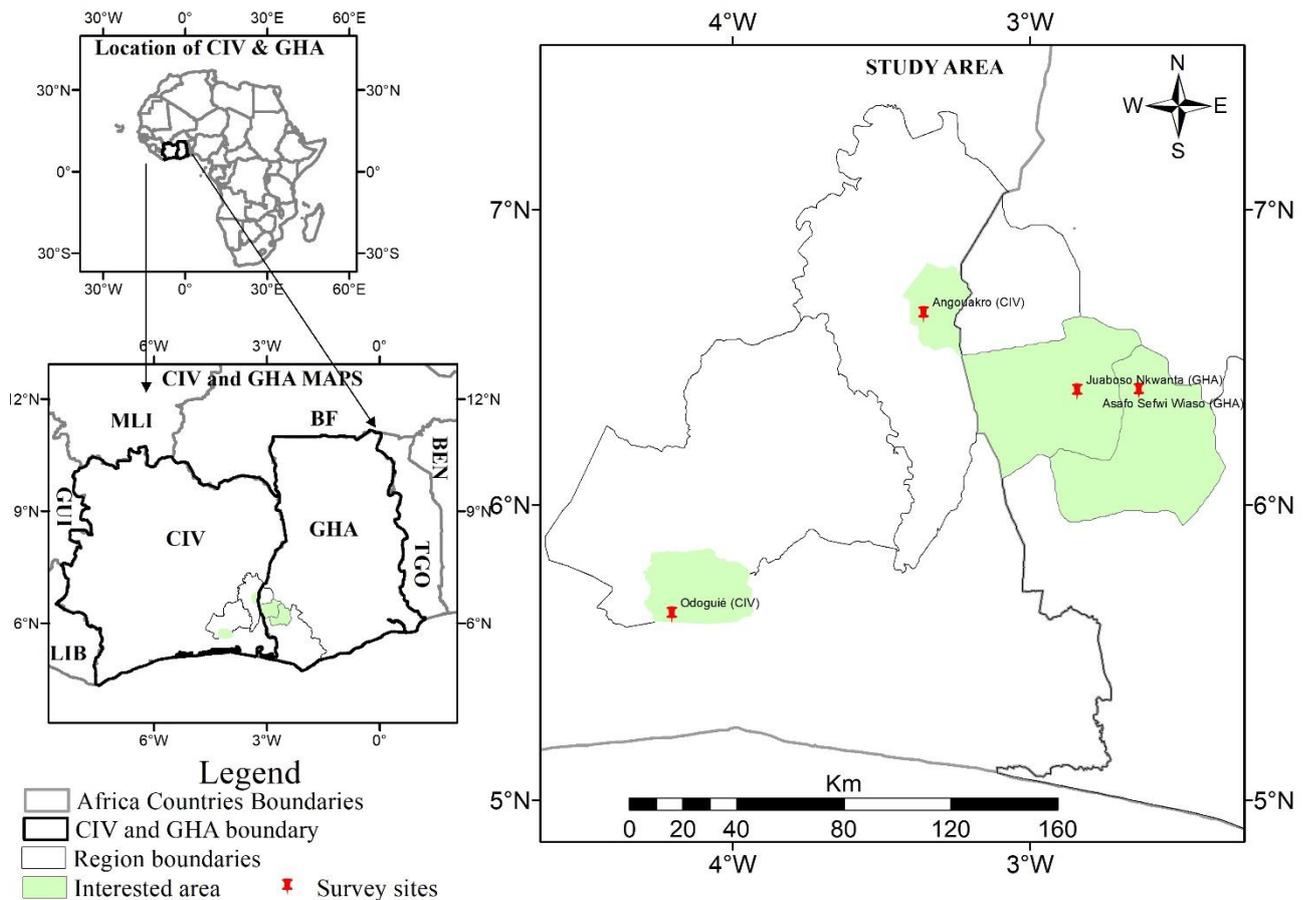
**Objective 1** Cocoa farmers and stakeholders' perceptions of sustainable agroforestry system through the cocoa supply chain.

#### **3.1 Study area**

This study was conducted in Ghana and Côte d'Ivoire. The Agricultural landscape of the study area in Côte d'Ivoire was dominated by cocoa (*Theobroma cacao*), rubber (*Hevea brasiliensis*), as main cash crops and cassava (*Manihot esculenta*) and Maize (*Zea mays*) as the staple food crops. The agricultural landscape in Ghana was similar to that of Côte d'Ivoire except that rubber was not a dominant cash crop in the study area of Ghana. Although some forests exist in the study areas, deforestation and land use changes are occurring faster towards the forest frontiers. The study areas in both Ghana and Côte d'Ivoire experience double rainfall maxima characterized by two rainy seasons. The major rainy season occurs between May and August, with peak rainfall in June/July and the minor rainfall season occurs from September to October. The average annual rainfall for the study areas in the two countries ranges from 1600 to 2500 mm and the mean daily temperatures ranges between 22-35° C (Walz *et al.*, 2015; Abdulai *et al.*, 2018). Ghana lies between latitudes 4°30' N-12°00' N and longitudes 1°12' E-3°15' W in West Africa and borders the Gulf of Guinea, between Côte d'Ivoire and Togo. Côte d'Ivoire (latitude 8°00 N, longitude 5°00 W) borders Ghana to the east, Liberia to the west, Burkina Faso to the northeast, Guinea and Mali to the northwest and joins a 515 km coastline to the Côte Gulf of Guinea, fringed by a network of large lagoons.

In Côte d'Ivoire, the study was carried out in Angoukro and Odogiué. Angoukro is a village near Affalikro and it's located in Indénié-Djuablin Region of the eastern part of Côte d'Ivoire. It lies within latitude 6.64417 N and 3.3575 W. Odogiué, also a farming village located in the Agnéby-Tiassa region in the southeast of Côte d'Ivoire, lies within latitude 5.62611 N and 4.20389 W. The study communities in Ghana were Juaboso Nkwanta in the Juaboso district (6.38167 N and 2.83972 W) and Asafo in the Sefwi Wiawso municipality (6.38389 N and 2.63278 W) (Fig. 3). The study areas share close borders with each other except Odogiué. These communities were purposively selected based on the idea that they are experienced cocoa producing communities.

## Map of survey study area



**Figure 3.** Map of survey study sites

### 3.1.2 Survey design and description of variables

In November 2020 and February 2021, we conducted semi structured interviews with 201 smallholder cocoa farmers from Ghana and Côte d'Ivoire, using random stratification within strata defined by occupation (cocoa farmers) and gender. 300 cocoa farmers were targeted for sampling from these study areas, but only 201 farmers participated in the survey. With the help of Agric Extension Agents (AEAs) from Ghana and in Côte d'Ivoire, the directors of the cocoa cooperatives, 2 communities were randomly selected and 75 farmers from each of these communities were selected to take part in the survey with the help of semi-structured questionnaires.

To determine the sampling size, simplified formula was used to calculate the sample size. This formula assumes 90 percent confidence level and maximum variance ( $p = 0.1$ ) (Mukundente *et al.*, 2020; Yamane, 1967)

The formula is

$$n = \frac{N}{1 + N \cdot e^2}$$

Where: n = the sample size, N = the population size (300), e = level of precision (0.1)

$$n = \frac{300}{1 + 300 \cdot (0.1)^2}$$

n = 75 (sample size per community), but only 50 to 51 farmers participated in the interview per community based on availability of farmers.



Images by Jessica during field survey, 2020-2021 in Ghana and Côte d'Ivoire. *Survey ethics were applied*

Stakeholders including ministries of Environment and climate change, Food and Agriculture, and the CEOs of Forestry commission from both countries and officials of the Cocoa Research Institute of Ghana, Cocoa College of Ghana Cocoa board of Ghana were also interviewed to seek their perceptions of management practice that can result in achieving sustainable agroforestry systems in these two countries. The reason for interviewing farmers together with stakeholders was to ascertain their perceptions and knowledge about strategies of achieving sustainable agroforestry system and to identify the key researchable and communication gaps. Information solicited from respondents included general demography, farm history and management practices, and perception and knowledge of sustainable cocoa agroforestry and soil carbon management strategies. For each respondent, we recorded age, gender, farmer group membership status, residency status, and education level. All interviews were conducted individually in each study area, with the assistance of a local translator, and lasted approximately 30-60 min each. Our questionnaire was composed of closed and open-ended questions. To understand farmers' perceptions of the significance of enhancing soil organic carbon, farmers were asked closed and open-ended questions about key farm activities, farmer local knowledge of soil carbon and management practices under the cocoa production system.

For open-ended questions, responses were classified into categories after the interviews were completed to facilitate and standardize data analysis.

### **3.1.3 Data processing and statistical analysis**

Data obtained from this study were subjected to descriptive analysis of simple proportion using the SPSS Version 22 statistical software. The main tools of analysis were descriptive statistics including frequency distribution and percentage for farmers' demographic information, perception of soil carbon management and sustainable agroforestry. The age of respondents, number of active members, and children per household, number of plantations per farmer and size of their plantation were analyzed using boxplot in R software. The boxplot allows us to visualize the distribution of the parameters within each country. Multinomial logit regression model (MNL) was used to analyze factors that influence cocoa farmers' awareness of soil carbon management and their perception of a sustainable agroforestry systems. It permits the analysis of decisions across more than two categories. The multinomial logit regression model (MNL) has been used widely in many studies to test factors that determine individual knowledge of climate change adaptation, and climate change risk perception. The MNL model predicts the probability of a category membership of dependent variables based on several independent variables. The model uses maximum likelihood estimation to evaluate the probability of categorical membership in a dependent variable based on multiple variables (Awgu *et al.*, 2018; Cramer, 2003). In this study, we considered socio-demographic variables of cocoa farmers as predictors (country, village, age, gender, education, residence) and perception variables as dependent variable (e.g., awareness of agroforestry, system, soil carbon management, biodiversity and climate change). The MNL reflects the expected changes in the probability that farmers are aware of agroforestry or soil carbon management with respect to one-unit change in a predictor variable keeping all other predictors constant. We considered alpha ( $\alpha$ ) less than 0.05 and 0.001 as statistically significant. All data collected were analyzed using SPSS version 22 software for the descriptive statistics and R 3.6.3 software was used for the multinomial logit regression and the stakeholders' responses were assessed using thematic content analysis.

**Objective 2/3.** Amount of soil carbon sequestered and concentration of soil nutrient across cocoa farm ages and soil depths 3). Soil microbial communities across cocoa farm ages and soil depths

### **3.2 Site selection and establishment of treatment plots**

A reconnaissance survey was conducted in a number of farming communities out of which we selected the sites for the study. This selection was based on the availability of plots in terms of the required ages of cocoa agroforestry farms. Interviews were carried out to understand the land preparation methods, management practices, cocoa farm age and previous land use. Any land management with a history of fertilizer application was excluded; this was to ensure the system produces its own nutrients as the forest or the fallow system. Our basic definition of cocoa agroforestry system is a multifunctional system where woody perennials like cocoa are deliberately cultivated on the same pieces of land as other crops (Cocoa Forest, 2016). Plots were laid in completely randomized design with three age classes of cocoa agroforestry farms: 5, 15 and 30 year old as treatments. These agroforestry farms are owned and managed by different farmers in the two countries. Three replicate plots measuring 35 m × 35 m (Dawoe *et al.*, 2014) were established randomly in each selected cocoa farm making a total of 9 experimental plots in each country.

#### **3.2.1 Soil sampling and preparation**

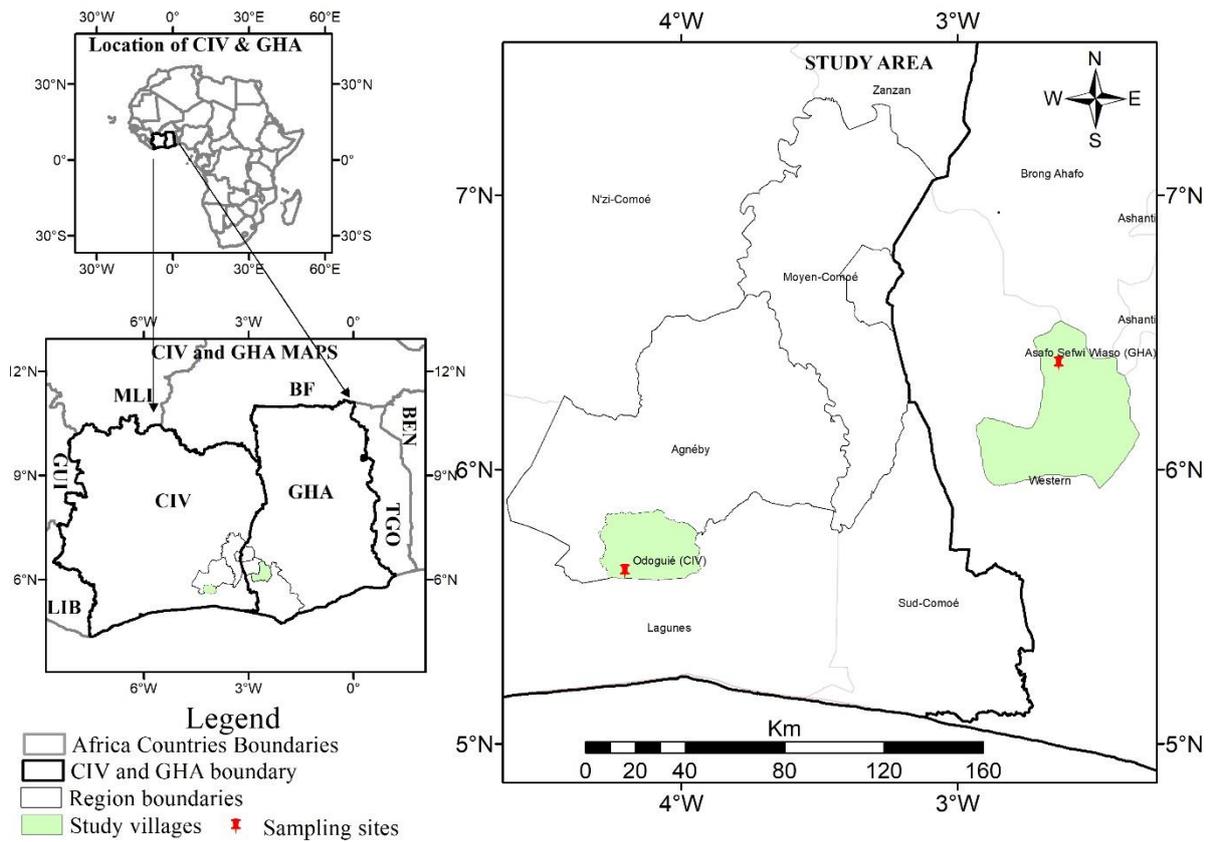
Soils were collected from the three cocoa agroforestry farms as treatment (5, 15 and 30 year old) between February and March 2021 in Asafo (Ghana) and Odoguié (Côte d'Ivoire) respectively (Fig.4), for the study of soil carbon sequestration, soil microbial population and biomass and other physico-chemical properties. These study areas are characterized by semi-deciduous degraded forest, and it is an intensive cocoa cultivation zone. The study areas are also characterized with bimodal rainfall patterns (Fig. 5), the major rainy season occurs between May and August and the minor season in September to October with the annual precipitation ranging from 1600 to 2500 mm. The mean daily temperature ranges from 22-35° C. Average annual rainfall and temperature are 1700 mm for Ghana and 1626.7 mm for Côte d'Ivoire and 31°C, respectively. The soils of the study area of Côte d'Ivoire are Ferralsols (World Soil Reference, 2006), acid in the top 20 cm (pH<sub>water</sub> < 6.5) with a sandy-loam texture along with low nutrient contents that decrease rapidly from the upper soil layer to 20 cm depth. The soils of the study area in Ghana are from weathered phyllites and dominated by ochrosols (FAO/UNESCO, 1990). They are generally deep, moderately well drained and brashy with a

sandy clay-loam humus texture in the 0-15 cm soil layer, which gives it a high moisture retention capacity (MoFA, 1998).

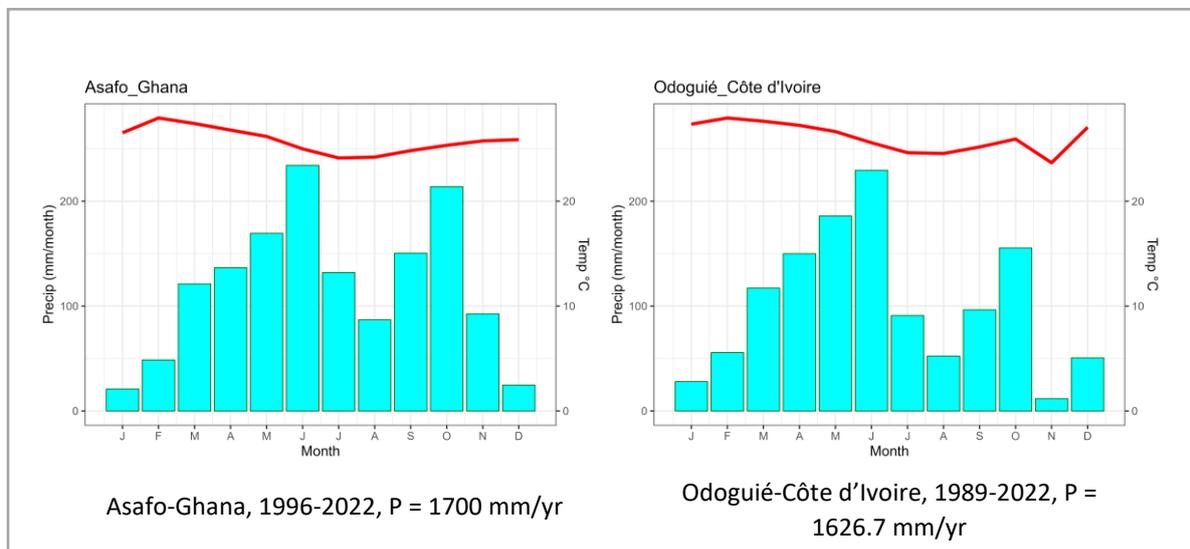
Cocoa cultivation in the regions is owned and managed by smallholders. Soil was sampled from each of the study plots underneath the surrounding a cocoa tree in 15 sampling points in an S-shape transect using soil augur at depths of 0-15 and 15-30 cm to study microbial community, soil carbon sequestration and physico-chemical properties of the soil. For the characterization of microbial community, soil was also sampled randomly surrounding a cocoa tree in each age stands (5, 15 and 30 year old farm) in February 2022 in both countries. This was done to ensure that the microbes are associated with the cocoa crop. The samples were mixed thoroughly to form a composite sample and sub-sample were taken from it and taken to the laboratory of the Soil Research Institute (SRI) Kwadaso-Kumasi, Ghana for laboratory analysis of Soil phyco-chemical properties, microbial population counts, microbial biomass (MBC and MBN (mg/kg)) and mineral N (ammonium-nitrogen ( $\text{NH}_4^+$ -N), nitrate-nitrogen ( $\text{NO}_3^-$ -N) and permanganate oxidizable carbon (POXC). Fungal spore isolation was carried out in the MyTIPS (Tropical mycology and Plants-soil fungi interaction) laboratory in the University of Parakou Benin. The molecular characterization of microbial communities was performed in Estonia.

### **3.2.1.1 Soil and cocoa stem disc sampling sites**

Soil samples were taken from Odogiué in Côte d'Ivoire and Asafo in Ghana as show in the map below. Odogiué lies within latitude 5.62611 N and 4.20389 W and Asafo in the Sefwi Wiawso municipality (6.38389 N and 2.63278 W) (Fig. 4).



**Figure 4.** Map of soil and stem disc sampling sites



**Fig. 5.** Climatic diagram (Precipitation and Temperature) of the two study areas (Source: Data retrieved from power Nasa)

**Objective 2.** Amount of soil carbon sequestered and concentration of soil nutrient across cocoa farm ages and soil depths

### 3.2 Soil analysis for soil organic carbon density (SOCD)

A specific soil depth increment (e.g., 0-30 cm depth) was purposively chosen following the IPCC (2006) recommendation for soil C inventories. In this study, soil samples were collected within two layers of the soil profile 0-15 and 15-30 cm using auger. Stocks of organic C in soils were determined from two variables, namely SOC concentration and bulk density. A soil corer tool of a known volume with a diameter between 5 by 5 cm, was driven into each depth of soil sampled, which allowed for the determination of soil C content and bulk density. Bulk density samples were taken at the same time as soil carbon samples. The cylinders were then removed, and the dry weight of the contained soil was expressed per unit volume (g soil/cm<sup>3</sup>). Soil bulk density was determined as the dry weight per unit volume of the soil core after a 48-h drying period in an oven at 105°C. Organic carbon was determined by Walkley and Black (1934) method.

#### 3.2.1 Analytical Methods

**Wet oxidation:** The Walkley-Black wet oxidation method (Walkley and Black, 1934) is the most common soil test for carbon. After these parameters were measured, the SOC density was calculated using this formula for each depth increment (*i*):

Estimating Soil Organic Carbon Density (SOCD)

SOCD was calculated using the following equation (Zhang *et al.*, 2008)

$$\text{Equation: } SOCD_n (\text{Mg C ha}^{-1}) = t_i \times SOC_i \times BD_i \times (1 - S_i/100) \times 0.1$$

where

$SOCD_n$  is the total amount of SOC at depth  $h$  per unit area (Mg C ha<sup>-1</sup>);  $n$  is the number of layers considered;  $i$  represents the  $i$ th layer;  $SOC_i$  is SOC content (g kg<sup>-1</sup>);

$BD_i$  is bulk density (Mg m<sup>-3</sup>); and  $S_i$  is the proportion (%) of coarse (> 2 mm) fragments in the  $i$ th layer.

$t_i$  is the thickness (depth, in cm) of the depth increment  $i$

<sup>0.1</sup> is a factor for converting mg C cm<sup>-2</sup> to Mg C ha<sup>-1</sup>

#### 3.2.2 Soil mineral nitrogen analysis

**Ammonium nitrogen:** A 25 mL 2 (M) KCl solution was added to 5 g soil, and shaken for half an hour, filter using whatman 42 filter paper. Use 10-20 mL extra KCl solution to rinse out the entire soil from conical flask. The entire filtrate was transferred into micro-kjeldahl flask, add 0.5 g MgO powder, set the flask in kelplus distillation system. Distill it for 6 mins (no hard and

fast rule, you need at least 50 mL distillate) and collect the evolved NH<sub>3</sub> in 15 mL 4% boric acid-mixed indicator, titrate the distillate against 0.02/0.05 N H<sub>2</sub>SO<sub>4</sub>. **Nitrate nitrogen:** 5g into micro-kjeldahl flask and add a pinch of Devarda's alloy and 10 mL 1% NaOH and distill it again and collect ammonia in 4% boric acid-mixed indicator solution. Titrate it in same way.

**Calculation:** Exchangeable NH<sub>4</sub><sup>+</sup>-N % in soil =  $(V_s - V_B) * S * 0.014 * 100/W = Z$

Exchangeable NH<sub>4</sub><sup>+</sup>-N (mg g<sup>-1</sup>) =  $Z * 10^4$

Where, V<sub>s</sub> = vol. of H<sub>2</sub>SO<sub>4</sub> required for sample titration

V<sub>B</sub> = vol. of H<sub>2</sub>SO<sub>4</sub> required for blank titration

S = strength of H<sub>2</sub>SO<sub>4</sub> W = wt. of oven dry soil.

Soil physico-chemical properties were determined as follows in Table 1.

**Table 1. Laboratory analysis of soil physico-chemical properties**

<b>Parameters</b>	<b>Methods</b>
Bulk density	Core Method, (Blake, 1965)
Particle size	Bouyoucos hydrometer, (Bouyoucos, 1962; Day, 1965)
Soil pH	Glass electrode (H19017 Microprocessor) pH meter.
Soil organic carbon	Walkley-Black (1934)
Total nitrogen	Kjeldahl digestion and distillation (Bremner and Mulveney, 1982)
Available nitrogen	Alkaline permanganate method (Subbiah and Asija, 1956)
Total phosphorus	Olsen and Sommers (1982)
Available phosphorus	Bray and Kurtz (1945)
Potassium	Flame photometry, (Thomas, 1982)
Permanganate oxidizable carbon (POXC)	Bosch and Lomb 2500 spectrophotometer (Weil <i>et al.</i> , 2003)
Ammonium and nitrate-nitrogen	Bremner and Keeney (1966)

### 3.2.3 Data processing and statistical analysis

The data were processed and analyzed statistically in the Integrated Development Environment of Rstudio (RStudio Team, 2021) under the software R (R Core Team, 2021). To comprehend the distribution pattern of physico-chemical properties in the entire soil sample, at farm, soil depth, and site (Ghana and Côte d'Ivoire), principal components analysis was performed using *FactoMineR* packages (Le *et al.*, 2008) and biplots was drawn using *factoextra* package (Kassambara and Mundt, 2020).

To assess the distribution pattern, of the physico-chemical the mean and standard deviation of BD, pH, TOC, C/N Available N, Available P, Available K, percentage of sand, silt and clay were computed per soil depth class in each farm (year) of each site (country). The results were presented in graphic using mean plot under *ggplot2* R package (Wickham *et al.*, 2016).

In order to explore the interactive effect of soil pH, on total organic carbon, available nitrogen, available phosphorus and available potassium, at each soil depth class, farm (year) and country respectively, we use scatter plot with linear regression fit. However, to assess the relationship between soil pH and total organic carbon (TOC), available nitrogen, phosphorus and potassium of the entire soil samples we first test for correlation using Spearman rank correlation test. Thereafter, the relationship between soil pH and total organic carbon (TOC), available nitrogen, phosphorus and potassium and its significance at 5 % threshold was analyzed by fitting simple linear model and generalized additive model under *mgcv* package (Wood, 2017) for each country and plotted using *ggplot2* package (Wickham, 2016).

To assess the distribution pattern of soil organic carbon concentration (SOC) and SOCD, median soil organic carbon was compared between soil depth class, farm (year) and site (country) using boxplots under *ggpubr* R package (Kassambara, 2020). Barplots (mean  $\pm$  standard error) was used to compare SOCD per farm (year) within country. To test the relationship/interaction between TOC content and available nitrogen (N) and available phosphorus (P) per site, Spearman rank correlation test was used first to test correlation. We strengthened the correlation finding with covariance analysis to compare the amount of TOC content per site but taking into account the variation of available phosphorus and available nitrogen in two different models.

Mean and standard deviation were computed to get a quick and descriptive view of the variation of total organic carbon (TOC), total nitrogen (TN),  $\text{NH}_4^+\text{-N}$ ,  $\text{NO}_3^-\text{-N}$  and POXC. For better description of the distribution pattern of organic carbon (OC),  $\text{NH}_4^+\text{-N}$ ,  $\text{NO}_3^-\text{-N}$  and POXC between depth classes for each farm (year) and site, principal components analysis (PCA) was

performed using *FactoMineR* packages (Le *et al.*, 2008) and biplots was drawn to present our findings under *factoextra* package (Kassambara and Mundt, 2020)

**Note:** Mean values ( $\pm$ sd) of parameters are presented and the results are discussed without an ANOVA, but in light of the dynamics and/or changes (trends) in the measured parameters from one age group to the other in each country due to small sampling size. However, the Kruskal Wallis test was used to determine the significant difference in SOCD between farms while the Wilcoxon test was used to check the significance of differences in SOCD between countries.

### **Objective 3. Soil microbial communities across cocoa farm (year) and soil depths**

#### **Laboratory analysis**

##### **3.3.1 Enumeration of microbes**

###### **3.3.1.2 Media preparation**

The spread plated technique employed by Zuberer (1994) was used to estimate the number of viable cells in the soil samples. The media used for culturing the microbes were prepared following the specifications on the media bottle. Plate Count Agar (PCA) and Potato Dextrose Agar (PDA) were used for enumerating total viable bacteria and fungi respectively. The PCA and PDA were prepared by suspending 23.5 and 39 g of the media into conical flasks containing 1 L of distilled water. The mixture was boiled on a hot plate to dissolve the media. The prepared media were then dispensed into media bottles and sealed tightly. They were sterilized by autoclaving at a temperature of 121°C for 15 min at a pressure of 15 psi. After autoclaving, the media were allowed to cool to a temperature of 45-50 °C before pouring into Petri dishes. The poured media were allowed to stay overnight before being used for the enumeration.

###### **3.3.1.2.1 Serial dilution preparation**

A 1 in 10 serial dilution was prepared up to the 10<sup>5</sup> dilutions for bacteria and 10<sup>4</sup> fungi. The 10<sup>1</sup> dilution was prepared by weighing 10 g of the sample into a conical flask containing 90 ml of 0.85 % sterile saline water and shaken vigorously for 10 to 15 min. The 10<sup>2</sup> dilution was prepared by pipetting 1 ml from the 10<sup>1</sup> dilutions into a test tube containing 9 ml of sterile saline water and mixed thoroughly for 2 min using a vortex mixer. The 10<sup>3</sup> dilution was prepared from the 10<sup>2</sup>; 10<sup>4</sup> from 10<sup>3</sup> and 10<sup>5</sup> from 10<sup>4</sup> following the same procedure.

###### **3.3.1.2.2 Inoculation, incubation and counting of colonies**

Using 3 replicates for each dilution level, 100 µl of the thoroughly mixed suspension was pipetted onto the center of a Petri dish containing the growth media. A heat sterilized glass rod spreader was used to uniformly spread the suspension on the surface of the media. The plates were then cultured in the incubator at a temperature of 30-35 °C for 24 h for bacteria and 25 °C for 72 h for fungi. The colonies formed on the surface of the growth media were counted using a colony counter. The counting was done by selecting dilution plates having colonies between 25-250 and 10-150 for bacteria and fungi respectively. The number of bacteria/fungi in the sample is then estimated using the formula;

$$\text{Number of colony forming unit/g of sample (cfu/g)} = \frac{\text{number of colonies} \times \text{dilution factor}}{\text{volume of culture}}$$

Microbial biomass carbon (MBC), and nitrogen (MBN) were estimated with chloroform fumigation extraction method (Brookes *et al.*, 1985; Vance *et al.*, 1987).

### 3.3.1.2.3 Analyses of microbial biomass carbon and nitrogen

Microbial biomass C and N were determined using the chloroform fumigation-extraction procedure (Brookes *et al.* 1985; Vance *et al.*, 1987). Three subsamples of 20 g of soil sample were weighed for the fumigation analysis and three corresponding subsamples were used as controls. After fumigation for 24 h, the fumigated and non-fumigated samples were wetted to 60 % of water holding capacity (WHC) and soluble organic C and N were extracted by shaking samples for 0.5 h in 0.5 mol/L K<sub>2</sub>SO<sub>4</sub>. The extracts were passed through Whatman 5 filters and immediately frozen. Analyses of soluble organic C (Technicon Industrial Method 455-76WA) and N (Technicon Industrial Method 759-841) were made using automated UV digestion. The soluble organic C and N (the difference between the fumigated and unfumigated samples) were converted to microbial C and N by multiplying with conversion factors of 2.64 (Vance *et al.*, 1987) and 2.22 (Brookes *et al.*, 1985), respectively.

calculated using the following formula (Vance *et al.*, 1987):

$$\text{MBC} = E_C \times 2.64$$

where  $E_C$  is the difference between C fumigated and unfumigated soil samples.

MBN was calculated by:

$$\text{MBN} = E_N \times K_{EN},$$

where  $E_N$  is difference in N in fumigated and non-fumigated soil samples. We used a  $K_{EN}$  value of 0.54 proposed by Brookes *et al.* (1985). This is the correct value as shown by Joergensen and Mueller (1996).

### 3.3.1.3 Statistical analysis

The data were processed and analyzed entirely in the Integrated Development Environment of Rstudio (RStudio Team, 2021) under the software R (R Core Team, 2021).

The influence of soil depth and cocoa agroforestry farm (age) on total bacteria and fungi populations in each sampling site were analyzed. Bar charts (mean and standard error) were plotted under *gpubr* package (Kassambara, 2020) for the number of bacteria, the number of yeasts and total number of bacteria and yeasts per soil depth class for each farm (year) and site (Ghana and Côte d'Ivoire). Moreover, bar charts (mean and standard error) were plotted to assess the influence of plantation age on microbial population for each site (Ghana and Côte d'Ivoire). Spearman rank correlation was used to check the relationship of total bacteria and yeasts with soil carbon and nitrogen for each site using the fit of Generalized least squares model under the package *nlme* (Pinheiro *et al.*, 2021) separately for each site. The microbial

biomass MBC and MBN were compared between soil depth classes and farm (year) and site using mean and standard error bar chart.

### **3.3.2 Arbuscular Mycorrhizal fungi (AMF) spore extraction**

#### **3.3.2.1 Treatment and conservation of soil samples**

Fungal spore isolation from soil samples was carried out by wet sieving and Decanting, and centrifugation method (Gedermann & Nicolson, 1963; Brundrett *et al.*, 1996). Soil samples were processed and dried in an electric dryer for 24h at 45 °C. Roots, dead leaves fragments, or other debris were removed from each sample. The soil samples were then poured into zip-lock bags, kneaded by hand to separate the soil from the large particles making sure that the spores did not escape as dust. The samples were sifted through 1 mm sieves to obtain a very fine soil. A 50 g of soil was weighed into small zip-lock bags to represent our study sample and a silica gel was added to avoid re-humidification of the samples for later use.

#### **3.3.2.2 Actual extraction of AMF spores contained in the soil**

For the extraction of AMF, 50 g of the soil was mixed with water in a 500 ml beaker. The mixture was well stirred and decanted through series of nested sieves: 300, 200 and 40 microns (each collection is examined separately). After sieving, the contents of the 300 and 200  $\mu\text{m}$  sieves are poured into petri dishes and the 40  $\mu\text{m}$  sieve contents were poured into 15 ml flasks and centrifuged at 5000 rpm for 5 min. The supernatants from the flasks were carefully poured into a petri dish so as not to mix them with the deposits. Sucrose solution was added to the flasks containing the deposits, stirred and centrifuged at 5000 rpm for 3 min to separate the debris from the spores. Immediately after centrifugation, the sucrose solution was carefully decanted into a 40  $\mu\text{m}$  sieve. Thoroughly rinse the sediment retained on the sieve with water to wash off the sucrose. Then, the contents of the sieve were poured into a petri dish for the spores extraction under the stereomicroscope. The extracted spores were then placed in a petri dish containing distilled water. Two (2) to three (3) drops of glutaraldehyde were added to the extracted spores in the petri dish to prevent spore been attacked by nematodes and mites for long term storage.



**Fig. 6A-G. Presents the steps involved in the isolation of fungal spores**

### 3.3.2.3 Data processing and analyzing

Data processing: Data statistical analysis was based on different colours of spores recorded in this study. Abundance data of spores' colours were formatted as a community matrix. A second matrix was built for farm, soil depth and site. Plots were considered as repetition of treatments. A data frame combines all these data in a long format for spore's abundance comparison purpose. In order to detect dissimilarity pattern in fungal spore community, a non-Metric Multidimensional scaling was applied to distance matrix based on Bray-Curtis' distance from the community matrix using vegan R package (Oksanen *et al.*, 2020). Community similarity and dissimilarity were highlighted respectively for farms, soil depth and site using ggord R package (Beck, 2020). Analysis of similarity (AnoSim) was performed to test dissimilarity significance at 5 % threshold in each case.

### 3.3.3 Molecular analyses

#### 3.3.3.1 DNA extraction, sequencing and bioinformatics analyses

Total soil DNA was extracted from 2.0 g of homogenized dry soil using the PowerMax Soil DNA Isolation kit (Qiagen, Carlsbad, CA, United States) following the manufacturer's instructions. The DNA extracts were further purified using the FavorPrep™ Genomic DNA Clean-Up kit (Favorgen, Vienna, Austria). PCR reactions were performed using the universal eukaryote primers ITS9mun and ITS4ngsuni (Tedersoo and Lindahl, 2016; Tedersoo and

Anslan, 2019). These primers amplify nearly all known eukaryotes and all fungi excluding the Microsporidea (mismatches in ITS4ngsUni) and with potentially minor primer bias against Tulasnellaceae and Archaeorhizomycetes (one central mismatch; Tedersoo and Anslan, 2019).

### **3.3.3.2 Polymerase Chain Reaction (PCR) condition**

For amplification, the PCR mixture comprised 5 µl of 5 × HOT FIREPol Blend Master Mix (Solis Biodyne, Tartu, Estonia), 0.5 µl of each forward and reverse primer (20 mM), 1 µl of DNA extract and 18 µl ddH<sub>2</sub>O. Thermal cycling included an initial denaturation at 95 °C for 15 min; 25-30 cycles of denaturation for 30 s at 95 °C, annealing for 30 s at 57 °C, elongation for 1 min at 72 °C; final elongation at 72 °C for 10 min; and storage at 4 °C. The duplicate PCR products were pooled and the presence of a 600–800 bp DNA band was checked on a 1 % agarose gel. Samples yielding no visible PCR product were reamplified using 28 or 30 cycles (Tedersoo *et al.*, 2020). DNA concentrations were measured for a small subset of the amplicons using Qubit 3.0 (Thermo Fisher Scientific, Chicago, USA).

### **3.3.3.3 Sequencing, and taxonomic assignment analysis**

Amplicon libraries were pooled and sequenced. PacBio SMRTbell libraries were prepared following the manufacturer's instructions (Pacific Biosciences, Palo Alto, USA) and sequenced on a Sequel II instrument using Sequel II Binding kit 2.1, sequencing chemistry 2.0, loading by diffusion, movie time of 15 h and pre-extension time of 20 min. The samples producing < 2000 reads were re-amplified and re-sequenced. In total, sequencing was performed on 61 SMRT cells. Sequence processing was performed using seqkit v.0.16.0 (Shen *et al.*, 2016). PacBio sequencing was run on PacBio Sequel II machine.

### **3.3.3.4 Data processing and statistical analysis**

Alpha diversity was determined for each farm by calculating species richness and the Shannon diversity index. To illustrate the fungal taxonomic composition associated with the cocoa farms, we used the taxonomic ranks phyla, class, order, family and genera, to present our findings, because these are typically the most well-defined and robust levels in fungal systematics. Taxonomy of fungi follows Tedersoo *et al.* (2018) and Wijayawardene *et al.* (2020). A bar plot was constructed for each farm and sites using Protax-fungi in PlutoF platform from ASV diversity. All these analyses were carried out using ggplot2 package (Wickham, 2016) in the statistical software R version 3.6.2 (R Core Team, 2019).

**Objective 4.** Radial growth and anatomical response of *Theobroma cacao* to climate change

### **3.4 Study on climate-growth relationships of cocoa trees**

#### **3.4.1 Cocoa wood samples collection and processing**

Cocoa trees were selected from the same cocoa agroforestry systems (designated each 5, 15, and 30 year old farms) from Ghana and Côte d'Ivoire between February and March 2022. To minimize uncertainty associated with the identification of ring boundaries, stem discs were collected rather than increment cores. A total of 30 cocoa stem discs were collected (5 discs from each farm). The discs were air dried and transported to tree ring dendro-laboratory in the Friedrich-Alexander University of Erlangen-Nuremberg, Germany. The samples were prepared using standard dendrochronological methods. For the study of quantitative wood anatomy and ring growth boundaries, 3 cocoa discs were selected for each farm and polished gradually at various degrees using polishing bands (sandpaper) of 80-4000 grit (Stokes and Smiley, 1968) and the dust was removed using air compressor machine to enhance the visibility of the growth ring area boundaries.

##### **3.4.1.1 Data collection**

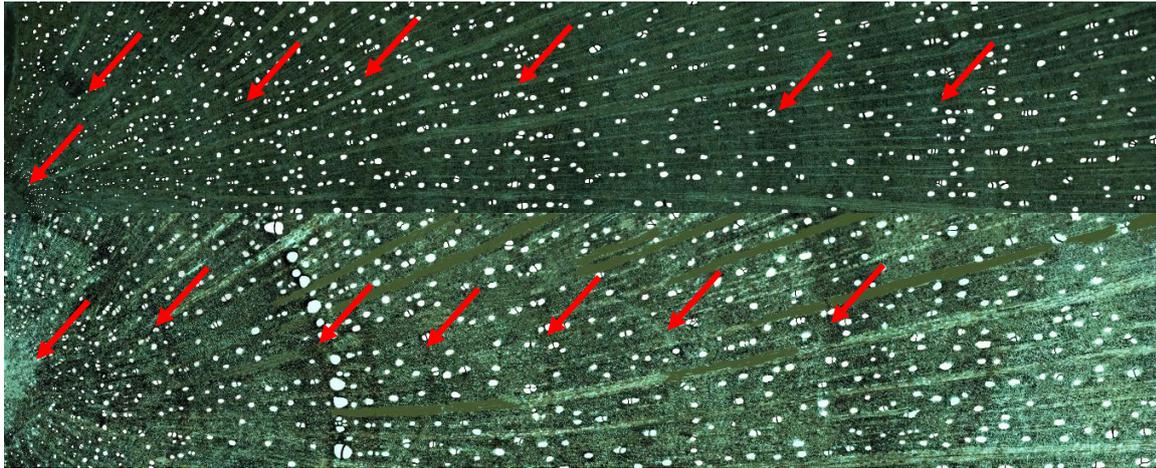
##### **3.4.1.2 Tree growth ring analysis**

Tree growth ring analysis provides information about the age, growth rate and the relationship between tree ring and climatic parameters (rainfall and temperature). On each polished disc sample, 2 to 3 perpendicular radii were selected under a microscope to minimize biases related to variability of growth ring within each disc and to check the existence of each ring around a disc. The tree ring boundaries were marked on 2-3 radii under microscope. Before measuring the ring width, every 10<sup>th</sup> ring was interconnected between the different radii to detect the wedging rings and discontinuous growth areas (Gebrekirstos *et al.*, 2008; Boakye *et al.*, 2016). Tree ring width were measured to the nearest 0.01 mm along the 2-3 radii outwards from the pith to bark per sampled disc perpendicular to anatomical ring boundaries using a LINTAB 6.0 measuring table systems with a resolution of 0.01 mm, supported by the software Times Series Analysis and Presentation, for Windows (TSAP-Win) Rinntech, Heidelberg, Germany (Rinn *et al.*, 1996). Pointer years (narrow or extreme wide) were used for visual cross-dating. pointer years, according to Gebrekirstos *et al.*, (2008), enabled to reveal and rectify errors due to the presence of false or missing rings. The ring-width series were both visually and statistically cross-dated between radii within each disc, between disc within farm and between disc of each site (Cook *et al.*, 1990) using TSAP. The quality of cross-dating was verified by considering statistical parameters such as *t*-value (Baillie and Pilcher, 1973) and Gleichläufigkeit (GLK:

coefficient of parallel variation) values which specifies the proportion of agreement or disagreement of inter-annual growth tendencies among the trees (Eckstein and Bauch, 1969).

### **3.4.1.3 Measurement of wood vessel variables**

Using the clean surface polished wood for the wood anatomical measurements, vessel features were measured on the microscopic images (200×) taken by digital microscope Zeiss Smartzoom 5 (Carl Zeiss Microscopy GmbH 2014, Jena, Germany) as it provides high resolution images as compared to micro-sections. The accuracy and the quality of vessel feature measurements depend on the quality of the digital images (Spiecker *et al.*, 2000; von Arx *et al.*, 2016) of the wood surface from which vessel features are measured. The images were taken at high resolution with 200× magnification which is sufficient for measuring cell parameters using image analysis software. The wood surface images were processed (contrast enhancement and manual correction of image errors) in Adobe photoshop software to improve the visibility of vessel traits and quality of the image. The image analysis software WinCELL Pro 2012, (Regent Instruments Inc., Québec, Canada) which is specifically designed for wood cell analysis was used to measure anatomical vessel traits. First, tree-ring boundaries were identified with the year of formation on each image. Then, an analysis region was created in each tree ring by closing the regions delimited by the ring boundary paths in WinCELL. Vessels were measured in each analyzed region by using necessary filters (area, length, width, form, and length-to-width ratio). Due to diffuse-porous anatomy of the species, earlywood and latewood vessels were not differentiated but considered them together as one analysis region per tree-ring. All vessels were measured within the analyzed area, regardless of their size and shape. A test was performed to check if all vessels were measured, then filters were applied (vessel area < 0.005-20.0 mm<sup>2</sup>, form coefficient > 0.5000. length/width ratio > 2.5000. other features smaller or larger were discarded) to ensure measurement of all vessels. This ensures that approximately 99 % of all vessels within the annual ring were correctly measured. For each ring seven vessel variables, each calculate per tree ring: number of Vessels (NV), mean vessel area (MVA), total vessel area (TVA), total vessel area % (TVAP), mean vessel tangential diameter (MVTD), mean vessel radial diameter (MVRD), and vessel density (VD). Six variables were directly measured by WinCELL, but vessel density (VD) was calculated as the ratio between the number of vessels (VN) and the size of the analyzed area.



**Figure 7.** Scanned image of vessel distribution with red arrows showing tree-ring boundaries of cocoa stem disc

### 3.4.2 Statistical analyses

The mean radial growth rate of the cocoa trees was calculated for each farm and site. Tree ring series were detrended to assess the relationship between radial growth of the trees and climatic parameters. The detrending of tree ring series allow to estimate and to remove tree's natural biological growth trend (Cook and Kairiukstis, 1990). Tree ring series were detrended by a spline with a 50% frequency response. The detrended tree ring series were used to develop a ring-width index (RWI) chronology which was further correlated with local climate variables. The detrending of tree ring series was performed by using the dendrochronology program library in R statistical software "dplR" (Bunn, 2008 and 2010). Pearson correlation analysis was conducted for the ring width index of each site to climatic parameters (precipitation and temperature) using "treeclim" in R. Mean annual precipitation and temperature of each site were taken into account. These climate data were obtained/extracted from the climate power Nasa online using the coordinates of the study sites. The mean radial growth rate of the cocoa stem discs was calculated for each farm and sites. The annual growth diameter of each stem was calculated (in  $\text{cm year}^{-1}$ ) as average growth of the different radii. Cumulative growth trajectories over the trees' life span were used to describe the variation in growth pattern of the cocoa trees within and between sites. Wood anatomical features were statistically analyzed for each tree ring. Differences in wood anatomical features were tested between and within sites. Mean values and coefficient of variation were computed for the wood anatomical features per farm within sites. Simple t-test was performed on the wood anatomical traits between sites (Ghana and Cote d'Ivoire) to check whether the measured trait varied or were statistically significant. All data analysis were performed in "treeclim" R language version 4.2.2.

## CHAPTER IV

### RESULTS

**Objective 1.** Cocoa farmers and stakeholders' perceptions of sustainable cocoa agroforestry system through the cocoa supply chain

#### 4. 1.1 Respondent demographic background

A total of 201 smallholder cocoa farmers were interviewed in the two countries. Most of the respondents (82 % and 53 %) from Côte d'Ivoire and Ghana respectively were male (Table 2). Most of the respondents (94 % and 85 %) from Ghana and Côte d'Ivoire were natives of the study area. Table 2 shows that most of the respondents had formal education particularly up to secondary school; only a few (5 to 7 %) had tertiary education from both countries. Large number of the respondents from both countries (82 % from Côte d'Ivoire and 75 % from Ghana) were married while some were widowed (2 % from Côte d'Ivoire and 7 % from Ghana), single (13 % from Côte d'Ivoire and 5 % from Ghana) and divorced (3 % from Côte d'Ivoire and 14 % from Ghana). Out of the 201 interviewees, about 70 % of the respondents from Ghana and 60 % from Côte d'Ivoire were involved in only cocoa farming (Table 2). The average age of the participants was 50 years in both countries; however, it ranges from 44 to 59 years for Ivoirian respondents and 45 to 62 years for Ghanaian (Fig 8a). Also, every household had an average of 3 children with a range of 2 to 4 children per household for Ghana and 2 to 5 children for Côte d'Ivoire (Fig 8b). Regarding number of active members of a household, Côte d'Ivoire had about 4 members and Ghana had 3 as shown in Fig 8c.

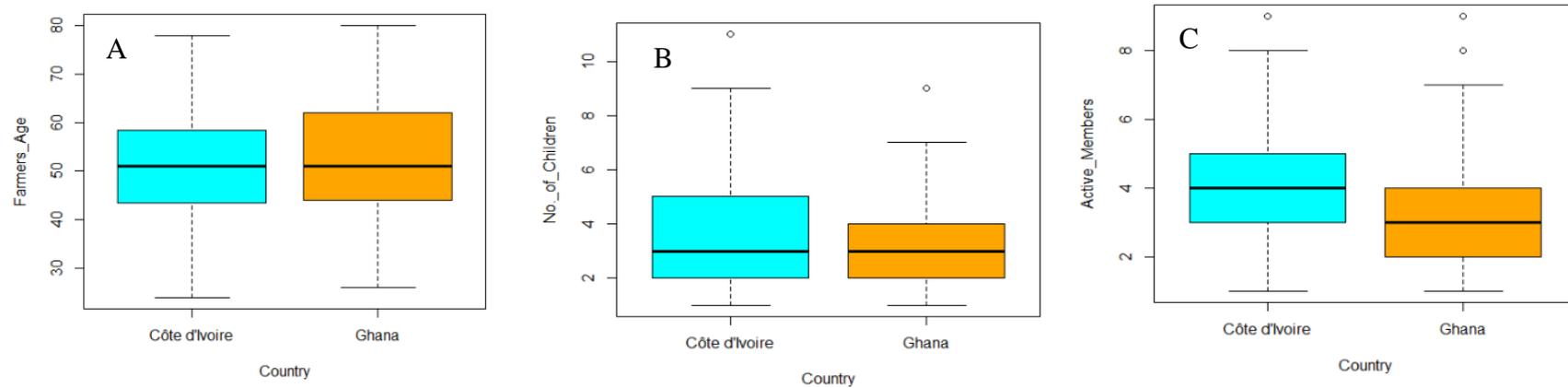
**Table 2.** Socio-Demographic characteristics of the respondents in Ghana and Côte d'Ivoire

Côte d'Ivoire			Ghana		
Respondent	Frequency	Percentage	Respondent	Frequency	Percentage
<b>Village</b>			<b>Village</b>		
Anguakro	49	49	Asafo	50	49.5
Odoguie	51	51	Nkwanta	51	50.5
Total	100	100	Total	101	100
<b>Residence</b>			<b>Residence</b>		
Resident	85	85	Resident	95	94.1
Non-resident	15	15	Non-resident	6	5.9
Total	100	100	Total	101	100
<b>Gender</b>			<b>Gender</b>		
Male	82	82.0	Male	53	52.5
Female	18	18.0	Female	48	47.5
Total	100	100	Total	101	100
<b>Marital status</b>			<b>Marital status</b>		
Divorced	3	3	Divorced	14	13.9
Married	82	82	Married	75	74.5
Single	13	13	Single	5	5
Widowed	2	2	Widowed	7	6.9
Total	100	100	Total	101	100
<b>Education status</b>			<b>Education status</b>		
None	17	17	None	23	22.8
Primary	27	27	Primary	28	27.7
JHS	24	24	JHS	36	35.6
SHS	25	25	SHS	9	8.9
Tertiary	7	7	Tertiary	5	5
Total	100	100	Total	101	100
<b>Principal Activity</b>			<b>Principal Activity</b>		
Cocoa farming only	60	60	Cocoa Farming only	70	69.3
Business/cocoa	27	27	Business/Cocoa	24	23.8
Public/Cocoa	4	4	Public/Cocoa	7	6.9
Others	9	9	Others	0	0
Total	100	100	Total	101	100

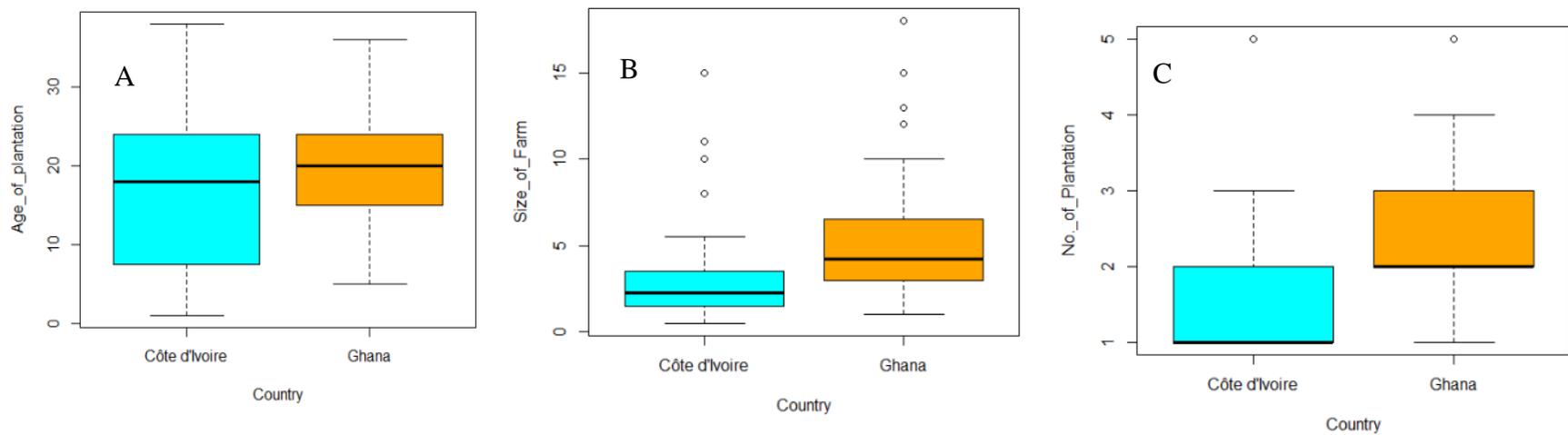
#### 4.1.2 Farmers' farm history

Figure 9a -9c presents the farmers' farm characteristics. The age of cocoa plantation among the two countries varied with Côte d'Ivoire having younger plantation (9 - 25 years) than Ghana (15 - 25 years) (Fig 9a). Farm sizes were larger in Ghana (4 - 6 ha) than in Côte d'Ivoire, (3 - 4 ha) (Fig 9b). Fig 9c shows the number of cocoa plantations a farmer can have in both countries. Regarding number of plantations, farmers in Côte d'Ivoire had on the average 1 to 2 cocoa farms and in Ghana a farmer had at least 2 to 3 plantations of cocoa (Fig 9c). About 94 % of the respondents from Côte d'Ivoire and 90 % from Ghana were landowners. The remaining were engaged in sharecropping arrangements 10 % and 4 % from Ghana and Côte d'Ivoire

respectively (Table 3). Only 2 % of the respondents from Côte d'Ivoire worked on rented cocoa farmland. Majority (82 % from Ghana and 44 % from Côte d'Ivoire) of the respondents reported of using chemical fertilizer when asked about soil amendments or fertilizer applications (Table 3). However, high number of respondents (43 %) from Côte d'Ivoire admitted of not using any chemical fertilizers on their farms meaning the plantation depended on the inherent soil fertility for obtaining plant available nutrients (self-sustaining) and 17 % from Ghana reported same. Few (12 %) of them from Côte d'Ivoire reported applying bio-fertilizers (generally compost and green manure) on their farms. Only 1 % of these respondents from both countries stated using cover crops as soil amendment. The result showed that most of the participants from Côte d'Ivoire admitted practicing cocoa agroforestry while 17 % practice cocoa monoculture. About 51 % of the respondents from Ghana practiced cocoa agroforestry and 49.5 % practiced monoculture. It was observed that only 20 % of the farmers from Côte d'Ivoire and 7.9 % from Ghana reported practicing agropastoral (rearing some small ruminants such as sheep and/or chicken) on their farms (Table 3).



**Fig 8.** Socio-demographic characteristics (A) Age of farmer, (B) Number of children per household (C) Number of active members per household



**Figure 9.** Farmers' farm history (A) Age of plantation (B) Farm size (C) Number of Plantation

**Table 3.** Farmers' farm history continuous

Côte d'Ivoire			Ghana		
Respondent	Frequency	Percent age	Respondent	Frequency	Percent age
<b>Origin of land</b>			<b>Origin of land</b>		
Owner	94	94	Owner	91	90.1
Rent	2		Rent	0	0
Others	4	2	Other	10	9.9
Total	100	100	Total	101	100.0
<b>Soil amendment practices</b>			<b>Soil amendment practices</b>		
Cover crop	1	1	Cover crop	1	1
Bio-fertilizer	12	12	Bio-fertilizer	0	0
Synthetic fertilizer	44	44	Synthetic fertilizer	83	82.2
Self-sustaining	43	43	Self-sustaining	17	16.8
Total	100	100	Total	101	100
<b>Type of plantation</b>			<b>Type of plantation</b>		
Agroforestry	83	83	Agroforestry	51	50.5
Monoculture	17	17	Monoculture	50	49.5
Total	100	100	Total	101	100
<b>Cocoa agroforestry/poultry/small ruminants</b>			<b>Cocoa agroforestry/poultry/small ruminants</b>		
No	80	80	No	93	92.1
Yes	20	20	Yes	8	7.9
Total	100	100	Total	101	100

#### **4.1.3 Farmers level of knowledge about cocoa agroforestry and perception of its livelihoods**

It was noticed that many of the respondents from both Côte d'Ivoire (67 %) and Ghana (66.3 %) were not knowledgeable about cocoa agroforestry systems even though they had been practicing this technology on their farms (Table 4). About 33 and 34 % from Côte d'Ivoire and Ghana, respectively admitted having some knowledge about cocoa agroforestry systems. The result indicates that high number of participants, about 80 % from Côte d'Ivoire and 78.2 % from Ghana had no training in agroforestry on their farms. About 32 and 21 % of respondents from Côte d'Ivoire and Ghana, respectively reported of improved livelihoods when they practiced agroforestry on their farms while 13 % from Côte d'Ivoire and as high as 37 % from Ghana stated of not observing any improvement in their livelihoods when they practiced agroforestry. About 23 % of respondents from Ghana and 11 % from Côte d'Ivoire reported that their livelihood was worsened when they practiced agroforestry systems 44 and 21 % from Côte d'Ivoire and Ghana respectively mentioned that they do not know if they had experienced any improvement in their livelihoods whether they practiced agroforestry or not and if there is anything good about their livelihood, it is not due to agroforestry practice. About 53 and 20.8 % from Côte d'Ivoire and Ghana, respectively perceived agroforestry system to be better than cocoa monoculture while the rest said no.

**Table 4.** Farmers' perception of agroforestry system, and its livelihoods

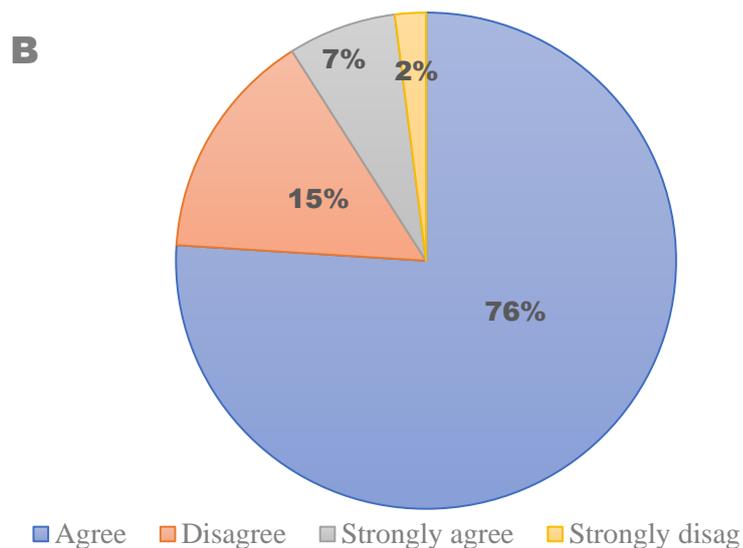
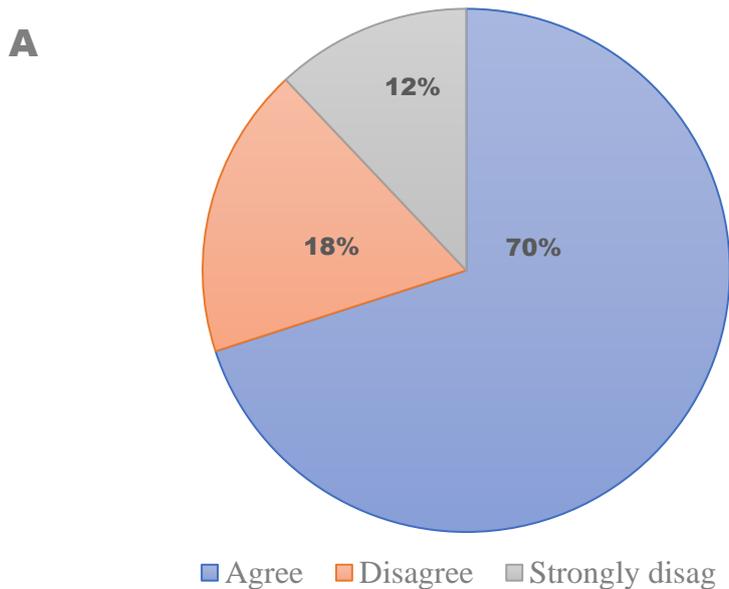
<b>Cote d'Ivoire</b>			<b>Ghana</b>		
<b>Respondent</b>	<b>Frequency</b>	<b>Percentage</b>	<b>Respondent</b>	<b>Frequency</b>	<b>Percentage</b>
<b>Knowledge of Cocoa Agroforestry</b>			<b>Knowledge of Cocoa Agroforestry</b>		
No	<b>67</b>	<b>67</b>	No	<b>67</b>	<b>66.3</b>
Yes	33	33	Yes	34	33.7
Total	100	100	Total	101	100
<b>Any training</b>			<b>Any training</b>		
No	<b>80</b>	<b>80</b>	No	<b>79</b>	<b>78.2</b>
Yes	20	20	Yes	22	21.8
Total	100	100	Total	101	100
<b>Livelihood of farmer</b>			<b>Livelihood of farmer</b>		
Improved	32	32	Improved	21	20.8
Worse	11	11	worse	23	22.8
I don't know	44	<b>44</b>	I don't know	21	<b>20.8</b>
No improvement	13	<b>13</b>	No improvement	<b>36</b>	<b>35.6</b>
Total	100	100	Total	101	100
<b>Agroforestry better</b>			<b>Agroforestry better</b>		
No	25	25	No	39	<b>38.6</b>
Not interesting	22	<b>22</b>	Not interesting	41	<b>40.6</b>
Yes	53	<b>53</b>	Yes	21	20.8
Total	100	100	Total	101	100

#### **4.1.4 Local knowledge and perception of soil organic carbon**

About 89 and 87 % of the respondents from Côte d'Ivoire and Ghana respectively were not aware of soil carbon (Table 5). Majority of the farmers (93 % from Côte d'Ivoire and 92 % from Ghana) had not heard about soil organic carbon. However, about 5 and 3 % from Côte d'Ivoire and Ghana respectively said they were aware of soil organic carbon and the source of information was extension officers. The results show that 42 % of the respondents from Côte d'Ivoire and 34 % from Ghana perceived that soil organic carbon contribute to soil fertility improvement after they were familiarized with the term soil organic carbon. About 30 and 9 % of farmers from Côte d'Ivoire and Ghana respectively mentioned that SOC makes the cocoa production system more productive while about 27 % and 37 % of the respondents from Ghana and Côte d'Ivoire respectively were not sure of the benefits of SOC to the cocoa system. About the idea that farmers' farm practices influence soil carbon storage as presented in Fig 10a, 70 % of respondents from Côte d'Ivoire and 76 % from Ghana agreed that their farm practices could influence the soil carbon content of their soil either through sequestration or emission.

**Table 5.** Local knowledge of farmers on soil carbon, its source, and benefits to the cocoa farmer

Cote d'Ivoire			Ghana		
Respondent	Frequency	Percentage	Respondent	Frequency	Percentage
<b>Aware of soil carbon</b>			<b>Aware of soil carbon</b>		
No	89	89	No	88	87.1
Yes	11	11	Yes	13	12.9
Total	100	100	Total	101	100
<b>Do you know /source</b>			<b>Do you know /source</b>		
No	89	89	No	90	89.1
Yes	11	11	Yes	11	10.9
Total	100	100	Total	100	100
<b>What the source of SOC is</b>			<b>The source of SOC is</b>		
God	36	36	God	71	70.3
Organic matter	20	20	Organic matter	8	7.9
Soil	27	27	Soil	18	17.8
Sun	17	17	Sun	4	4
Total	100	100	Total	101	101
<b>Source of information</b>			<b>Source of information</b>		
Extension officer	5	5	Extension officer	3	3
Farmer-farmer	2	2	Farmer-farmer	3	3
No	93	93	No	92	91.1
Total	100	100	Total	101	100
<b>Importance of SOC</b>			<b>Importance of SOC</b>		
More productive system	9	9	More productive system	30	29.7
Regulate climate	2	2	Regulate climate	10	9.9
Soil more fertile	42	42	Soil more fertile	34	33.7
All the above	10	10	All the above	3	3
None of the above	37	37	None of the above	24	23.7
Total	100	100	Total	101	100



**Fig 10a.** Circular diagram summarizing the farmers' views about their management practices' effects on soil carbon loss. Diagram A = Côte d'Ivoire and B = Ghana

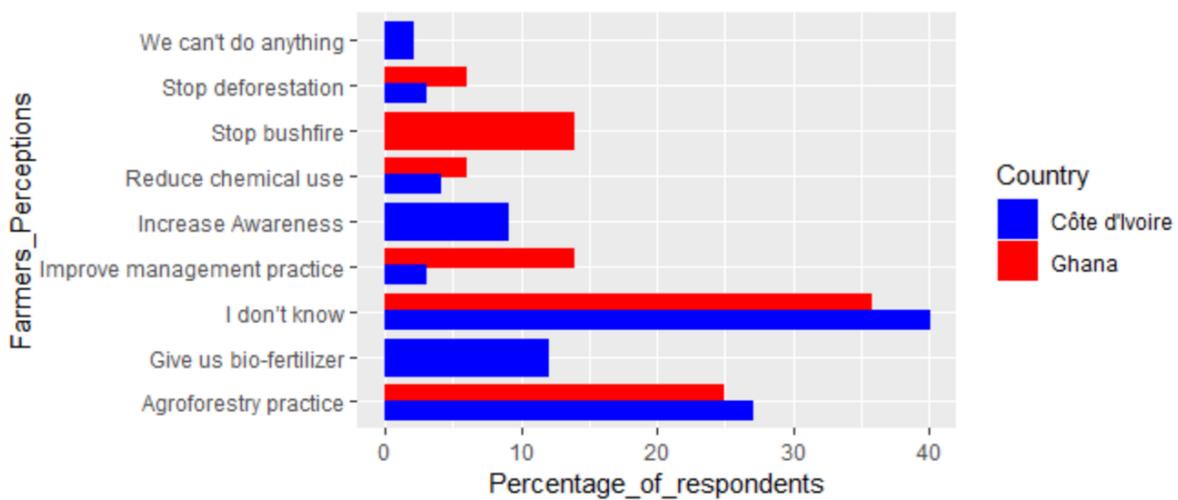
#### 4.1.5 Perceptions of farmers about the strategies use to reduce soil carbon loss

Figure 10b illustrates the strategies farmers mentioned that can reduce soil carbon loss from farmers' farm. Farmers from Côte d'Ivoire and Ghana mentioned 8 and 6 strategies respectively for reducing carbon loss from soil. They identified strategies like agroforestry practices, reduce chemical use and improved management practices such as improved seed germination, irrigation, harvest and post-harvest see Fig. 10b. Many of the respondents 40 % from Côte d'Ivoire and 38 % from Ghana could not mentioned any strategy that could be used to reduce

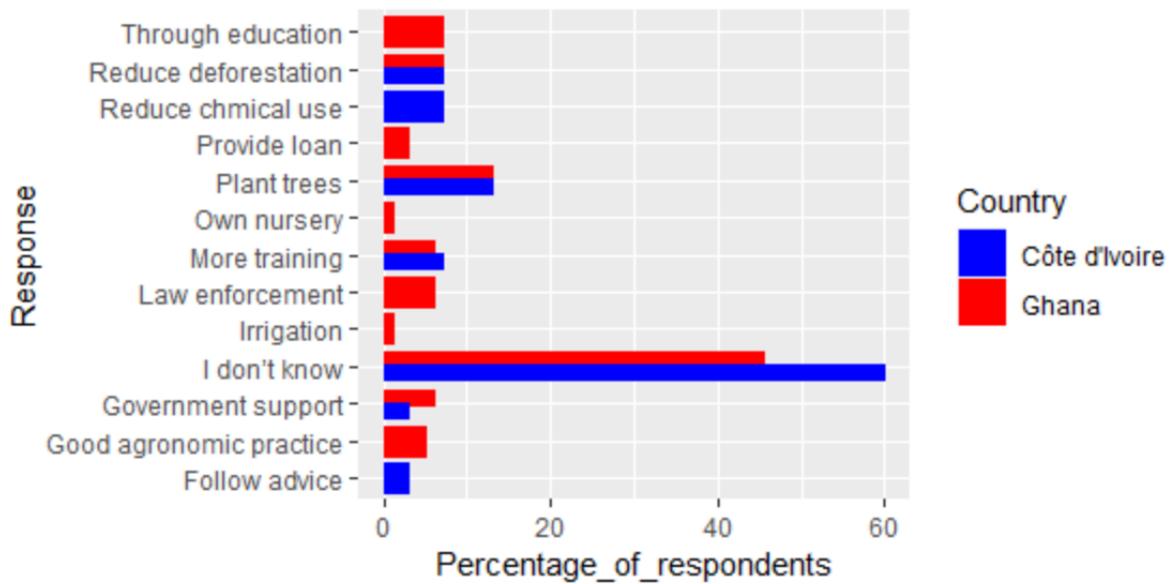
soil carbon loss on their farms even though majority of the respondents agreed that their management practices could influence soil carbon status on their farms as shown in Fig. 10a.

#### 4.1.6 Perceived approaches toward sustainable agroforestry management

The perceptions of farmers toward achieving sustainable cocoa agroforestry system in Ghana and Côte d'Ivoire are shown in Fig. 11. At least a total of 7 and 11 different approaches from the participant of Côte d'Ivoire (strategies: reduce deforestation, reduce chemical use, plant trees, more training, I don't know, government support and follow advise) and Ghana (Through education, reduce deforestation, provide loan, plant trees, own nursery, more training, irrigation, I don't know, government support and good agronomic practice) were identified. About 45 and 60 % of farmers from Ghana and Côte d'Ivoire, respectively had no idea about the strategies of achieving sustainable cocoa agroforestry system (Fig. 11). About 1-15 of the cocoa farmers outlined meaningful approaches in both. Indicating that some respondents have some knowledge in achieving a sustainable cocoa agroforestry system under climate change.



**Fig. 10b.** Bar plots of the perceptions of farmers about the strategies use to reduce soil carbon loss



**Fig.11.** Bar plots of the perceptions of farmers about the strategies to achieve sustainable agroforestry system

#### 4.1.7 Other stakeholders view on designing and achieving sustainable cocoa agroforestry in Ghana and Côte d'Ivoire

From table 6. it is clear that there were some similarities and dissimilarities among the strategies mentioned by the stakeholders and the cocoa farmers. Some of the stakeholders mentioned that a sustainable cocoa agroforestry system can be achieved when they educate landowners about its benefits. How it should be designed the stakeholders mentioned many reasonable policies Table 6.

**Table 6.** Stakeholders view on designing and achieving sustainable cocoa agroforestry systems in Côte d'Ivoire and Ghana

Country	Stakeholders	Stakeholders' strategies	Agroforestry Design
<b>GHANA</b>			
Ghana	Crop service/MoFA	Provide incentives to farmers	Integrated in school curriculum
Ghana	CRIG	Motivation (financial supports)	Basic school curriculum for easy absorption
Ghana	Cocoa collage	Education on the benefits to landowners and farmers	Field demonstration
Ghana	Forestry Commission	Continuous Education	By all relevant stakeholders.
Ghana	Ministry of Environment	Field demonstrations	Integrated in school curriculum and involve landowners in meetings of farmers.
Ghana	Ghana Cocoa-Board	Increased sensitization	Incorporate into strategic plans.
<b>CÔTE D'IVOIRE</b>			
Côte d'Ivoire	SODE FOR (Forestry)	Govt. should support farmers financially. Advise and be close to farmers through extension officers	Train farmer more/reinforce network among stakeholders in Ghana and Côte d'Ivoire. Including farmer's needs, involve farmers in more training.
Côte d'Ivoire	Université (UFHB)	Explain the effectiveness of the system to farmers	
Côte d'Ivoire	Ministry of Agric/Rural Dev.	Experiment with attractive short-term financial returns could help drive adoption	Mostly through field demonstration and participation of landowners. By collaborating with research institutes such as cocoa colleges, cocoa research institutes and Agric colleges.
Côte d'Ivoire	Ministry of Env. & Sust. Dev.	Give farmers a new variety of cocoa with high yield capability.	

#### **4.1.8 The demographic factors that influence cocoa farmers' knowledge/awareness of agroforestry and soil carbon management and perceptions of practices to store soil carbon**

Table 7 and 8 present the results of the multinomial logit regression models of the variables that influence the respondents' awareness of soil carbon and agroforestry. According to the model, the awareness of soil carbon and cocoa agroforestry by farmers was influenced by increasing educational level of the farmer. However, a negative relationship was obtained between cocoa farmers' awareness of soil carbon and agroforestry from one village to another. The awareness of a farmer on soil carbon and agroforestry decreases with villages that is the awareness level was not influenced by farmers' village (Table 7). About the farmers' perceptions of whether their farm management practices could favour soil carbon storage or not (Table 8) taken "I don't know" or "No" as reference in a multinomial logit model, variables such as residential status, level of education gender and age of farmer did not influence respondents' perceptions about whether their management practices can support soil carbon storage or soil on its own can sequester carbon when left undisturbed. A negative relationship was also obtained between variables such as country and village farmers' perceptions about whether their farm practices can make the soil store carbon and or sequester carbon. Meaning that from country to another either the response "I don't know" or "No" was higher than "Yes" when asked if their farm practices can help store carbon in soil. Thus, the socio-demographic characteristics especially country and village were negatively influencing the farmers' knowledge about the effect of their farm practices on soil carbon storage or emission (Table 8)

**Table 7.** Results of multinomial logit regression of socio-demographic factors determining cocoa farmers' awareness of soil carbon and agroforestry

Explanatory variable	Category	Awareness of soil carbon	Awareness of agroforestry
		Yes Coef <sup>Sig</sup> (SE)	Yes Coef <sup>Sig</sup> (SE)
Country	Cote d'Ivoire (Ref.		
	Ghana	0.277(0.428)	0.271(0.285)
Village	Angouakro (Ref. group)		
	Asafo, Sefwi Wiaso	<b>-0.500(0.427)</b>	0.089(0.274)
	Juaboso Nkwanta	0.777(0.398)	0.182(0.265)
	Odoguié	0.074(0.718)	-0.053(0.466)
Age	Age	0.014(0.022)	-0.014(0.015)
Gender	Female (Ref. group)		
	Male	0.147(0.571)	0.713(0.388)
Education	JHS (Ref. group)		
	None	0.071(0.827)	-0.443(0.504)
	Primary	0.601(0.689)	0.116(0.412)
	SHS	1.047(0.758)	0.279(0.483)
	<b>Tertiary</b>	<b>3.094*** (0.842)</b>	<b>3.238*** (1.102)</b>
Origin	Native (Ref. group)		
	Non-native	-1.008(1.120)	0.396(0.551)
AIC		149.707	251.335

\* p<0.05; \*\*\* p<0.01

**Table 8.** Results of multinomial logit regression of socio-demographic factors determining cocoa farmers' awareness of farm practices and capacity of soil to store carbon

Explanatory variable	Category	Farm practices can store carbon		Capacity of soil to store carbon	
		No Coef <sup>Sig</sup> (SE)	Yes Coef <sup>Sig</sup> (SE)	I don't know Coef <sup>Sig</sup> (SE)	Yes Coef <sup>Sig</sup> (SE)
	Cote d'Ivoire (Ref. group)				
Country	Ghana	-4.619*** (0.629)	-0.708** (0.28)	2.086*** (0.407)	-5.212*** (0.410)
	Angouakro (Ref. group)				
Village	Asafo Sefwi Wiaso	5.130*** (0.629)	-0.106(0.264)	0.974*** (0.312)	-10.493*** (0.000)
	Juaboso Nkwanta	-9.749*** (0.000)	-0.602** (0.256)	1.113*** (0.308)	5.281*** (0.410)
	Odoguié	1.296(1.152)	-0.906** (0.46)	3.376*** (0.675)	1.801*** (0.628)
Age	Age	0.013(0.035)	-0.027(0.015)	-0.001(0.017)	-0.011(0.026)
	Female (Ref. group)				
Gender	Male	0.133(0.933)	-0.582(0.365)	0.096(0.415)	-0.387(0.678)
	JHS (Ref. group)				
Education	None	0.338(1.029)	0.053(0.465)	-0.954(0.501)	-2.001(1.155)
	Primary	-0.120(0.908)	-0.594(0.411)	0.111(0.480)	0.196(0.685)
	SHS	-1.442(1.238)	-0.665(0.485)	-0.013(0.591)	0.819(0.714)
	Tertiary	0.734(1.395)	0.986(0.859)	-0.086(0.985)	<b>3.229**</b> (1.282)
	Native (Ref. group)				
Origin	Non-native	-0.847(1.192)	-0.736(0.532)	0.894(0.698)	0.269(0.945)
AIC		348.697	348.697	339.009	339.009

\* p<0.05; \*\*\* p<0.01

#### **4.1.9 Cocoa farmers' knowledge about the causes of climate change and changes in climatic variables**

Farmers mentioned deforestation (45 % and 47.5 % from Côte d'Ivoire and Ghana respectively as the main causes of climate change from both countries (Table 9). Additionally, 24 % of farmers from Ghana observed that agriculture is second most serious cause of recent climate change in the country whereas 35 % of farmers from Côte d'Ivoire noticed that climate change is only caused by God. Generally, farmers are aware of climate change, but some farmers still doubt its cause. The respondents from both countries were also very much aware of changes in climate variables such as temperature about 99 % from Ghana and 87 % from Côte d'Ivoire noticed changes in recent temperature, rainfall (98 % participants from Ghana and 59 % from Côte d'Ivoire) admitted that rainfall has decreased drastically over the years, drought about (94.1 % and 81 %) from Ghana and Côte d'Ivoire respectively said drought has increased and finally farmers from Ghana about 69 % saw an increase in flood and related to shortened but heavy rainfall patterns nonetheless farmers from Côte d'Ivoire (59 %) said there was change in flood when it rains (see Table 9).

#### **4.1.10 Farmers' current knowledge about biodiversity**

High percentage 71.3 % farmers from Ghana and 82 % from Côte d'Ivoire in this interview admitted that they were not aware or knowledgeable about biodiversity. Majority of the respondents both countries mentioned God as biodiversity when asked about what biodiversity is before teaching about biodiversity (Table 10). Concerning the management practices, most of the interviewees (58.4 %) from Ghana clearly stated that “No” their farm practices cannot promote biodiversity conservation but respondents from Côte d'Ivoire about 55 % said “Yes” their management practices could support biodiversity on their cocoa farms. The rest were not sure whether their management practices can meet the standard of conserving biodiversity.

**Table 9.** Knowledge about the causes of climate change, and changes in climate variables

Parameters	Cote d'Ivoire (n = 100)		Ghana (n = 101)	
	Frequency	Percentage	Frequency	Percentage
<b>Cause of Climate Change</b>				
Agriculture	4	4	25	<b>24.8</b>
Deforestation	<b>45</b>	<b>45</b>	<b>48</b>	<b>47.5</b>
God	35	35	20	19.8
I don't know	8	8	6	5.9
It doesn't exist	3	3	0	0
Others	5	5	2	2
Total	100	100	101	100
<b>Temperature</b>				
Decrease	8	8	1	1
Increase	<b>87</b>	<b>87</b>	<b>100</b>	<b>99</b>
No change	5	5	0	0
Total	100	100	101	100
<b>Rainfall</b>				
Decrease	<b>59</b>	<b>59</b>	<b>99</b>	<b>98</b>
Increase	33	33	2	2
No change	8	8	0	0
Total	100	100	101	100
<b>Drought</b>				
Increase	<b>81</b>	<b>81</b>	<b>95</b>	<b>94.1</b>
No change	7	7	0	0
Total	100	100	101	100
<b>Flood</b>				
Decrease	15	15	32	31.7
Increase	26	26	<b>69</b>	<b>68.3</b>
No change	<b>59</b>	<b>59</b>	0	0
Total	100	100	101	100

**Table 10.** Farmers' current knowledge about biodiversity conservation

Respondents	Côte d'Ivoire (n = 100)		Ghana (n = 101)	
	Frequency	Percentage	Frequency	Percentage
<b>Awareness of biodiversity</b>				
No	<b>82</b>	<b>82.0</b>	<b>72</b>	<b>71.3</b>
Not sure	1	1.0	15	14.9
Yes	17	17.0	14	13.9
Total	100	100.0	101	100.0
<b>Biodiversity</b>				
All living organism	23	23.0	13	12.9
Animals	5	5.0	1	1.0
God	<b>44</b>	<b>44.0</b>	<b>41</b>	<b>40.6</b>
Trees	25	25.0	13	12.9
Trees & Animal	3	3.0	33	32.7
Total	100	100.0	101	100.0
<b>Management practices</b>				
No	45	45.0	<b>82</b>	<b>81.4</b>
Yes	<b>55</b>	<b>55.0</b>	19	18.8
Total	100	100.0	101	100.0
<b>Benefits of conserving biodiversity</b>				
No	<b>59</b>	<b>59.0</b>	<b>73</b>	<b>72.3</b>
Yes	41	41.0	28	27.7
Total	100	100.0	101	100.0

#### **4.1.11 Possibilities of mitigating climate change and biodiversity loss through the cocoa production systems**

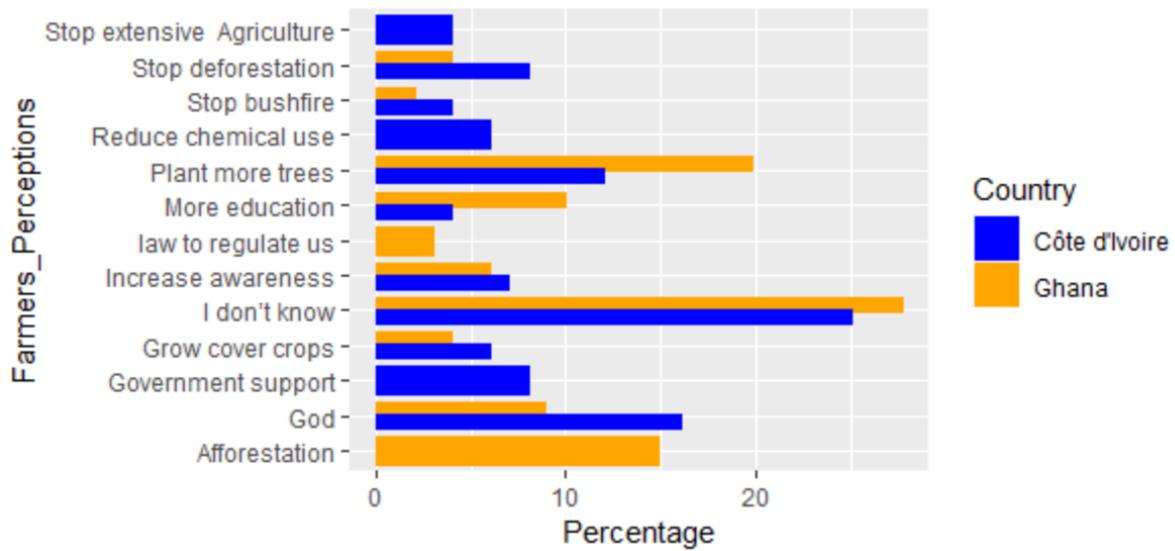
Regarding the possibilities of mitigating climate change and biodiversity loss in cocoa production systems, a high number of respondents, about 35 % and 30 % from Ghana and Côte d'Ivoire respectively were not aware of any possibility that can help to mitigate these phenomena on their farms (Fig.12a). As such many of the participants from both countries outlined many ways in which climate change and biodiversity loss can be mitigated through the cocoa production systems (see Fig. 12a). About 20 % of respondents from Ghana mentioned that planting more trees could help mitigate climate change. About 11 % from Côte d'Ivoire were of the same view. However, some participants from Côte d'Ivoire (16 %) and Ghana (9 %) were still of the view that only God can help us to mitigate climate change and biodiversity loss and not what they do or practice on their farms (Fig. 12a).

#### **4.1.12 Farmers' strategies to achieve ecological, economic and social benefits through the cocoa supply chain**

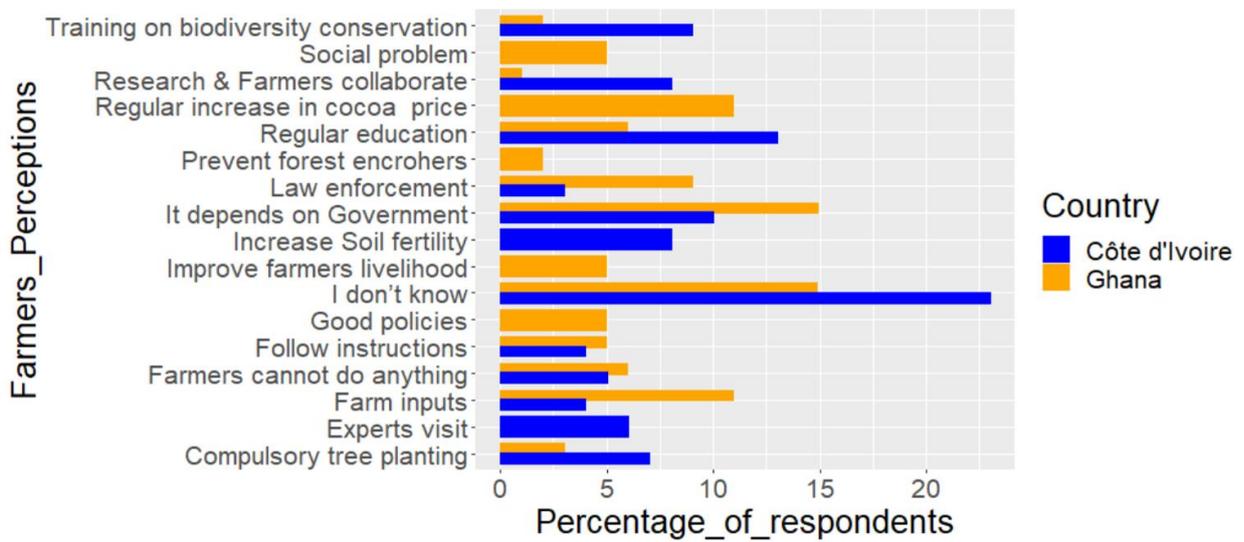
Fig. 12b. illustrates the strategies farmers can employed on their farm to achieve ecological, economic and social benefits of the cocoa production system. Majority of the cocoa farmers (25 % from Côte d'Ivoire and 15 % from Ghana) lack knowledge of what practices they can employ on their farms to achieve these. About 15 % and 10 % of the participants from Ghana and Côte d'Ivoire respectively were convinced that it takes the intervention of government for them to be able to achieve these objectives through the cocoa value chain. However, many other strategies were mentioned among the farmers from the two countries as shown in Fig. 12b.

#### **4.1.13 Perceived strategies of achieving climate change mitigation and biodiversity conservation**

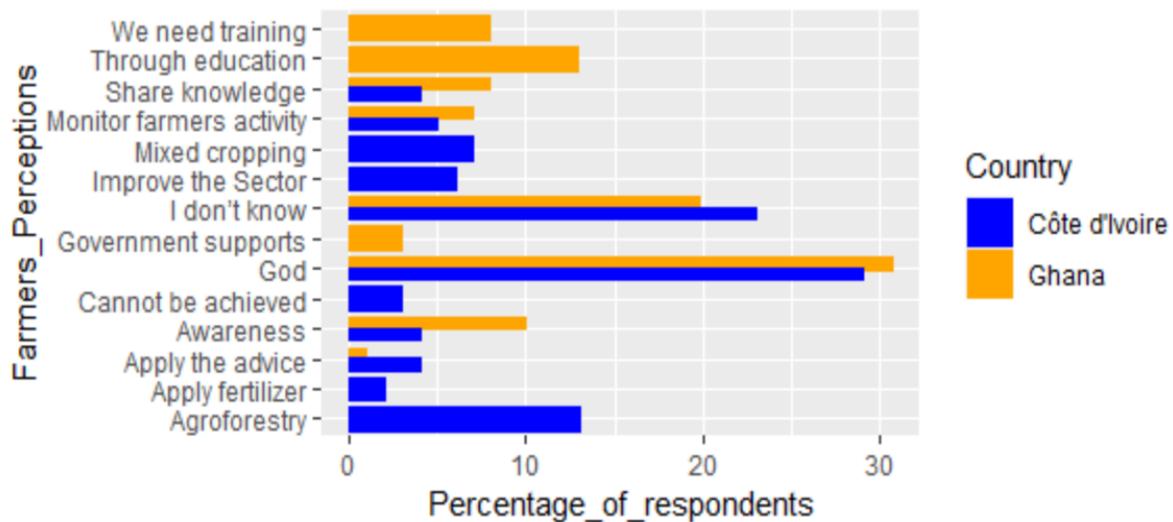
Regarding respondents' awareness about the strategies of to be used to achieve climate change mitigation and biodiversity conservation on their farms, again most farmers related this to God with the highest percentage from Ghana (45 %), and many others said they do not know the strategies that can be adopted on their farms to achieve this goal of conservation and mitigation (Fig. 12c). About 15 % of the respondents from Ghana said it can only be achieved through education, and 13 % from Côte d'Ivoire also said through the practice of agroforestry on their farms. Many others about 14 % of participants from Ghana said climate change mitigation and biodiversity conservation on their cocoa farms can be achieved through awareness creation among farmers particularly the smallholder cocoa farmers (see Fig 12c).



**Fig. 12a.** Bar plots of the perceptions of farmers about the approaches to be used to mitigate climate change and reduce biodiversity loss through cocoa supply chain



**Fig. 12b.** Bar plots of the perceptions of farmers about the approaches to achieve ecological, economic and social benefits through cocoa supply chain



**Fig. 12c** Bar plots of the perceived strategies to achieve climate change mitigation and biodiversity conservation through cocoa supply chain

**4.1.14 Stakeholders’ strategies of achieving ecological, economic and social benefits, promote biodiversity security and climate change mitigation**

About achieving ecological, economic and social benefits, promotion of biodiversity security and climate change mitigation, stakeholders mentioned relevant approaches that can be used to obtain these benefits (Table 11). Although some farmers were able to give similar answers the highest percentage exhibited little or no knowledge about these issues suggesting the need to sensitize farmers on key strategies as outlined by one of the stakeholders from Ghana.

**4.1.15 Factors influencing cocoa farmers’ knowledge/awareness of the causes of climate change and changes in climatic variables**

Concerning the model to determine if the demographic variables have influenced the farmers' knowledge about the causes of climate change (Table 12) and whether they observed changes in climate variables such as temperature, rainfall, drought and flood (Table 13a-b), we observed that, country of the respondents influenced the knowledge of farmer implying that a farmer in one country may be more knowledgeable about the causes of climate change over the other. Taking villages for instance, we observed that farmers from Juaboso Nkwanta in Ghana were more knowledgeable about agriculture as the main cause of climate change when deforestation was taking as a reference variable. The result also shows that there was no positive relationship between gender, education origin and age of a farmer on his knowledge about the causes of climate change. Also, about whether the farmer observes any changes in temperature, rainfall, drought and flood (Table 13a-b), there was no relationship between the explanatory variables and the farmers knowledge about these changes. This means that the farmers knowledge or a farmer noticing a change in these climate variables does not depend on the age, village, country,

education or gender. Therefore, the demographic variables had not influenced the farmers' knowledge.

Table 14 shows the farmers awareness of biodiversity and perception of its benefits to the farmer and the environment. The model shows that education and village influenced positively the farmers' awareness of biodiversity. The model also revealed that there was a negative relationship between villages of the farmers and their level of awareness of the benefits of conserving biodiversity as well as the importance of conserving biodiversity on their farms. This shows that number of participants who said I don't know were more than those who said Yes.

**Table 11.** Stakeholders' strategies of achieving ecological, economic and social benefits, promote biodiversity security and climate change mitigation

Country	Workplace	Strategies to achieve ecological/economic and social benefits	Promote Biodiversity security	Mitigate climate change
<b>GHANA</b>				
Ghana	Crop service/MoFA	Adopt tree crops on all type farms	Incorporate food crops	Encourage Agroforestry globally
Ghana	CRIG	Educate farm families	Pay attention to all systems	Education/Improve farming system
Ghana	Cocoa collage	Adhering to recommendations	Provide guidelines to farmers	More awareness
Ghana	Forestry Commission	Practice farm diversification	Sensitization/Education	Adhering to Climate smart cocoa practices
Ghana	Ministry of Environment	Explain climate change in local language and its implication for economic & ecological development.	Improve farming technology	Adopting climate smart systems
Ghana	Ghana Cocoa-Board	Increase education to all	Through agroforestry system	Increase training & Sensitization of key strategies
<b>CÔTE D'IVOIRE</b>				
Côte d'Ivoire	SODE FOR (Forestry)	Use best seeds, best practice, protect forest/have good price for produce.	Continue agroforestry/grow more food crops.	Continue agroforestry, keep forest trees, Plant many trees even in town
Côte d'Ivoire	Université (UFHB)	Pay attention to the choice of associated trees	Improve farming technology	Promote agroforestry systems
Côte d'Ivoire	Ministry of Agric/Rural Dev.	By setting up consultation framework/a dynamic collaborative platform accessible to all parties in the cocoa value chain	Increase awareness and introduce new crop techniques	Stop converting fallow land into cocoa production
Côte d'Ivoire	Ministry of Env. & Sust. Dev.	Government to implement new system of environmental safetiness	Agroforestry/other techniques that improve soil system	Increase awareness

**Table 12.** Results of multinomial logit regression of socio-demographic factors determining cocoa farmers' awareness of the causes of climate

Explanatory variable	Category	Causes of climate change				
		Agriculture Coef <sup>Sig</sup> (SE)	God Coef <sup>Sig</sup> (SE)	I don't know Coef <sup>Sig</sup> (SE)	It doesn't exist Coef <sup>Sig</sup> (SE)	Others Coef <sup>Sig</sup> (SE)
Country	Côte d'Ivoire (Ref. group)					
	Ghana	<b>21.187***</b> (0.667)	0.608(0.595)	<b>-1.116***</b> (0.000)	<b>-7.172***</b> (0.000)	-7.772***(0.000)
Village	Angouakro (Ref. group)					
	Asafo	-14.969** (0.667)	1.734*** (0.595)	-21.603*** (0.000)	-31.050*** (0.000)	-25.223*** (0.000)
	Nkwanta	36.156*** (0.000)	-1.125*** (0.00)	20.487*** (0.000)	23.878*** (0.000)	17.451*** (0.000)
	Odoguie	-0.952(1.240)	0.951(0.490)	1.760(0.946)	1.167(1.929)	-45.607*** (0.000)
Age		-0.008(0.041)	-0.011(0.024)	-0.021(0.041)	0.149(0.147)	-0.305** (0.149)
Gender	Female (Ref. group)					
	Male	0.269(0.953)	0.137(0.621)	0.114(1.295)	-2.118(1.836)	0.155(1.814)
Education	JHS (Ref. group)					
	None	-1.851(1.355)	-0.330(0.779)	0.456(1.561)	1.127(1.561)	1.211(1.602)
	Primary	-2.400** (1.164)	-0.449(0.672)	1.358(1.257)	-24.938*** (0.000)	-33.512*** (0.000)
	SHS	-2.183(1.204)	-0.933(0.677)	-0.720(1.514)	-29.014*** (0.000)	-3.787(2.111)
Origin	Tertiary	-2.193(1.565)	0.129(0.910)	-21.866*** (0.000)	-33.384*** (0.000)	-39.979*** (0.000)
	Native (Ref. group)					
	Non-native	-24.357** (0.000)	-0.243(0.658)	-0.912(1.340)	-27.099** (0.000)	-29.387** (0.000)
AIC						244.7603

\*\* p<0.05; \*\*\* p<0.01

**Table 13a.** Results of multinomial logit regression of socio-demographic factors determining cocoa farmers' awareness of changes in climatic variables Temperature, Rainfall, drought and flood

Explanatory variable	Category	Change in Temperature		Change in Rainfall	
		Increase Coef <sup>Sig</sup> (SE)	Decrease Coef <sup>Sig</sup> (SE)	Decrease Coef <sup>Sig</sup> (SE)	Increase Coef <sup>Sig</sup> (SE)
Country	Côte d'Ivoire (Ref. group)				
	Ghana	25.657 <sup>***</sup> (0.000)	11.340 <sup>***</sup> (0.458)	-2.255 <sup>***</sup> (0.576)	1.613 <sup>***</sup> (0.572)
Village	Angouakro (Ref. group)				
	Asafo	13.118 <sup>***</sup> (0.000)	-5.464 <sup>***</sup> (0.335)	-1.935 <sup>***</sup> (0.695)	0.267 (0.424)
	Nkwanta	12.539 <sup>***</sup> (0.000)	-5.876 <sup>***</sup> (0.000)	-0.320(0.679)	1.345 <sup>***</sup> (0.501)
	Odoguié	18.555 <sup>***</sup> (0.786)	17.182 <sup>***</sup> (0.745)	-0.701(0.838)	2.648 <sup>***</sup> (0.961)
Age		0.064(0.034)	0.049 <sup>**</sup> (0.0200)	0.020(0.031)	0.017(0.026)
Gender	Female (Ref. group)				
	Male	-0.511(0.988)	-0.852(0.478)	0.100(0.751)	-0.040(0.600)
Education	JHS (Ref. group)				
	None	-1.088(1.194)	-0.674(0.640)	2.439 <sup>**</sup> (1.23)	1.570(1.116)
	Primary	-1.265(1.052)	-0.800(0.551)	1.105(0.808)	0.819(0.676)
	SHS	-1.175(1.108)	-0.462(0.769)	-0.111(0.795)	0.167(0.69)8
	Tertiary	-1.806(1.502)	-1.818(1.022)	22.472 <sup>***</sup> (0.524)	20.304 <sup>***</sup> (0.524)
Origin	Resident (Ref. group)				
	Non-resident	0.528(1.132)	0.418(0.918)	14.701 <sup>***</sup> (0.338)	13.937 <sup>***</sup> (0.338)
AIC		238.319	238.319	268.397	268.397

**Table 13b.** Results of multinomial logit regression of socio-demographic factors determining cocoa farmers' awareness of changes in climatic variables: drought and flood

Explanatory variable	Category	Change in drought		Change in flood	
		Increase Coef <sup>Sig</sup> (SE)	Decrease Coef <sup>Sig</sup> (SE)	Decrease Coef <sup>Sig</sup> (SE)	Increase Coef <sup>Sig</sup> (SE)
Country	Côte d'Ivoire (Ref. group)				
	Ghana	-3.491*** (0.711)	-13.300*** (0.000)	2.048*** (0.815)	-13.247*** (0.000)
Village	Angouakro (Ref. group)				
	Asafo	-1.988*** (0.450)	-6.786*** (0.000)	0.541 (0.503)	-6.135*** (0.000)
	Nkwanta	-1.503*** (0.432)	-6.514*** (0.000)	1.507*** (0.540)	-7.112*** (0.000)
	Odoguie	-2.121 (1.115)	-0.300 (1.393)	2.056 (1.235)	-2.880*** (0.820)
Age		-0.001 (0.020)	0.070 (0.043)	0.012 (0.022)	-0.025 (0.033)
Gender	Female (Ref. group)				
	Male	0.350 (0.482)	-1.294 (0.942)	-0.395 (0.535)	1.349 (0.932)
Education	JHS (Ref. group)				
	None	-0.579 (0.643)	-1.578 (1.360)	-0.594 (0.702)	1.139 (0.995)
	Primary	0.311 (0.538)	-0.210 (1.120)	-0.566 (0.601)	-0.283 (0.868)
	SHS	-0.108 (0.730)	0.024 (1.091)	-0.498 (0.679)	-1.259 (0.956)
	Tertiary	0.416 (0.993)	-0.132 (1.703)	16.918*** (0.753)	16.401*** (0.753)
Origin	Native (Ref. group)				
	Non-native	-0.408 (0.781)	-0.746 (1.177)	-1.453 (0.748)	0.312 (0.924)
AIC		245.729	245.729	237.932	237.932

**Table 14.** Results of multinomial logit regression of socio-demographic factors determining cocoa farmers' awareness of biodiversity, its benefits and appropriate management practices

Explanatory variable	Category	Awareness of Biodiversity		Awareness of benefit of conserving biodiversity		Importance of Management practices	
		Yes Coef <sup>Sig</sup> (SE)	No Coef <sup>Sig</sup> (SE)	Yes Coef <sup>Sig</sup> (SE)	No Coef <sup>Sig</sup> (SE)	Yes Coef <sup>Sig</sup> (SE)	
	<b>Cote d'Ivoire (Ref. group)</b>						
Country	Ghana	0.383(0.441)	-1.940*** (0.436)	-1.333*** (0.444)	2.970*** (0.740)	-0.078(0.350)	
	<b>Angouakro (Ref. group)</b>						
Village	Asafo Sefwi Wiaso	-0.587(0.452)	-0.156(0.333)	-1.092*** (0.385)	-0.083(0.474)	-0.948** (0.38)	
	Juaboso Nkwanta	0.970** (0.389)	-1.783*** (0.38)	-0.241(0.339)	3.053*** (0.571)	0.870(0.509)	
	Odoguié	1.358** (0.663)	-1.914*** (0.693)	-0.783(0.686)	2.357** (1.135)	0.211(0.456)	
Age	Age	0.005(0.019)	0.053*** (0.020)	0.036(0.018)	-0.017(0.022)	0.014(0.019)	
	<b>Female (Ref. group)</b>						
Gender	Male	0.219(0.515)	-0.403(0.453)	0.201(0.457)	-0.541 (0.503)	0.215(0.459)	
	<b>JHS (Ref. group)</b>						
Education	None	-0.539(0.618)	-1.087(0.577)	-1.017(0.573)	-0.731(0.642)	-1.119** (0.560)	
	Primary	-1.069(0.633)	0.052(0.523)	0.029(0.518)	0.024(0.595)	-0.211(0.501)	
	SHS	-0.286(0.643)	-1.024(0.636)	-0.239(0.607)	0.641(0.706)	-0.205(0.560)	
	Tertiary	1.952** (0.766)	0.697(1.228)	1.897(1.209)	-0.088(1.331)	1.341(0.891)	
	<b>Native (ref. group)</b>						
Origin	Non-native	0.411(0.630)	0.044(0.741)	0.317(0.669)	-1.037(0.878)	-0.406(0.599)	
AIC		170.937	416.482	416.482	368.644	368.644	

\*\*p<0.05; \*\*\* p<0.01

**Results of objective 2** Amount of soil carbon sequestered and concentration of soil nutrient across cocoa farm ages and soil depths

## **4.2 Soil physico-chemical properties and carbon sequestration potential of cocoa agroforestry farms in Ghana and Côte d'Ivoire**

### **4.2.1 Bulk density**

Bulk density of the soils differed across the various farms in both countries (Fig.13a) There was higher bulk density recorded at 0-15 cm depth of 5 and 30 year old farms in Côte d'Ivoire (Fig 13a). While in the 15 year old farms bulk density was relatively lower at the 0-15 cm, the distribution range in the different depths in Ghana was either lower in 0-15 cm or higher in the 15-30 cm soil depth in the 15 and 30 year old farms. The result however showed a slight difference in bulk density between 0-15 and 15-30 cm depth in the 5 year old farm in Ghana however, bulk density increased with soil depth, and this trend was seen in the 15 year old farms in Côte d'Ivoire (Fig. 13a).

### **4.2.2 Percentage sand, silt and clay**

Percentage sand was high in 0-15 cm soil depth in the 15 and 30 year old farms in Côte d'Ivoire, while in the 5 year old farm, it was higher at 15-30 cm (Fig. 13b). The trend for 0-15 cm in the order 15>30>5 years. Percentage sand was higher in 15-30 cm in the order 15>5 >30 years. In Ghana, sand percentage was higher in the 0-15 cm in the order of 30>5> 15 years and low in 15-30 cm depth which followed the order 5>30>15 years.

The analysis showed that percentage silt was higher at 0-15 cm in 15 and 5 year old farms in both countries than in the 15-30 cm soil depth. However, in the 30-year-old farms in both countries, silt percentage was higher in the 15-30 cm than in the 0-15 cm (Fig. 13c). Percentage clay content was lower in 0-15 cm and higher in 15-30 cm depth in all the farms in Ghana (Fig.13d).

### **4.2.3 Soil pH and available potassium**

Figure 13e presents soil pH (soil acidity level) in the various sites, at different depths and farms. It was observed that soils from cocoa farms of Côte d'Ivoire had lower pH values ranging from 4.5 in surface soil (0-15 cm) to 5.0 in subsoil (15-30 cm) which was very strongly acid soils whereas Ghana soils ha pH value of 6.5 to neutral in the 0-15 cm depth and 6.0 in the 15-30 cm depth which ranges from moderately acid to slightly acid Fig. 13e.

Available potassium was high at 0-15 cm and lower at 15-30 cm depth across all the cocoa farms in Côte d'Ivoire. The distribution pattern was in opposite direction for farms in Ghana

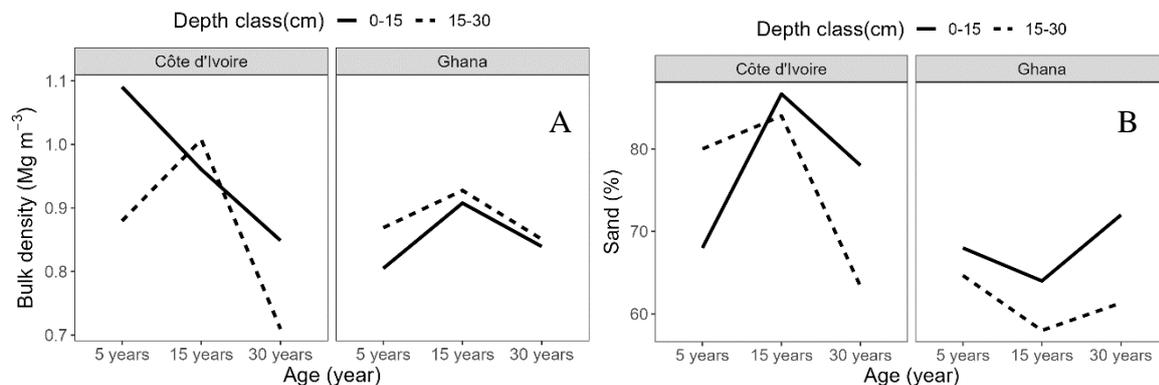
where in all the farms, available potassium was lower at 0-15 cm depth and higher at 15-30 cm (Fig. 13f).

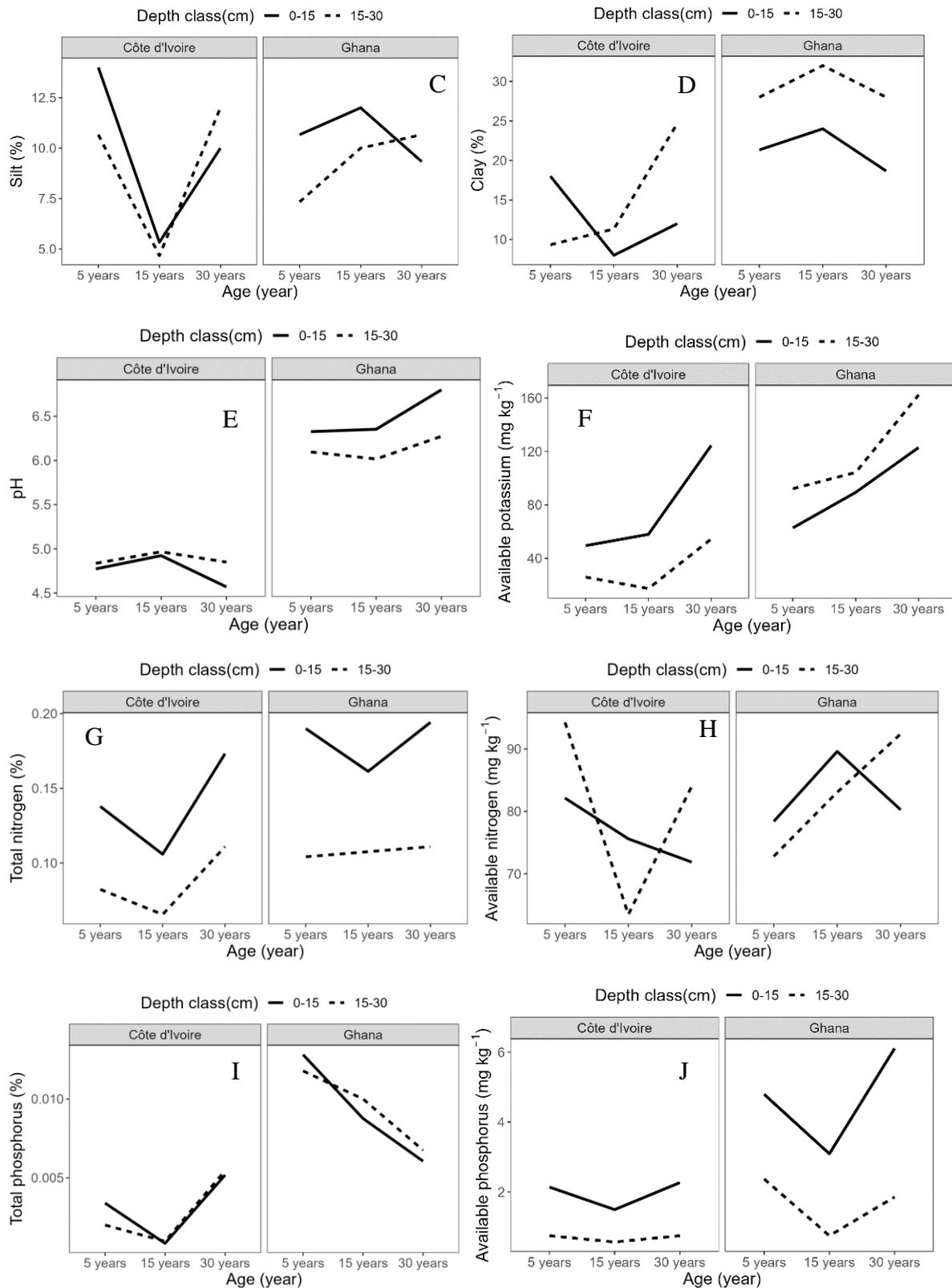
#### 4.2.4 Nitrogen content (total and available per soil depths of each farm)

The soil total nitrogen content was highest in 0-15 cm and lowest in 15-30 cm across all the farms (15, 30 and 5 year old farms) in both Ghana and Côte d'Ivoire (Fig 13g). The trend was completely the same for all the farms. However, the highest distribution range was found in the 5 and 30 year old farms in both countries. Available nitrogen differed across the farms at the different soil depths (0-15 cm) and (15-30 cm) in both countries. Total nitrogen content for the 15 old farm was 90 mg N/kg dry soil and 75 mg N/kg of dry soil at 0-15 cm depth in Ghana and Côte d'Ivoire respectively. Soil available nitrogen was higher in 15 year old farm at 0-15 cm in both countries and opposite trend was obtained in the 30-year-old farm. For the 5 years old farm the trend was opposite for both countries (Fig. 13h).

#### 4.2.5 Distribution pattern of total and available phosphorus per depth and farm (year)

Total phosphorus content varied across all the farms in both countries. In Côte d'Ivoire, low total phosphorus content was recorded at both depths of the 15 year old farm. Total phosphorus content was relatively higher at 0-15 cm depth in the 5 year old farm in both countries (Fig. 13i). Available phosphorus was higher in all the farms at 0-15 cm depth (Fig.13j). Comparably, Ghana farms records higher available phosphorus content at 0-15 cm soil depth than farms in Côte d'Ivoire (Fig. 13j).





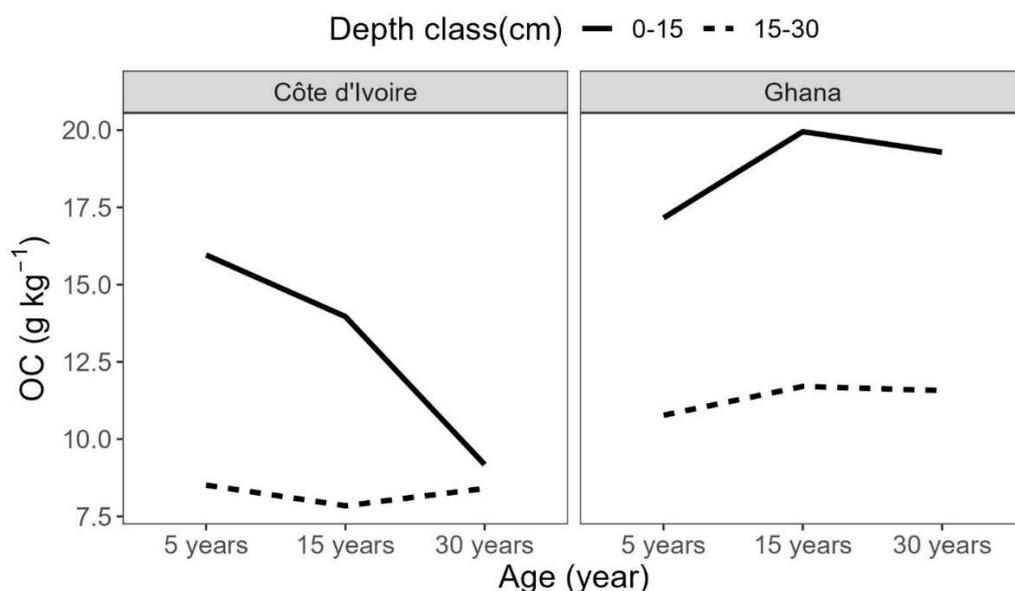
**Fig.13** Dynamics of soil physico-chemical properties across farms ages and soil depths, (A) Bulk density (B) Percentage sand (C) percentage silt (D) Percentage clay (E) pH (F) Available potassium (G) Total nitrogen (H) Available nitrogen (I) Total phosphorus and (J) Available phosphorus

#### 4.2.6 Soil organic carbon concentration (SOC) and soil organic carbon density (SOCD) per soil depth

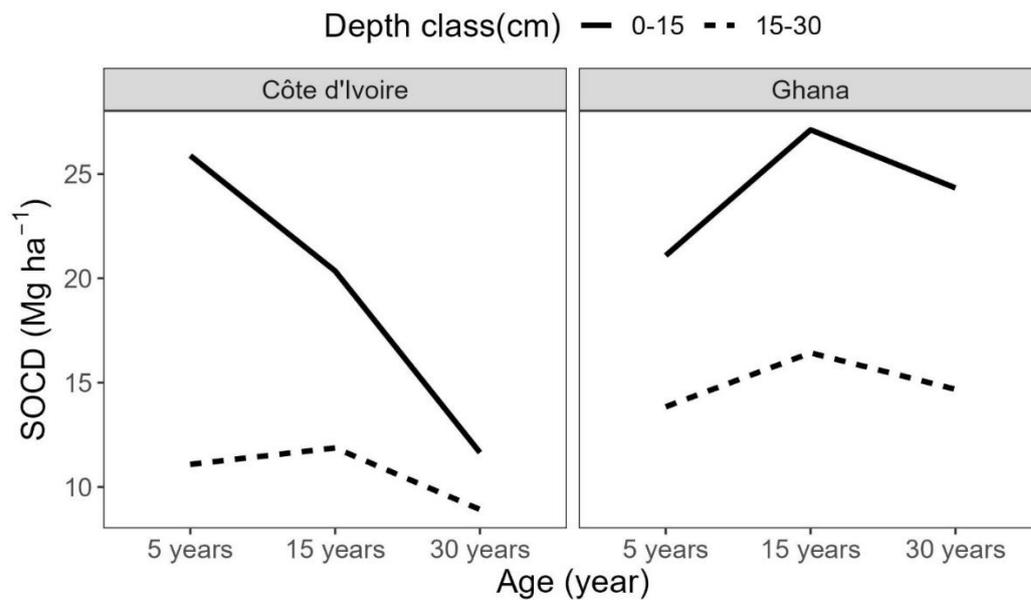
The boxplot showed that soil organic carbon (SOC) concentration varied across soil depths with the 0-15 cm containing the highest SOC concentration across the farms in both countries (Fig 14). The highest SOC concentration was observed in 5 year old farm in Côte d'Ivoire and 15 years old farm in Ghana at 0-15 cm depth. In Côte d'Ivoire, 5 and 15 year old farms recorded more SOC concentration at 0-15 cm depth. Whereas SOC concentration was higher at 0-15 cm soil depth across all the farms in Ghana. Soil organic carbon density (SOCD) Fig 15 was higher at 0-15 cm soil depth similar to the distribution pattern of SOC within farms. Averagely, higher soil carbon was sequestered in a depth of 0-15 cm in Ghana soils as compared to Côte d'Ivoire see Fig 14 and 15 below.

#### 4.2.7 Effect of cocoa agroforestry system on soil carbon sequestration

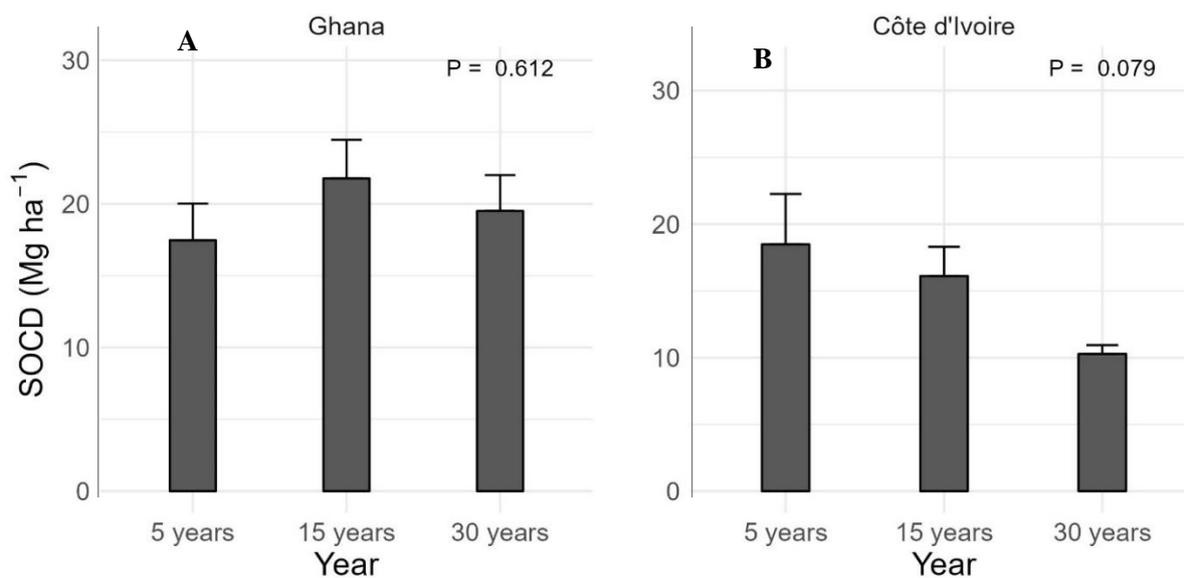
SOC sequestration varied across the cocoa agroforestry farms in the two countries even though the variations were not significantly different at  $p < 0.05$ . In Ghana, 15 and 30 year old farms showed higher SOCD than the 5 years old farm. In Côte d'Ivoire, 5 and 15 year old farms recorded the highest SOCD compared to the 30-year-old farm (Fig. 16). The results revealed that the age of the farms has no effect on soil organic carbon sequestration. The sequestration trend per farm age was in the order (5 > 15 > 30) in Côte d'Ivoire and Ghana, (15 > 30 > 5) instead of the expected (30 > 15 > 5). Table 15 presents the summary of variation of SOCD across farms, soil depth and sites, and indicates the site, farm age and soil depth at which soil organic carbon is optimized. SOCD varied statistically significant ( $p < 0.05$ ) between sites (Fig. 17).



**Figure 14.** Distribution of SOC per soil depth in each farm (year) of both countries



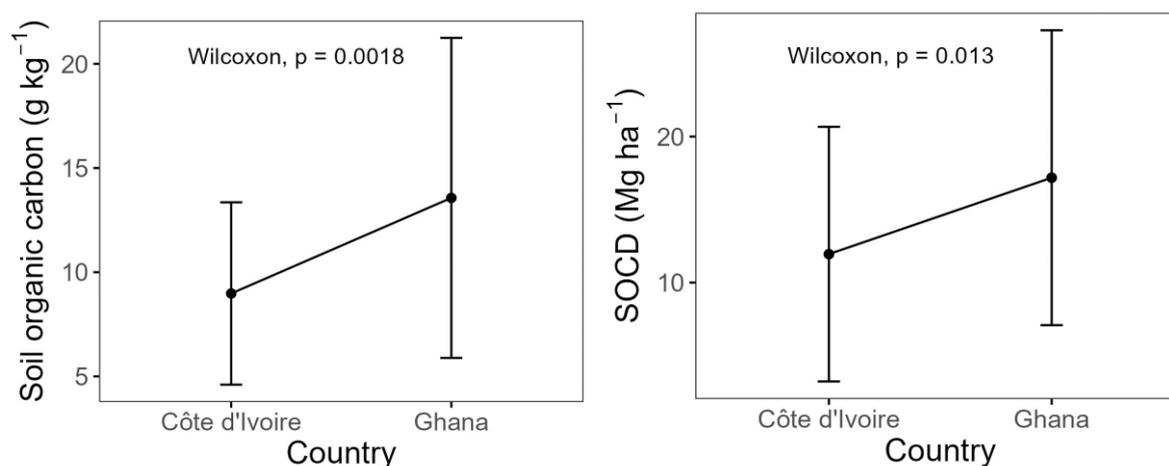
**Figure 15.** Amount of SOC sequestered per soil depth of each farm



**Figure 16.** Variation in SOC density across the cocoa agroforestry farms in (a) Côte d'Ivoire and (b) Ghana

**Table 15.** Means and standard deviation of SOCD per site, soil depth and farm (year)

Independent variable	Levels	Mean (sd) of SOCD
Site	Côte d'Ivoire	15.0 (6.8)
	Ghana	<b>19.6 (6.2)</b>
Depth	<b>0-15</b>	<b>21.7 (6.7)</b>
	15-30	12.8 (3.2)
Year	<b>15 years</b>	<b>18.9 (6.4)</b>
	30 years	14.9 (6.4)
	5 years	18.0 (7.5)



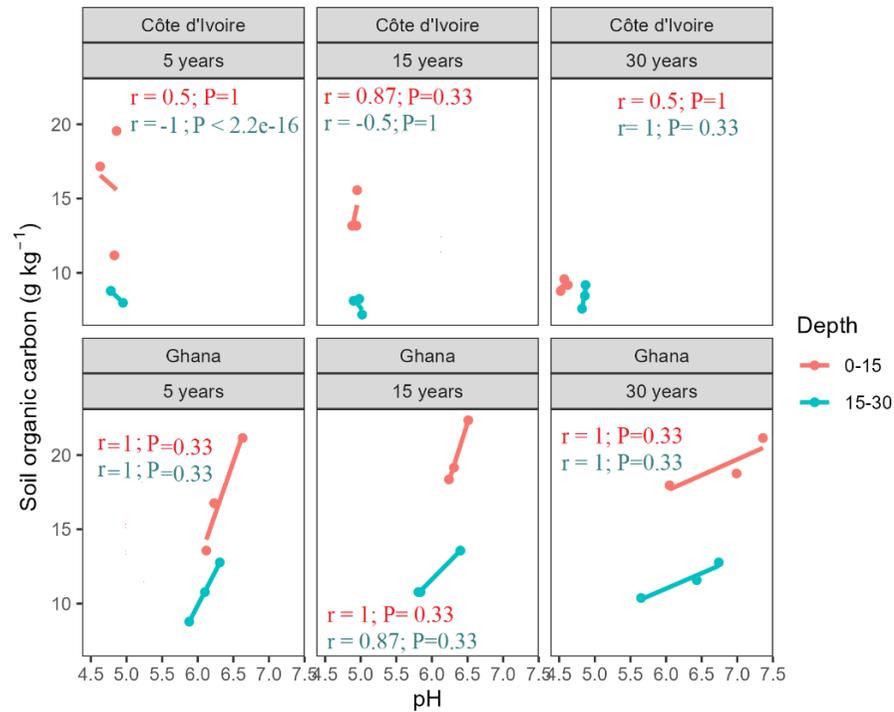
**Fig. 17.** Soil organic carbon sequestered (SOC and SOCD) between sites

#### **4.2.8 Relationship between soil pH and soil organic carbon, available nitrogen, available phosphorus, and available potassium of the cocoa farms**

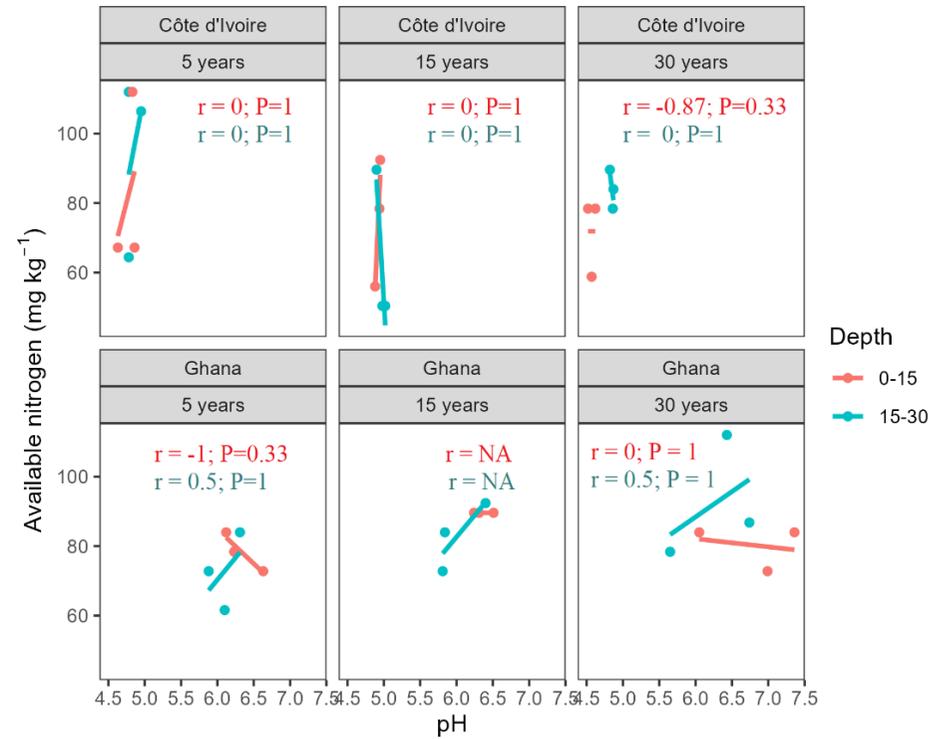
The scatter plot showed that soil pH did not influence soil organic carbon concentration at the two soil depths across farms in Côte d'Ivoire. In Ghana soils, SOC concentration correlated positively ( $r = 1^*$ ) with soil pH at both soil depths 0-15 and 15-30 cm across all the farms particularly at pH value of 6.3 to 7.1 but the result was not significant at  $p < 0.05$  (Fig. 18).

Effect of soil pH on nitrogen as shown in (Fig. 19) indicates that available nitrogen content correlated negatively with soil pH across soil depth and across farms in both countries. Positive correlation ( $r = 1$  and  $r = 0.5$ ) was recorded between soil pH and soil available phosphorus across all the cocoa farms in Ghana and 30 years farm in Côte d'Ivoire at both soil depths but however, the results were not significant (Fig. 20).

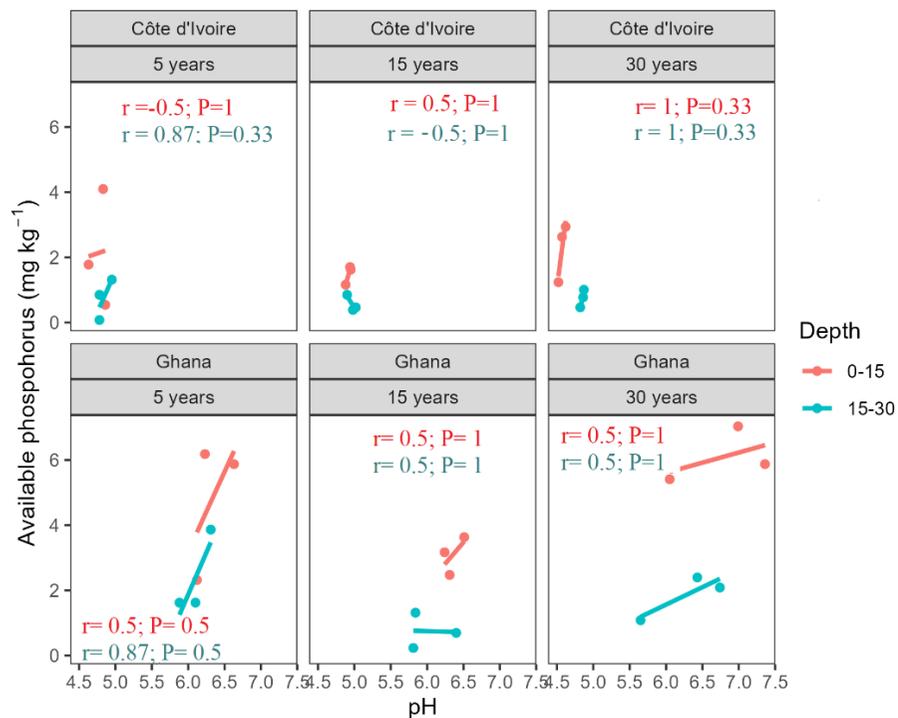
There was no positive correlation between soil pH and soil available potassium in both countries particularly in soils of Côte d'Ivoire (Fig. 21)



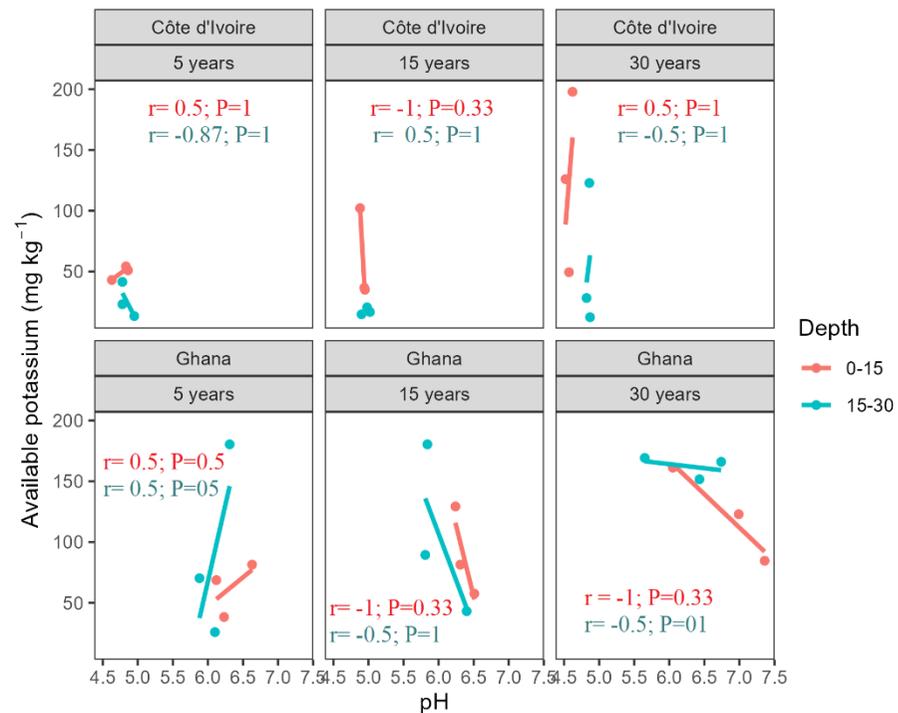
**Figure 18.** Relationship between soil pH and SOC per soil depth and farm (year) of each country (scatter plot with Spearman correlation).  $r$  = spearman correlation coefficient,  $P$  = p-value for  $r$  significance



**Figure 19.** Relationship between soil pH and available nitrogen per soil depth and farm (year) of each country (scatter plot with Spearman correlation).  $r$  = spearman correlation coefficient,  $P$  = p-value for  $r$  significance



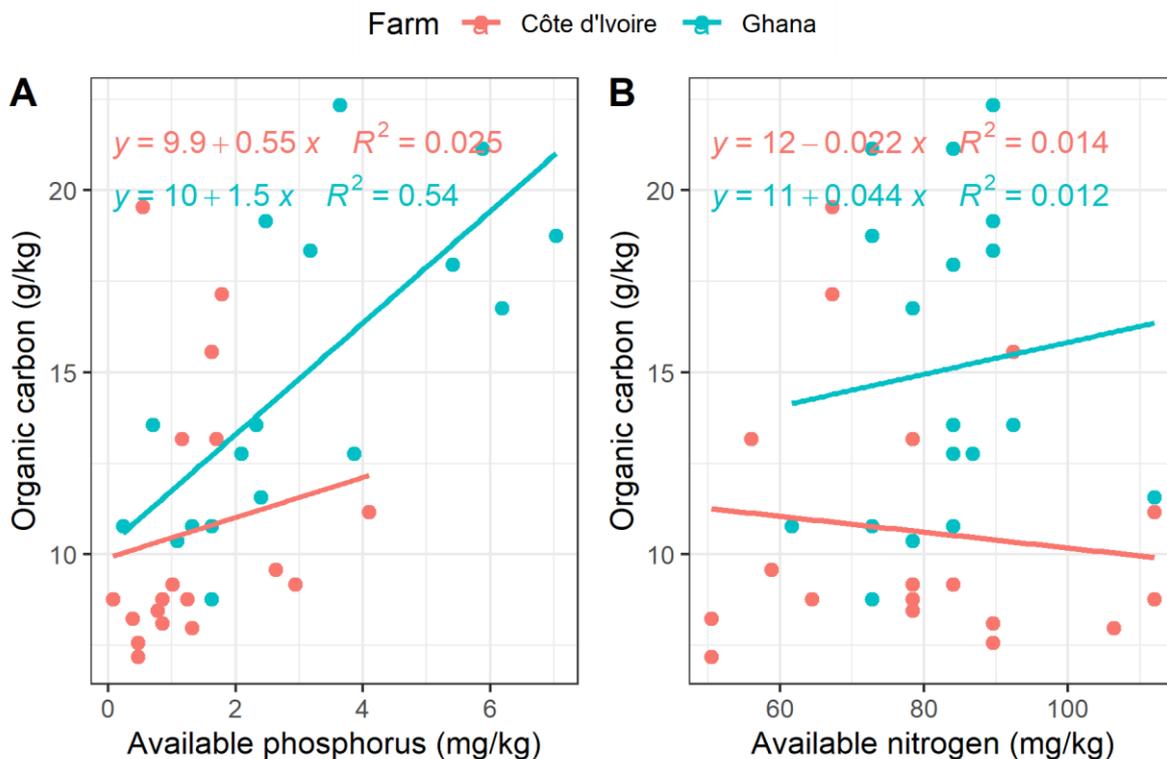
**Figure 20.** Relationship between soil pH and available phosphorus per soil depth and farm (year) of each country (scatter plot with Spearman correlation). r = spearman correlation coefficient, P = p-value for r significance



**Figure 21.** Relationship between soil pH and available potassium per soil depth and farm (year) of each country (scatter plot with Spearman correlation). r = spearman correlation coefficient, P = p-value for r significance

#### 4.2.9 Relationship between organic carbon, nitrogen and phosphorus in entire soil sample

The linear regression model results show a positive correlation between soil organic carbon and phosphorus (C-P) in farms of both countries. However, weak correlation exists between C-P ( $R^2 = 0.025$ ) in the soils of Côte d'Ivoire (Fig. 22a). Whereas there was a weak correlation between soil organic carbon and nitrogen (C-N) for Ghana ( $R^2 = 0.012$ ) and Côte d'Ivoire  $R^2 = 0.014$  (Fig. 22b). This indicates that the relationship of C-P and C-N can be fitted with linear model as observed with pH and OC, N, P, K.



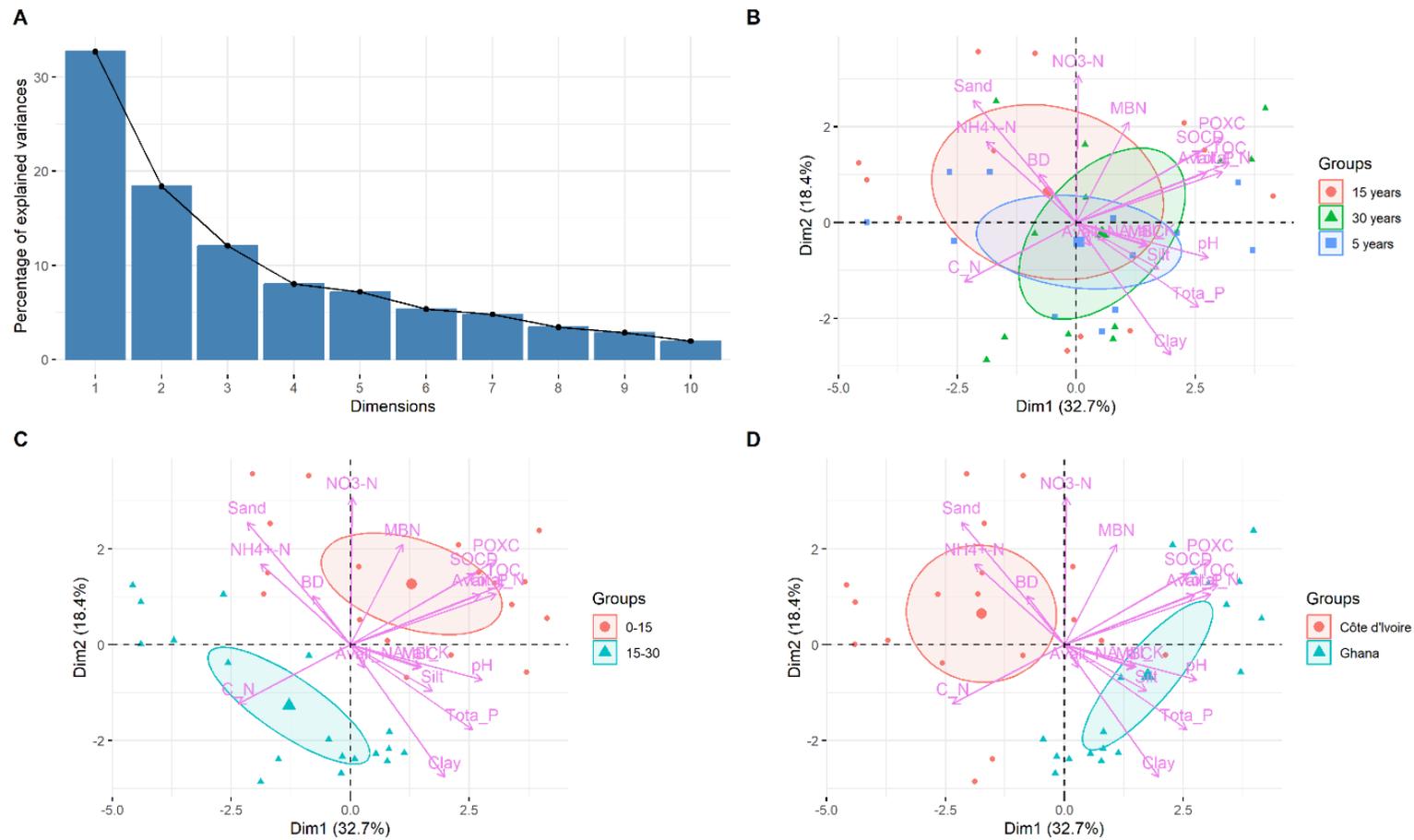
**Fig. 22.** Relationship between (a) SOC content and available P, (b) SOC content and available N, and amount in the entire soil sample of each country

#### 4.2.10 Effect of the production system on the distribution pattern of physico-chemical properties at soil depth, farm and site levels (Ghana and Côte d'Ivoire)

The first two principal components explained 51.1% of the variation in the physico-chemical properties included in the PCA (Fig. 23). The projection of the starting variables in the plan formed by these axes indicates two main opposite groups of variables. The first group includes POXC, SOCD, TOC, available nitrogen, available phosphorus, available potassium, total nitrogen, total phosphorus, total potassium, pH, silt and clay which are positively correlated. The second group includes ration carbon-nitrogen, BD,  $\text{NH}_4^+\text{-N}$ , and Sand which are also correlated. The two first axes did not cluster separately for the years (farms), so there is no difference between years in terms of physico-chemical properties of the soils. But depth classes

are clustered separately, so are sites (Ghana and Côte d'Ivoire). Indeed, the depth class 0-15 cm is characterized by a high concentration of MBN, SOCD, POXC, TOC, available phosphorus, total nitrogen and low concentration of Carbon/Nitrogen ratio. In contrast, the depth class 15-30 cm is characterized by high ratio C/N but low concentration of MBN, SOCD, POXC, TOC, available Phosphorus, total Nitrogen (Fig. 23).

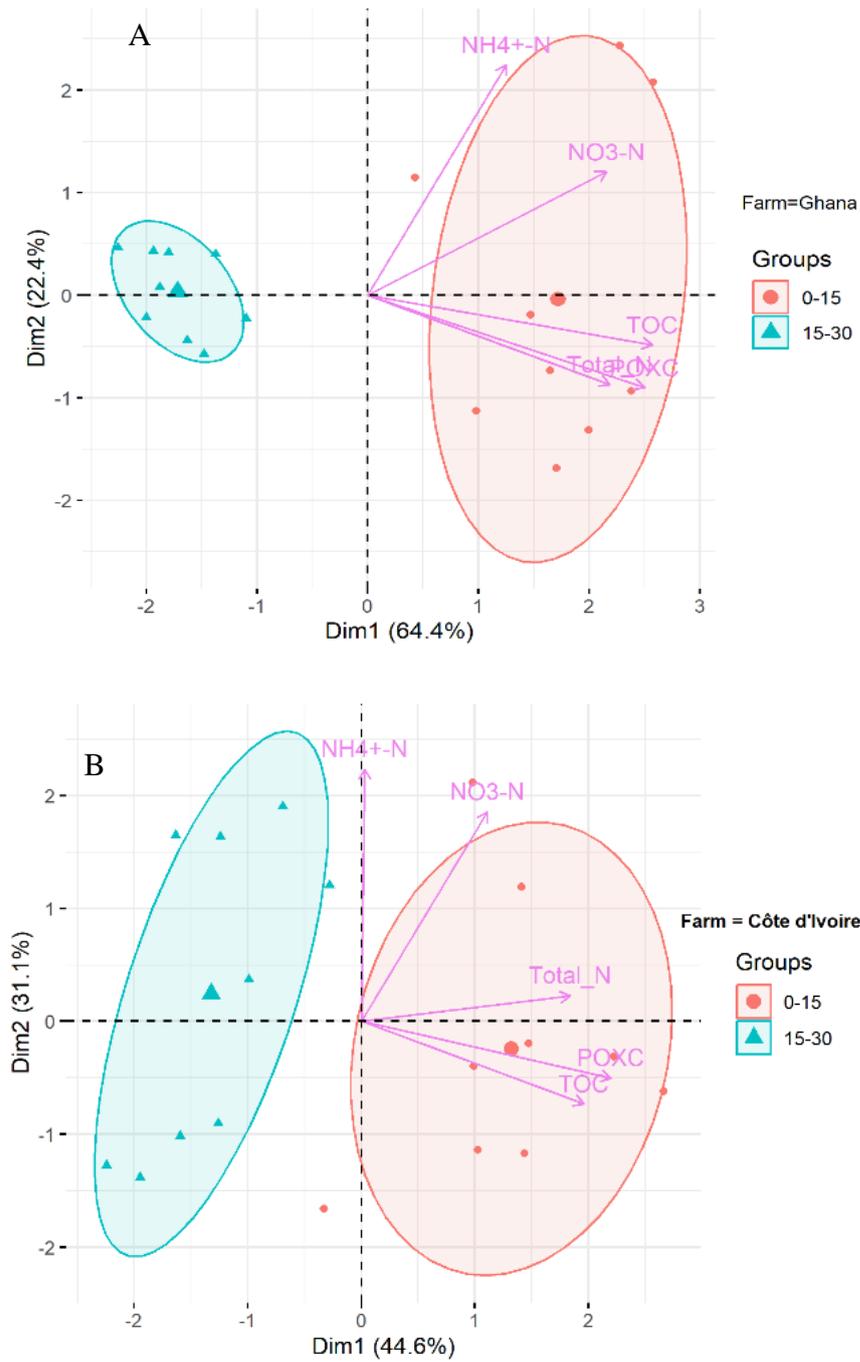
Considering sites, the site Ghana are characterized by high concentration of pH, POXC, SOCD, TOC, available phosphorus, total nitrogen, total phosphorus silt and clay but low C/N ratio, BD,  $\text{NH}_4^+\text{-N}$ , and Sand. On the other hand, the site Côte d'Ivoire are by high concentration of C/N ratio, BD,  $\text{NH}_4^+\text{-N}$ , and Sand but low pH, POXC, SOCD, TOC, available Phosphorus, total Nitrogen, total phosphorus silt and clay (Fig. 23).



**Fig. 23.** Principal component analysis (PCA) of the soil properties. The two first principal components are shown on the x- and y-axes, respectively (a) PCA scores represent soil samples, with colors indicating the corresponding (b) cultivation systems, (c) soil depth and (d) sites

#### **4.2.11 Effect of the production system on the distribution of SOC, $\text{NH}_4^+\text{-N}$ , $\text{NO}_3^-\text{-N}$ and POXC at different soil depth and site (Ghana and Côte d'Ivoire)**

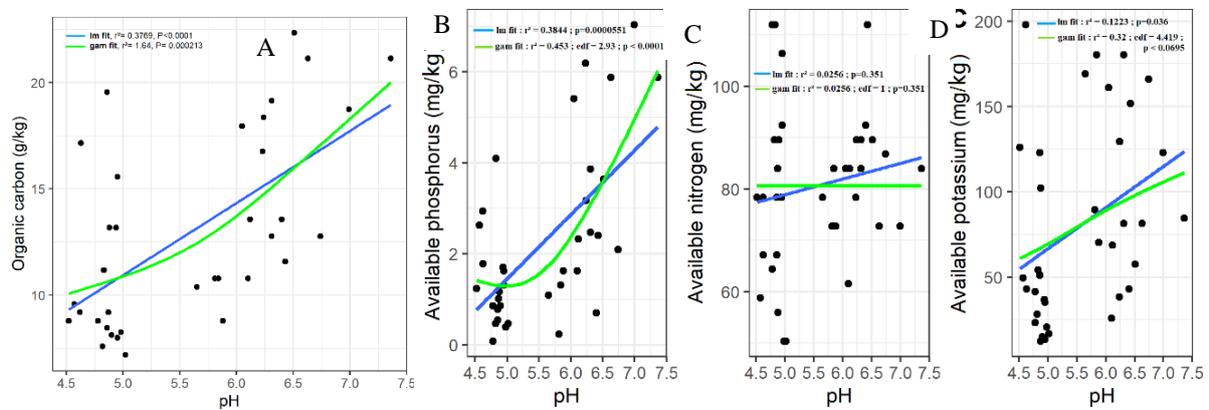
The first two PCA explained 86.8 % and 75.9 % of the variation of the dataset for Ghana and Côte d'Ivoire respectively. The axes indicate all the variables were positively correlated. The soil depth classes are clustered separately in the plan (Fig. 24). The results indicate that soil depth class 0-15 cm is characterized by a high concentration of total organic carbon (TOC), total nitrogen (TN), mineral N (ammonium-nitrogen ( $\text{NH}_4^+\text{-N}$ ), nitrate-nitrogen ( $\text{NO}_3^-\text{-N}$ ) and permanganate oxidizable carbon (POXC) in both countries particularly in Ghana. Further the result showed that  $\text{NH}_4^+\text{-N}$  and  $\text{NO}_3^-\text{-N}$  were negatively connected with the 0-15 cm depth but were not connected to the 15-30 cm either in Côte d'Ivoire. The  $\text{NH}_4^+\text{-N}$  was more common to 15-30 cm than  $\text{NO}_3^-\text{-N}$  in Côte d'Ivoire. The contents of total nitrogen, ammonium and nitrate forms of nitrogen, and POXC in the soil profiles decrease with depth. Depth distribution of nitrogen forms showed a similar trend as that of soil organic carbon.



**Fig. 24.** PCA biplot showing Distribution pattern of TOC, NH<sub>4</sub><sup>+</sup>-N, NO<sub>3</sub><sup>-</sup>-N and POXC at the two soil depths in (a) Ghana and (b) Côte d'Ivoire

#### 4.2.12 Effect of soil pH on soil organic carbon, available nitrogen, phosphorus, and potassium (NPK) in the entire soil sample

Using the linear regression and generalized additive models, the results revealed that pH has a positive influence on soil organic carbon and available N.P.K with the linear regression model (Fig. 25). Indicating that as soil pH increases these soil properties would also increase, that is from pH 4.5-7.5 these soil nutrients are made available. Whereas with generalized additive model, there were positive effects of pH on available potassium and soil organic carbon than phosphorus. With a generalized additive model, the result showed that pH has no influence on available nitrogen. This pH-OC, pH-N, pH-P, pH-K can be fit with the linear regression model than generalized additive model (Fig. 25).

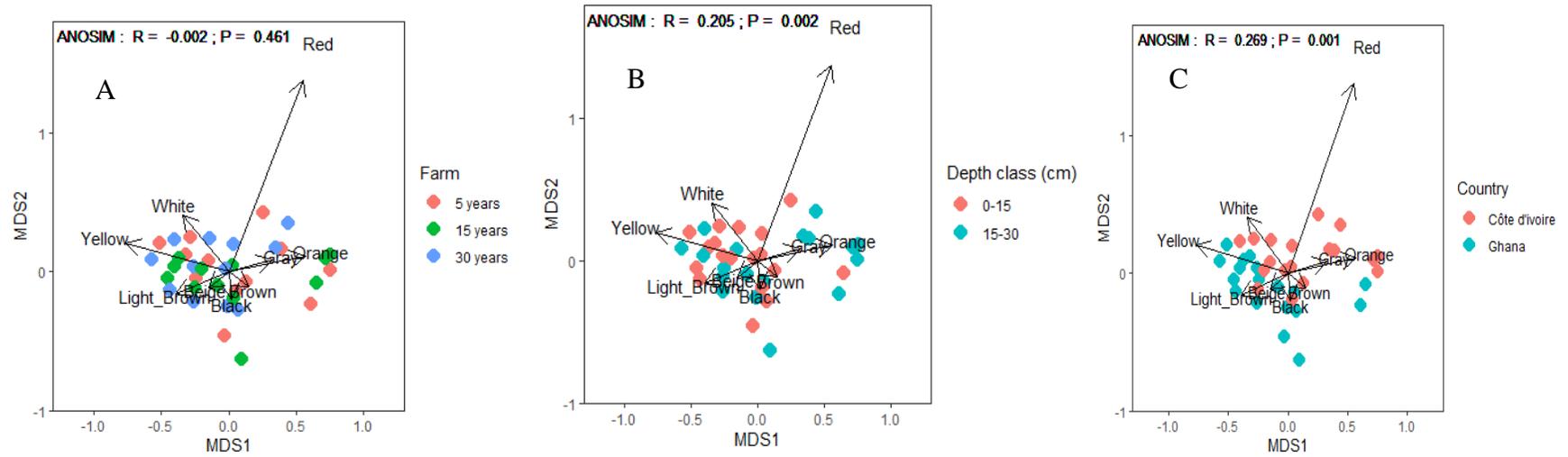


**Fig. 25.** Effect of soil pH on some key soil properties (a) soil total organic carbon, (b) available phosphorus, (c) available nitrogen and (d) available potassium in entire soil samples using linear regression and generalized additive model

**Objective 3.** Soil microbial communities across cocoa agroforestry farm (year) and soil depths  
This section shows results on the characterization of soil microbes, population, microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN) content of the cultivation systems in the study area.

#### **4.3.0 Soil fungal spores' community at the farms (year), soil depths, and sites (Ghana and Côte d'Ivoire)**

Figure 26 presents the abundance of fungal spore communities per cocoa agroforestry farm (year), soil depth, and sites. The statistic R Anosim analysis shows that at farm level, all colours of fungal spores clustered together indicating that the spore types found in the different cocoa farms 5, 15 and 30 year old were very similar irrespective of the site. Therefore, no significant difference between fungal spores colours was found in cocoa agroforestry farms of both countries (Fig. 26a). There was significant difference in spores' colours between soil depths (0-15 and 15-30 cm) and between sites (Ghana and Côte d'Ivoire) at ( $p < 0.05$ ). Red, white and yellow fungal spores were recorded at soil depth of 0-15 but gray and orange dominated 15-30 cm soil depth (Fig. 26b). Between countries the fungal spores clustered separately, the red, white, orange and gray coloured fungal spores were most found in soils of Côte d'Ivoire and yellow, light-brown and beige were dominant fungal spores recorded in soils of Ghana (Fig. 26c). This analysis was performed based on different colours of fungal spore isolated per soil depth, farm, and site.



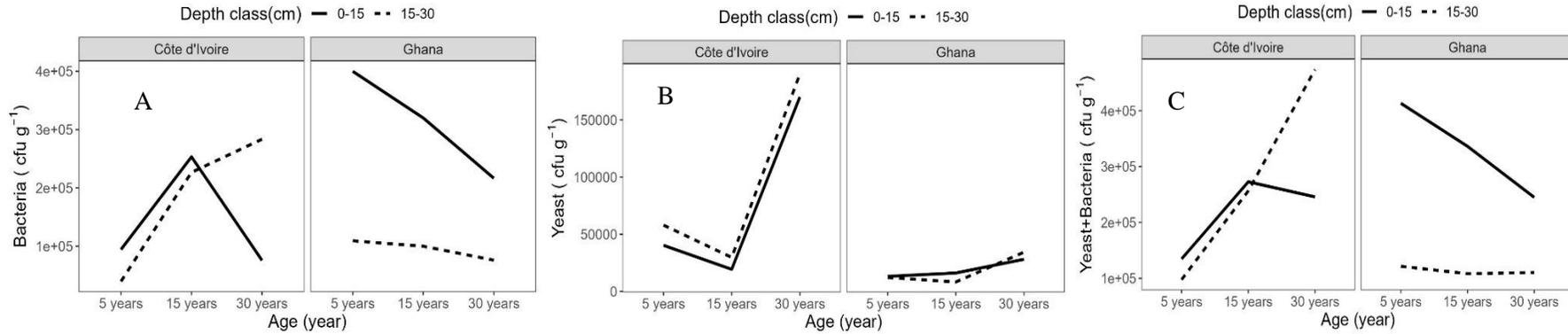
**Fig. 26.** Biplot of non-metric multidimensional scaling (NMDS) showing spore's types (in colour) per (a) farm (year), (b) soil depth and (c) sites with analysis of similarity (ANOSIM)

#### **4.3.1 Influence of soil depth on total bacteria and fungi counts**

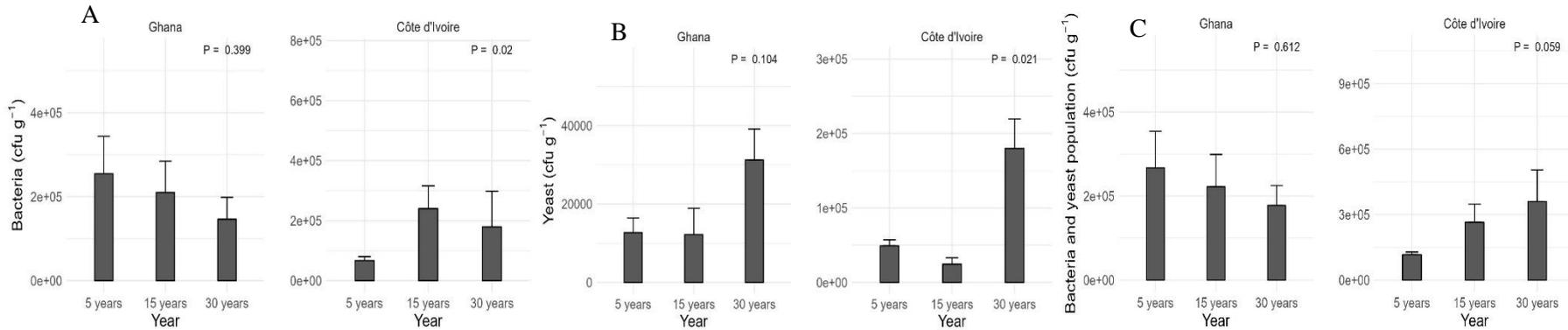
The result showed that soil depth influence bacteria and fungi (yeast) populations of the various sampling sites and farms (year). Bacteria population varied across soil depths in Ghana (Fig 27a). Generally, higher bacteria population was recorded at 0-15 cm depth across all the farms in Ghana. In Côte d'Ivoire, bacteria population was higher at 0-15 cm depth in the 15 years farm similar to the trends obtained across farms in Ghana (Fig. 27a). Similar bacteria population count was recorded at both soil depths (0-15 and 15-30 cm) in the 15 years farm of Côte d'Ivoire and increased in the 30 years old farm at 15-30 cm soil depth. Higher fungal population was recorded at both soil depths (0-15 and 15-30 cm) in the 30 years old farm in Côte d'Ivoire and no noticeable variability were found between soil depth of Ghana (Fig. 27b). The results showed that total bacteria and fungi population counts was higher in the 0-15 cm soil depth of farms in Ghana but varied at both soil depth of farms in Côte d'Ivoire. On the average, the highest total bacteria and fungi population counts was recorded at 0-15 cm soil depth in 5 years farm of Ghana and at 15-30 cm depth in 30 year old farm of Côte d'Ivoire (Fig. 27c)

#### **4.3.2 Effect of cocoa agroforestry system on bacteria and yeast populations**

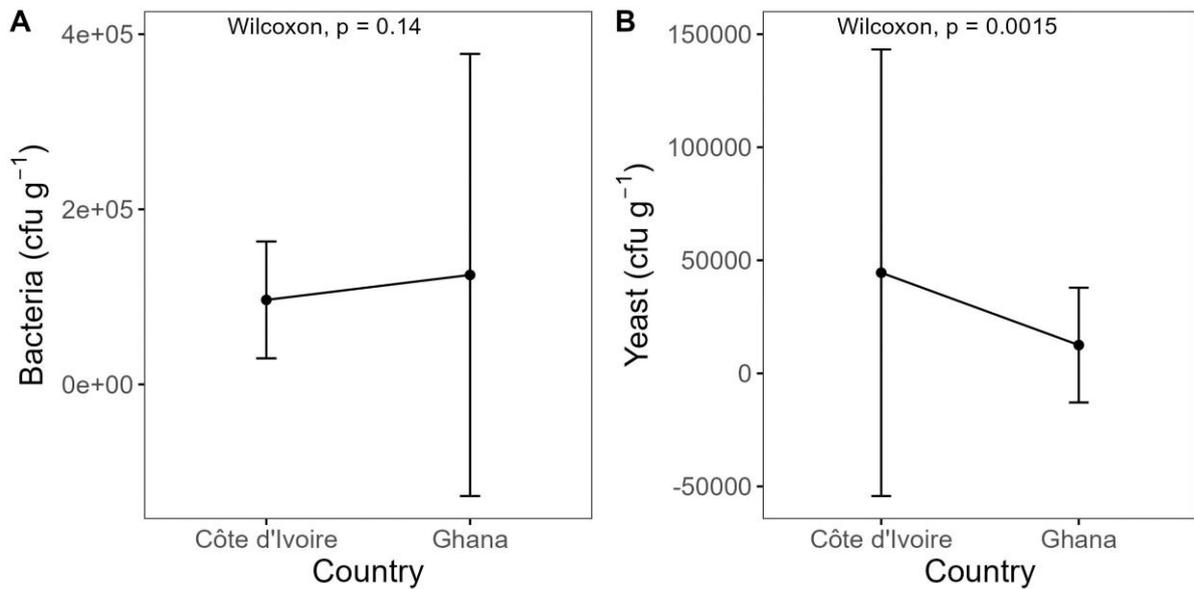
The bar plot analysis showed that the age of the cocoa agroforestry farm had no influence on the population of bacteria as presented in (Fig 28a). Recorded bacteria population was higher in 5 years old farm compared to 15 and 30 years old farms in Ghana in the order of  $5 > 15 > 30$  and in Côte d'Ivoire highest bacteria population was found in 15- and 30-year farm compared to 5 years old cocoa agroforestry farm in the order  $15 > 30 > 5$  years old farm. Yeast population was affected by age of farm (year) in both countries with 30 years old farm recording the highest yeast population compared to 5 and 15 year old farms however, this does not follow regular age trend like  $(30 > 15 > 5)$ . Comparatively, yeast population in 30 years farm was higher in Côte d'Ivoire compared to 30 years old farm in Ghana (Fig. 28b). There were some variations in total population counts of bacteria and yeast, with 30 years farm in Côte d'Ivoire recording the highest total count of bacteria and yeast, and in Ghana, the highest total count was recorded in 5 years farm (Fig. 28c). At site level, there was statistically significant difference between sites in terms of fungi population count, but bacteria population count was not significantly different between sites (Fig. 29).



**Figure 27.** Comparison of (a) Bacteria population (b) fungi (yeast) population and (c) total bacteria and yeast counts per soil depth (0-15 and 15-30 cm) of each sampling site

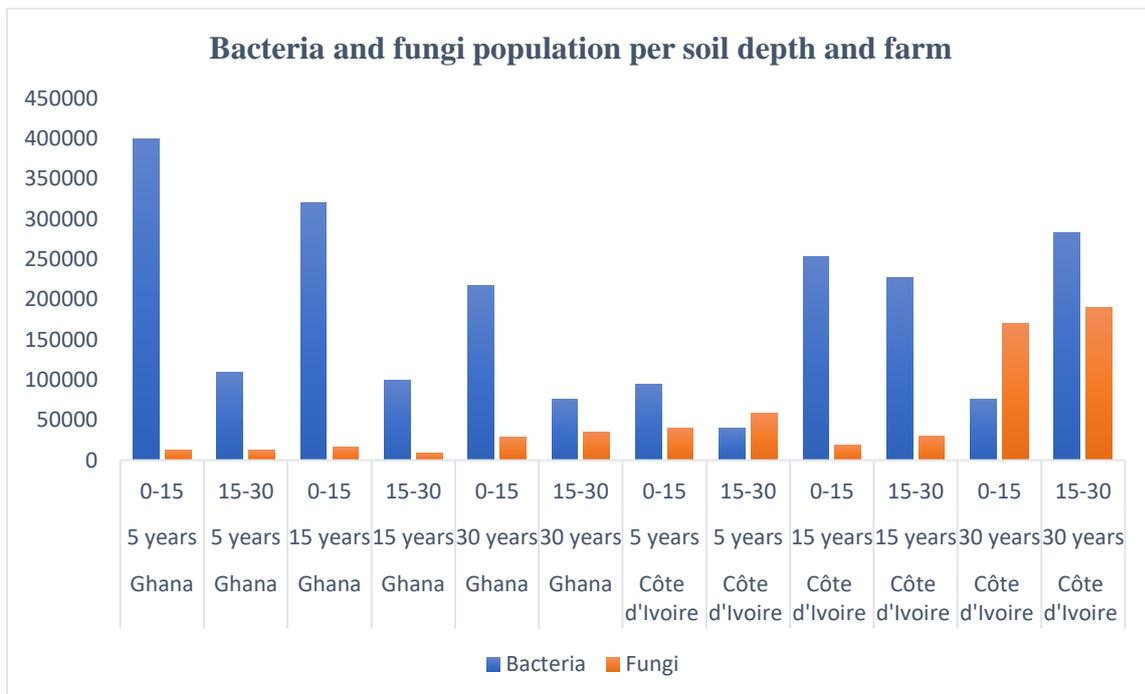


**Figure 28.** Effect of cocoa agroforestry farms (year) on (a) bacteria population and (b) fungi (yeast) population and (c) total bacteria and fungi populations counts



**Fig 29.** Comparison of (a) bacteria and (b) fungi (yeast) population between site

Figure 30 presents the general overview of the total mean of bacteria and fungi population of each cocoa agroforestry farms at the two soil depths in Ghana and Côte d'Ivoire. At site level, results showed that bacteria population increased with a decreased fungi (yeast) population across all farms in both countries except 30 years old farm in Côte d'Ivoire which showed higher fungi population at 0-15 cm depth.



**Fig. 30.** General overview of bacteria and fungi population per soil depth within each farm in Ghana and Côte d'Ivoire.

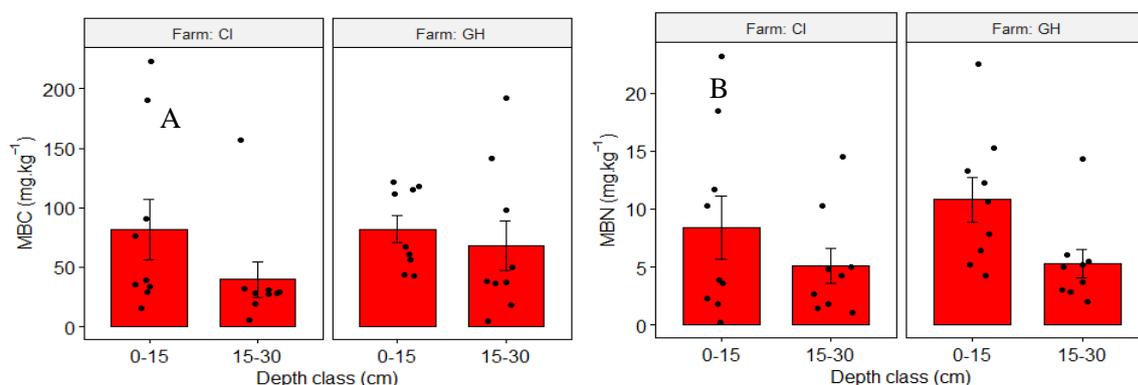
#### 4.3.3 The microbial biomass (MBC) and (MBN) content per soil depth and farm (year) of the two sites

Microbial biomass carbon (MBC ( $\text{mg kg}^{-1}$ )) and Microbial biomass nitrogen (MBN ( $\text{mg kg}^{-1}$ )) were influenced by soil depth in both countries (31a-b). Higher microbial biomass content (MBC and MBN) was recorded in the upper layer (0-15 cm), than the lower depth 15-30 cm in both countries (Fig. 31a). MBN was highest at 0-15 cm soil depth in soils of Ghana compared to Côte d'Ivoire suggesting that the MBN increases with increasing biomass carbon content at 0-15 cm soil depth in both countries (Fig. 31b).

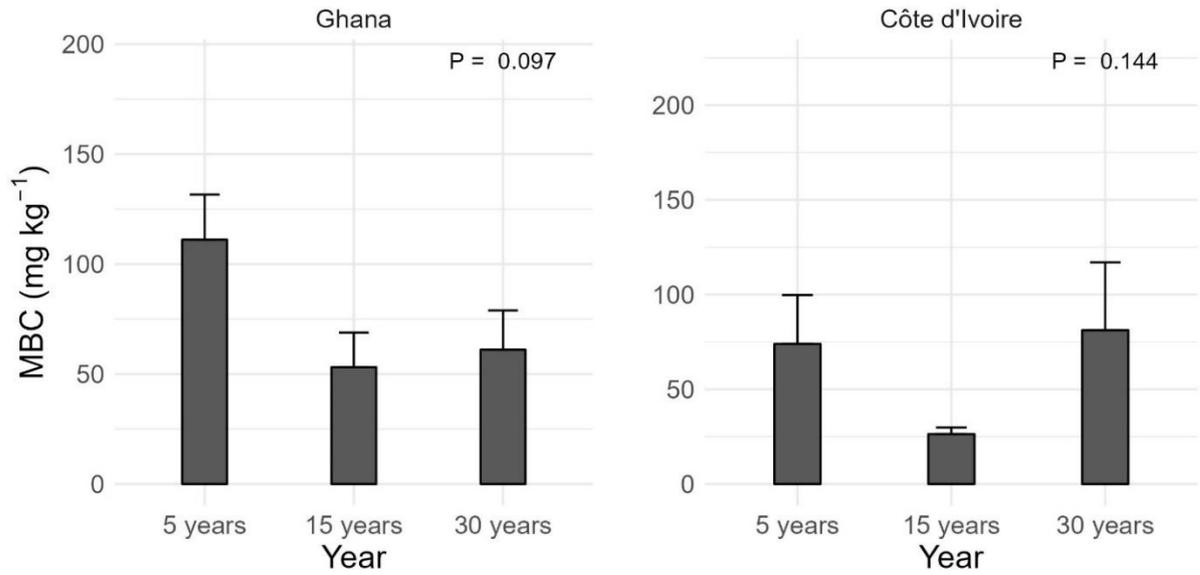
At farm level of both countries, MBC was highest in 5- and 30-year-old farms compared to 15-year-old farms in Côte d'Ivoire (Fig. 32). Results indicates that in farms of Ghana, MBC was highest in 5 year old farm as compared to the 15- and 30-year-old farms. However, these variations between farms were not statistically significant at  $p < 0.05$  (Fig. 32). There was variation in MBN content across farms, with 15- and 30-year-old farms of both countries recorded higher content of MBN compared to 5 year old farm (Fig. 33). MBC turned to be higher in the younger 5 year old farm while higher MBN content was recorded in older 15 and 30 year old farms (Fig. 33 and 33) of both countries.

#### 4.2.4 Correlation between microbial population, total carbon and nitrogen

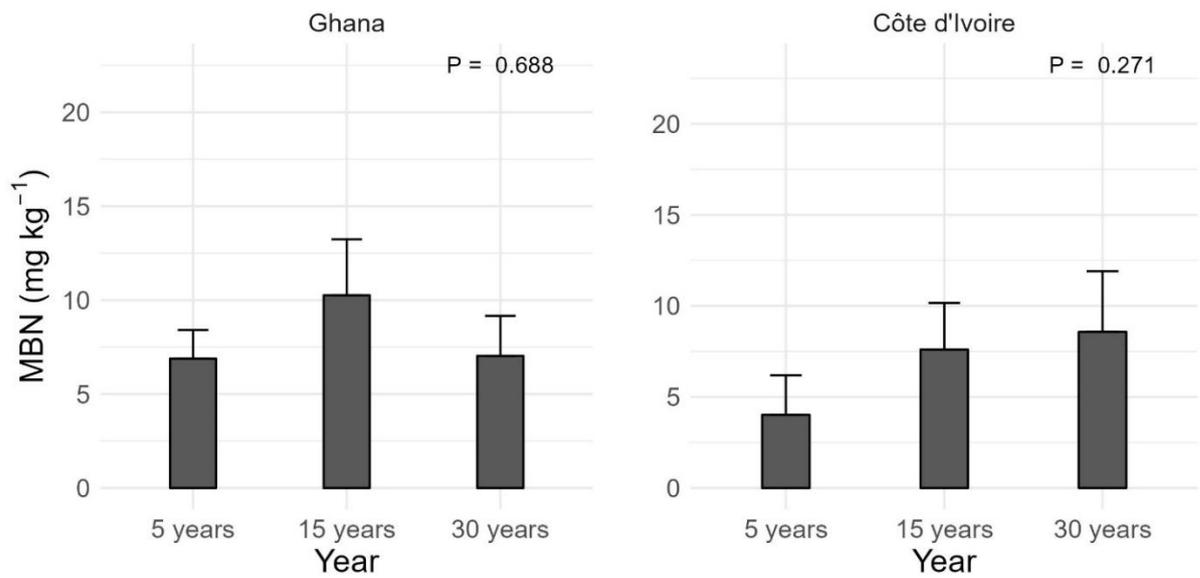
The results of this section are displayed in Fig 34a and 34b. There was a negative correlation between bacteria and fungi (yeast), yeast and organic carbon, and nitrogen in soils of Ghana. But a positive correlation was observed between bacteria population and total organic carbon and nitrogen (Fig 34a). In Côte d'Ivoire soils, negative correlation was obtained between all the variables total organic carbon, total nitrogen, bacteria and yeast (Fig. 34b).



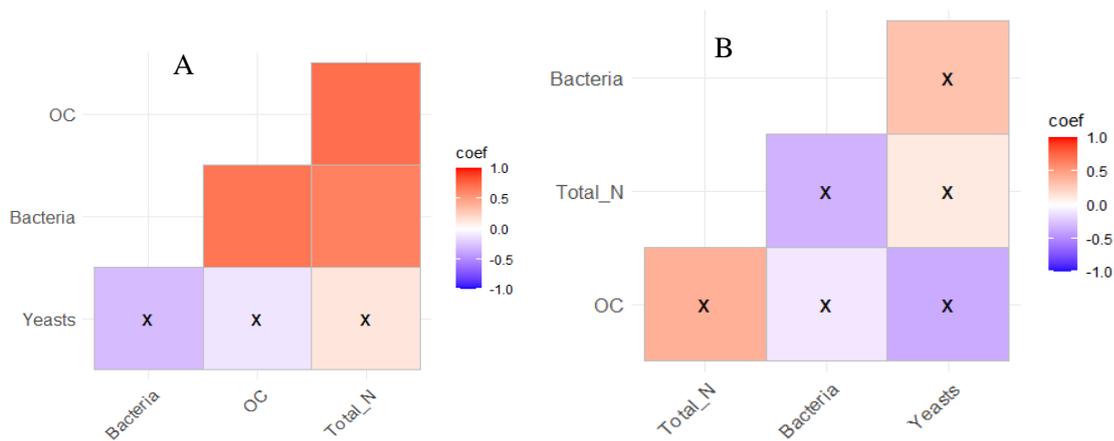
**Fig 31.** Microbial biomass content (a) microbial biomass carbon (MBC) (b) Microbial biomass nitrogen (MBN) per soil depth of each site



**Fig. 32.** Microbial biomass (MBC) per farm (year) of each site (Ghana and Côte d'Ivoire)



**Fig. 33.** Microbial biomass (MBN) per farm (year) of each site (Ghana and Côte d'Ivoire)



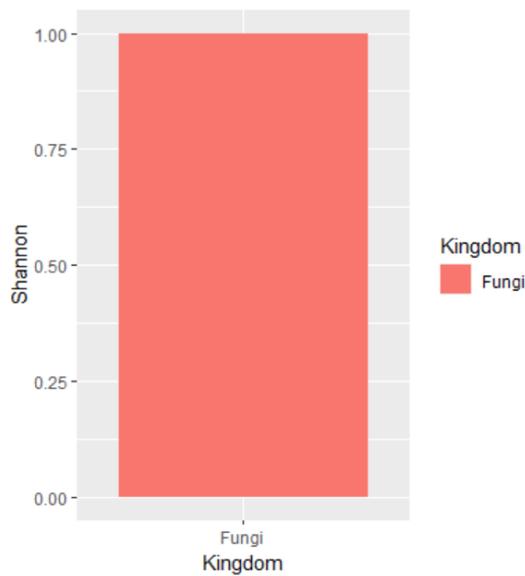
**Figure 34.** Correlation between microbial communities (yeast and bacteria) and total N and O C per site (a) Ghana and (b) Côte d'Ivoire. The character “x” indicates a non-significance at 5 % threshold.

#### 4.3.5 Characterization of microbes common to cocoa agroforestry system in Ghana and Côte d'Ivoire

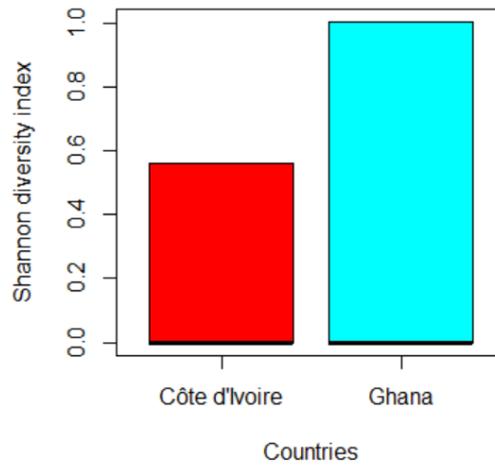
The molecular analysis showed that the kingdom fungi was the dominant microbes found in these soils after sequencing using the ITS primers (Fig.35). The Shannon diversity index showed that the diversity of fungi found in soils of Ghana was higher than Côte d'Ivoire (Fig. 36). Also, diversity was higher in shallow (0-15 cm) in Ghana and higher in deep (15-30 cm) depth in Côte d'Ivoire (Fig. 37). The richness by phylum in each country indicates that both Ascomycota and Basidiomycota were higher in Ghana soils compared to soils of Côte d'Ivoire (Fig. 38). Côte d'Ivoire soils contained higher percentage OTUs, 60 % than Ghana. Five (5) OTUs were identified as the most abundant OTUs for the entire soil samples (Fig. 39).

In the fungal kingdom, Ascomycota and Basidiomycota dominated the soils, in terms of OTUs richness. However, Ascomycota was higher in both 15 and 30 year old farm than Basidiomycota in both countries, with Ghana soils having the highest number of reads (10) than Côte d'Ivoire (Fig. 40).

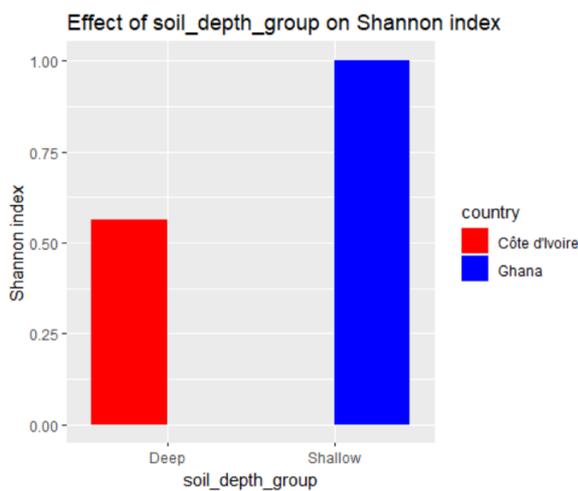
At the class level, Dothideomycetes, Eurotiomycetes, Malasseziomycetes, and Sordariomycetes were the most OTUs-rich groups. The order Capnodiales, Dothideales, Eurotiales, Malsseziales Onygenales, Pleosporales and Sordariales comprised the greatest number of OTUs. At the family level, Aspergillaceae, Chaetomiaceae, Cladosporiaceae, Dothidthiaceae, Malasseziaceae, Onygenaceae, Podosporaceae and Saccotheciaceae were the dominant groups. The genera *Arachnotheca*, *Cladorrhinum*, *Cladosporium*, *Humicola*, *Malassezia*, *Mycocentrospora*, and *Penicillium* were the greatest OTUs groups of the soils in both countries (Fig. 41).



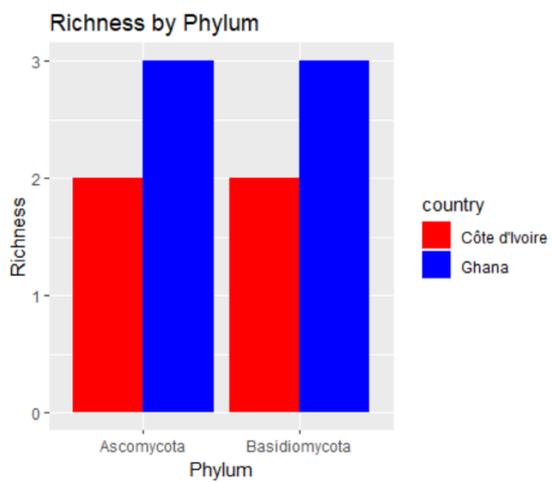
**Fig. 35.** Bar plot of dominant kingdom of the entire soil samples



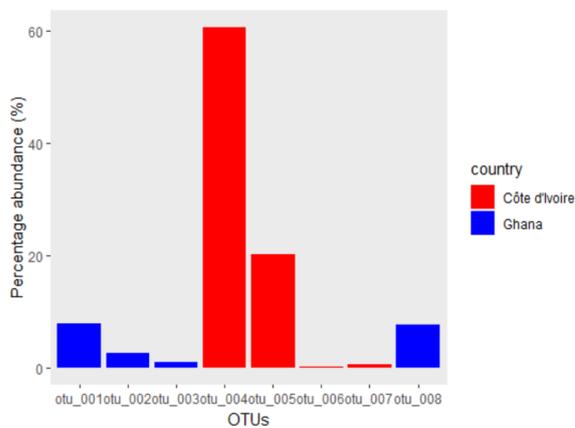
**Fig. 36.** Bar plot of Shannon diversity index per country



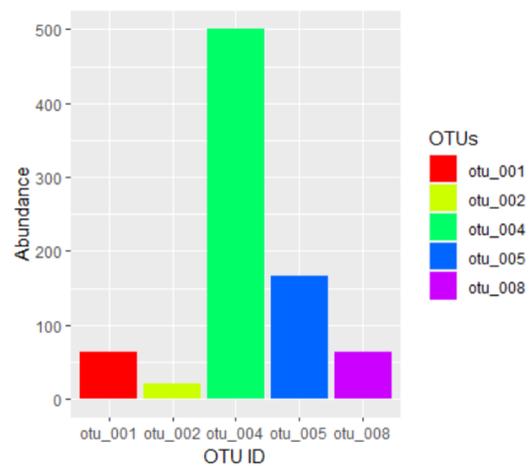
**Fig. 37.** Bar plot of the effect of soil depth on Shannon index in the entire soil samples



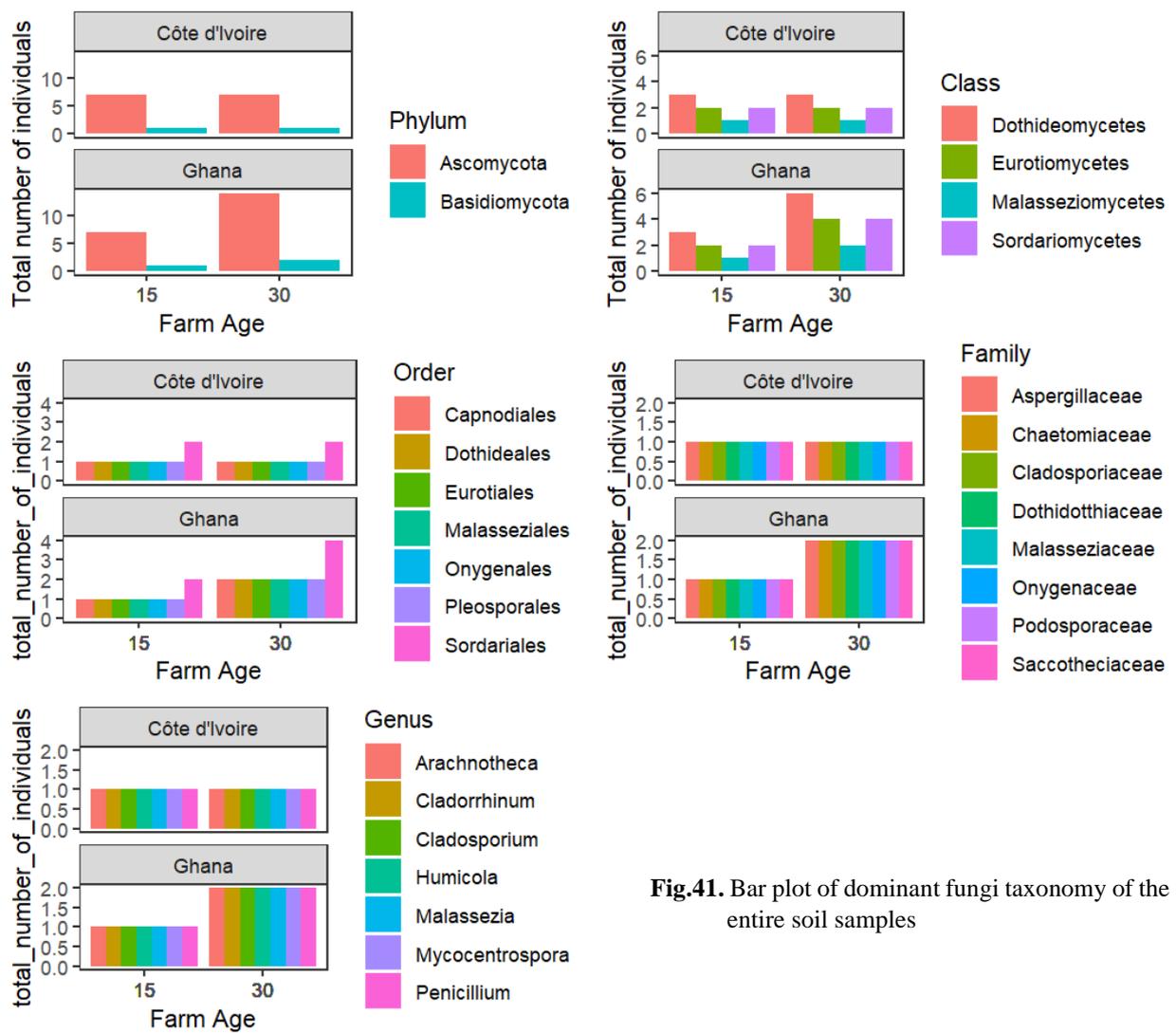
**Fig. 38.** Bar plot of richness by phylum in each country



**Fig.39.** Bar plot of percentage OTUs per country



**Fig. 40.** Bar plot of the most abundant OTUs of the entire soil samples



**Fig.41.** Bar plot of dominant fungi taxonomy of the entire soil samples

**Results for Objective 4** Radial growth and anatomical response of *Theobroma cacao* to climate change

**The anatomical responses of cocoa and tree growth relationship with climate change**

**4.4.0 Cross-dating potential, increment growth and tree age**

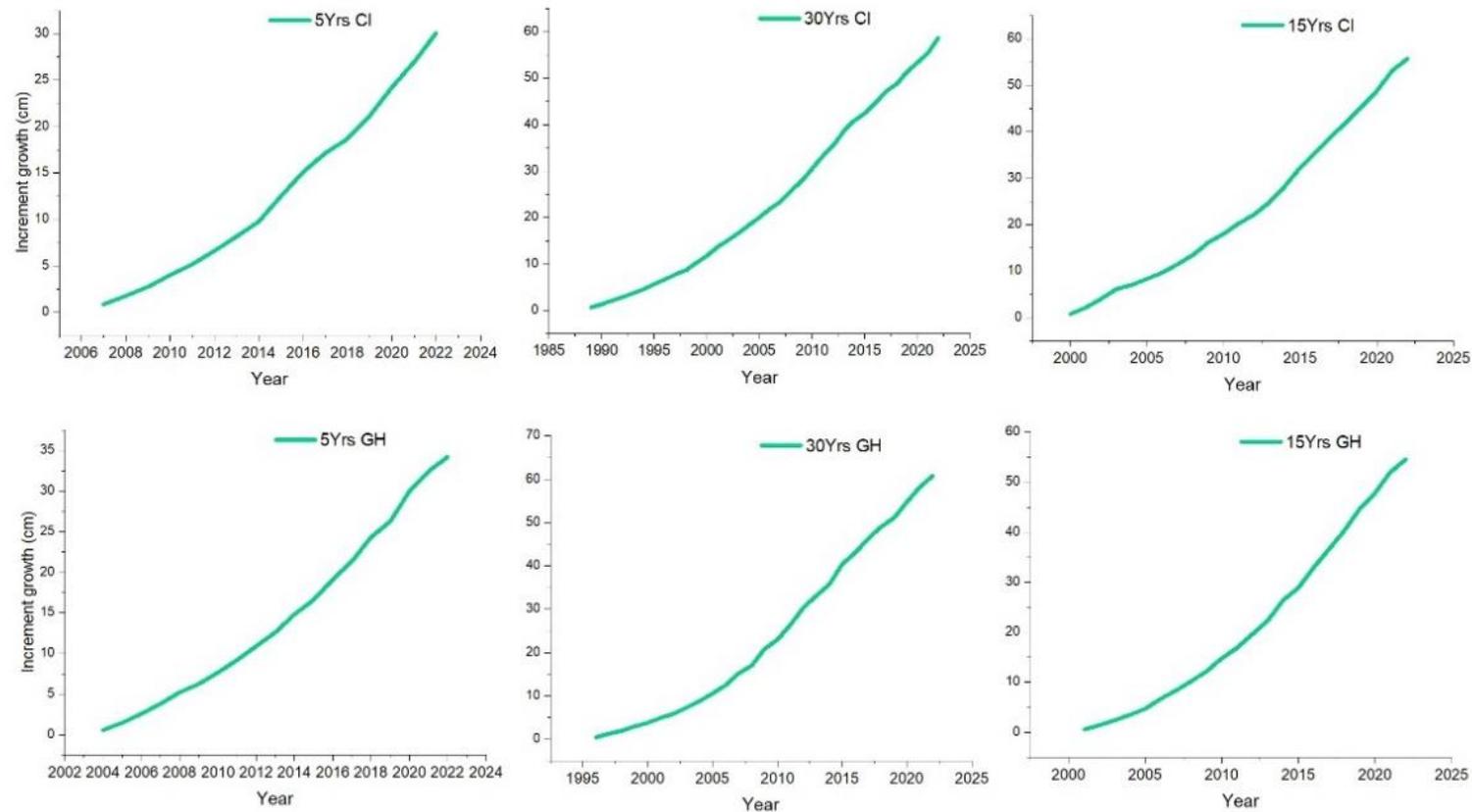
Cross-dating between radii of the same discs was successful for all the cocoa trees across all sites. The mean Gleichläufigkeit (GLK %) values are outlined in (Table 16). below. All the cocoa discs were successfully cross-dating within and between farms, yet cross-dating chronologies were not built for trees due to the young age of some of the samples. The mean radial increment growth varied between farm and sites (Table 16). The age of the cocoa tree ranges from (18 -27) and (14 -34) in Ghana Cote d’Ivoire respectively and the oldest cocoa tree was found in the sample site of Cote d’Ivoire which was (34 years old).

**4.4.1 Life-span (cummulative radial increment) growth of cocoa trees of both countries**

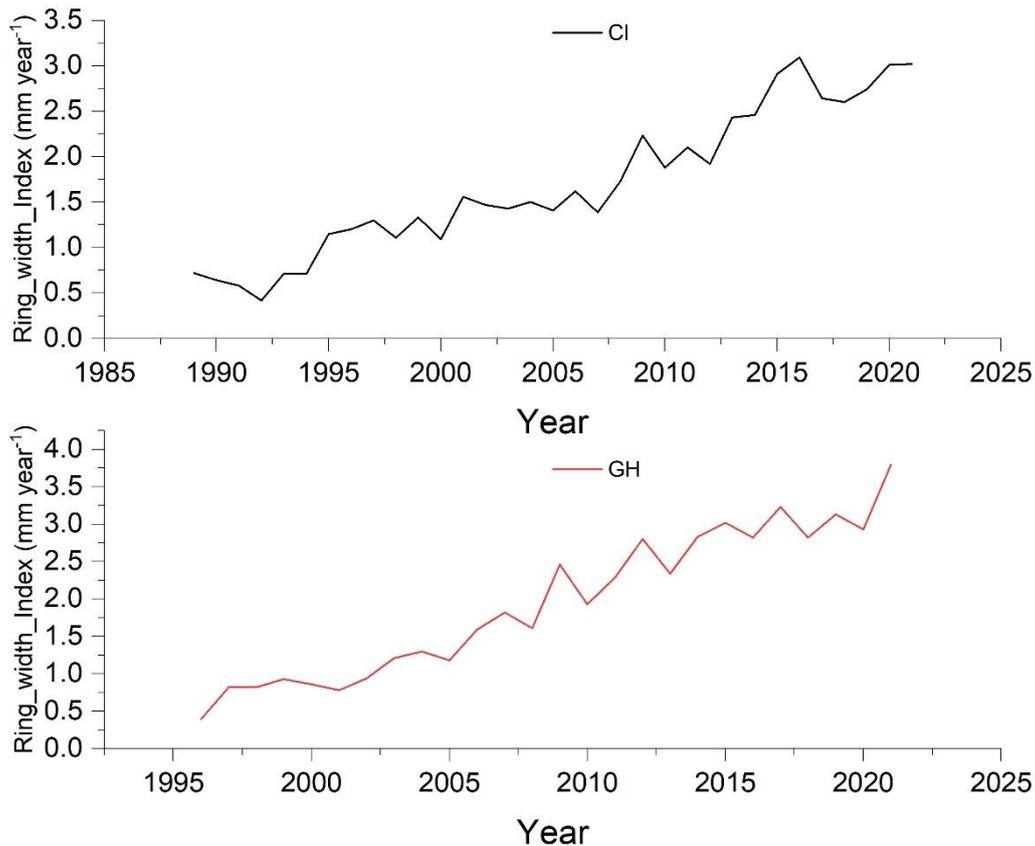
The tree-ring series showed similar growth patterns of the cocoa trees within farms (5, 15 and 30 years old) and between sites (Ghana and Côte d'Ivoire) though the different varieties of cocoa were not taken into account. Generally, the trees stage showed a low growth trend at the juvenile stage to the aging phase. However, there was an irregular but constant increase growth throughout the year. The cumulative ring width increment showed individual tree growth rates. Differences were observed in the growth rate of the individual trees across the year within and between farm and sites (Fig 42). The mean radial width shows that growth of cocoa trees was irregular but increasing over the various years in both countries irrespective of the variety grown (Fig. 43). However, in Ghana the growth rate was increasing steadily than in Côte d'Ivoire.

**Table 16.** Descriptive statistics of tree ring width series across study sites

Parameters	Ghana			Côte d'Ivoire		
	5 Years	15 Years	30 Years	5 Years	15 Years	30 Years
Number of samples	3	3	3	3	3	3
Age range (Year)	18 -19	18 -22	21- 27	14 -16	16 -23	24 -34
Time span	2004-2022	2001-2022	1996-2022	2007-2022	2000-2022	1989-2022
Radial width (mm year <sup>1</sup> )	1.80 ± 0.76	2.48 ± 1.17	2.25 ± 1.14	1.92 ± 0.88	2.58 ± 1.05	1.68 ± 0.72
Mean GLK %	73	68	68	74	78	68
Mean TV-BP	1.48	1.5	2.28	1.42	1.05	1.33
Maximum (mm)	3.71	4.34	3.51	3.5	4.29	3.22
Minimum (mm)	0.61	0.51	0.4	0.67	0.78	0.42



**Figure 42.** Cumulative radial increment growth of individual cocoa trees from Ghana (GH) and Côte d'Ivoire (CI) 30Yrs:15Yrs:5Yrs = 30, 15, and 5 years old farm



**Fig. 43.** Mean radial growth of cocoa stems for both countries GH = Ghana and CI = Côte d'Ivoire

#### 4.4.2 Relationship between ring width index of cocoa and climate parameters (precipitation and temperature)

##### 4.4.2.1 Correlation between ring-width index and rainfall and temperature for both countries

The analysis of Pearson's product-moment correlation shows that there was no correlation between precipitation and cocoa tree ring width (Table 17) in Ghana and Côte d'Ivoire respectively. Table 18 shows that temperature was significantly correlated with cocoa tree growth in both countries. Statistically, variations were observed between annual precipitation and mean temperature and ring width index for both countries when these three variables were correlated together (Figure 44 and 45). Yet the ring-width index (RWI) of cocoa correlated positively with mean annual temperature (Figure 44d and 45d).

**Table 17.** Pearson's product-moment correlation of tree ring width, precipitation and temperature

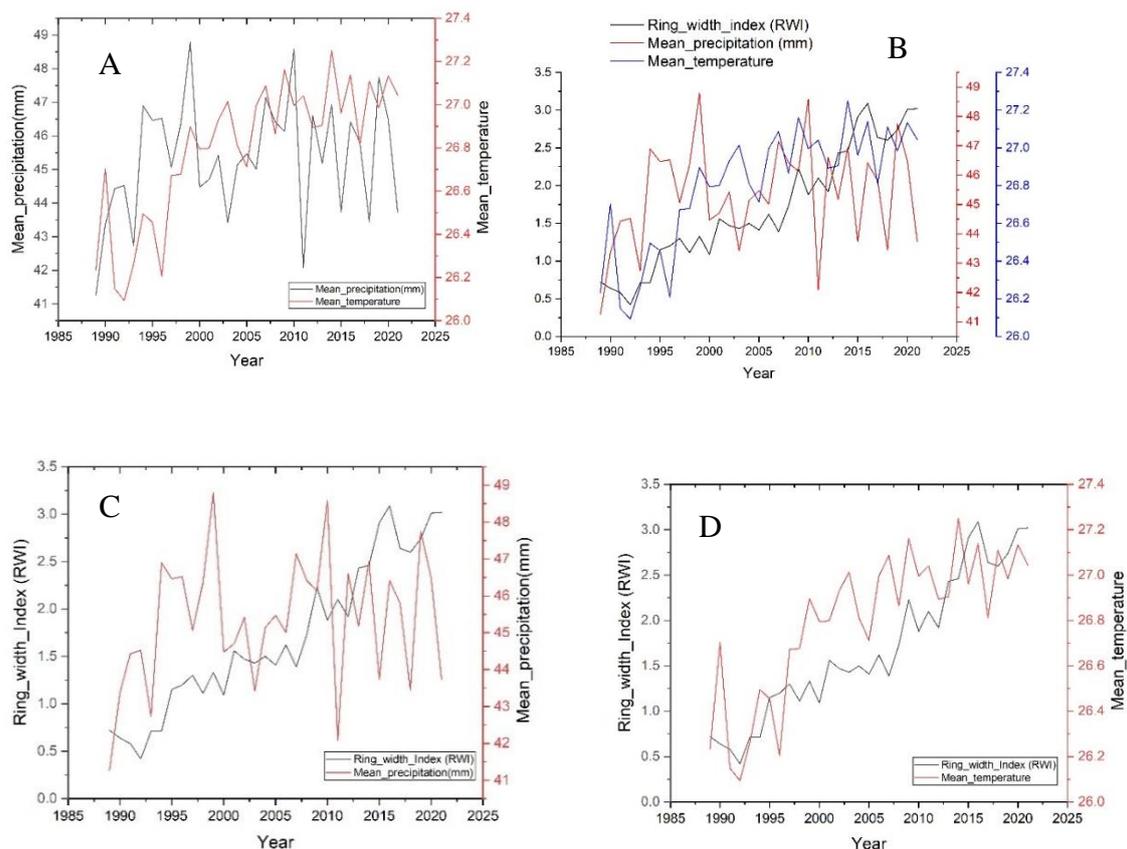
Variables	Ghana			Côte d'Ivoire		
	T	df	p-value	T	df	p-value
Precipitation	0.6857	24	0.4994	10.0741	9.72182	9.36957
Temperature	2.755	24	0.011*	6.6934	31	1.74E-07*

ns= no significant different (p>0.05), \* = significant different (p<0.05)

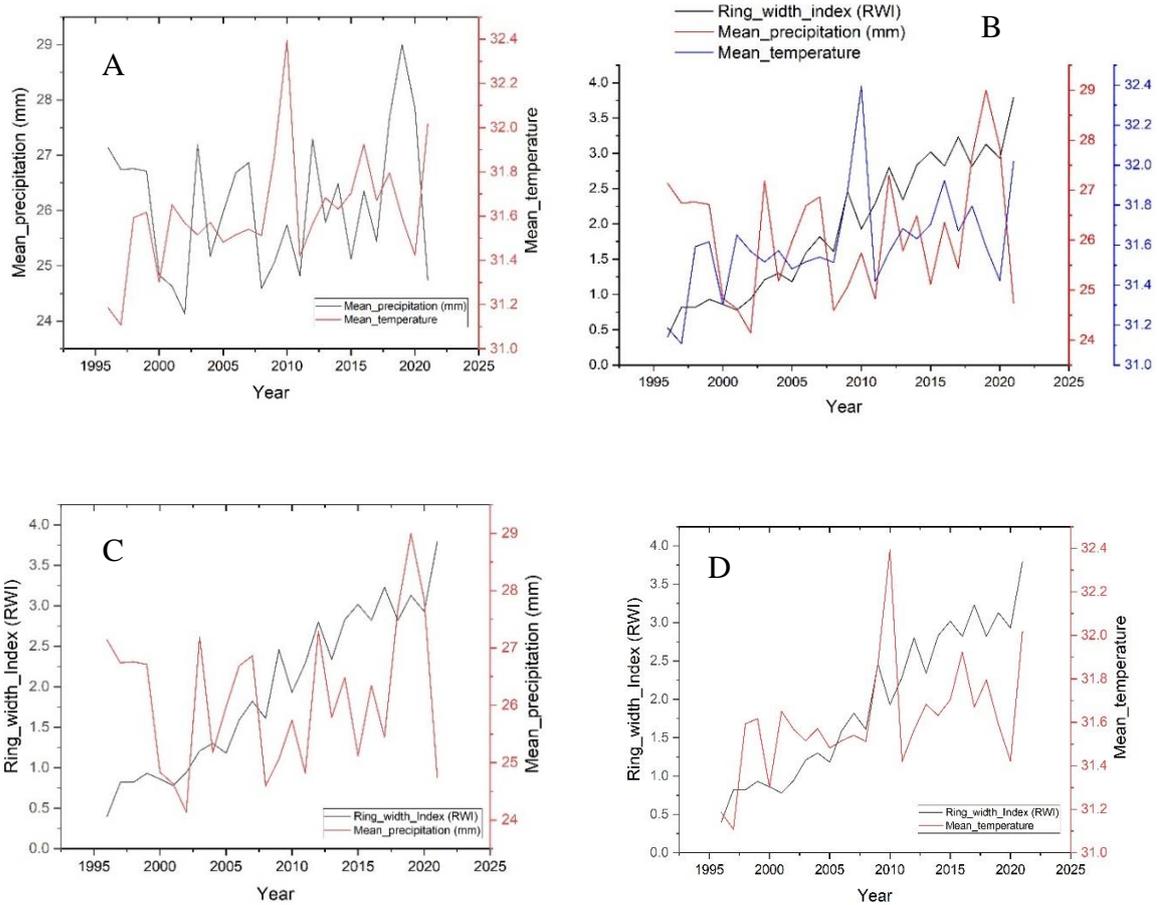
**Table 18.** Correlation between chronologies of tree ring and local climatic parameters from Ghana and Côte d'Ivoire

Country	Standard chronologies based on ring width index (RWI)	
	Mean of rainfall	Mean of temperature
Ghana	0.13 <sup>ns</sup>	0.49*
Côte d'Ivoire	0.18 <sup>ns</sup>	0.76**

Note: significant codes: p< \*\*0.01, \*0.05, ns = not significant



**Figure 44.** Correlation between ring-width index and rainfall and temperature (a) mean annual precipitation and temperature between 1989-2022 (Côte d'Ivoire) (b) correlation between ring width index (RWI) mean annual precipitation and temperature (c) correlation between ring width index (RWI) and mean annual precipitation and (d) correlation between ring width index (RWI) and mean temperature for Côte d'Ivoire.



**Figure 45.** Correlation between ring-width index and rainfall and temperature (a) mean annual precipitation and temperature between 1996-2022 (Ghana) (b) correlation between ring width index (RWI) mean annual precipitation and temperature (c) correlation between ring width index (RWI) mean annual precipitation (d) correlation between ring width index (RWI) and mean temperature for Ghana.

#### 4.4.3 Variations in anatomical vessel anatomical traits

Across all individual trees, vessel traits showed significant difference between the two study sites (Table 19). Vessel size (MVA, MVTD, MVRD, VN and VD) was significantly different at ( $p < 0.001$ ) within sites. Total vessel area percentage (%) was significantly higher across sites (Côte d'Ivoire:  $8.347 \pm 3.449$ ) than in (Ghana:  $6.618 \pm 2.509$ ). The vessel number was significantly higher in Ghana (80.09) compared to that of Côte d'Ivoire (73.62)

Comparison of wood anatomical traits across the various farms within Ghana and Côte d'Ivoire showed that the individual trees varied with high amplitude  $CV > 75\%$  in some farms, this was observed for Total vessel area in almost all the farms in both countries (Table 20a-b). Whereas vessel number varied across farms in Ghana with the 30 years old farm having the highest vessel number (99.01) followed by the 5 years old farm (74.46) and the 15 years old farm (65.94) (Table 20a), vessel number was observed to decrease with tree age in Côte d'Ivoire 5

years old farm had the highest vessel number (80.72) followed by 15 years old (73.71) and the 30 years old (62.55) cocoa farm (Table 20b).

**Table 19. Descriptive statistics and variations in anatomical vessel traits**

<b>Variables</b>	<b>CI</b>	<b>GH</b>	<b><i>p</i>-value</b>
TVAP (%)	8.347 ± 3.449 <sup>a</sup>	6.618 ± 2.509 <sup>a</sup>	< 0.001
TVA (mm <sup>2</sup> )	0.006 ± 0.003 <sup>b</sup>	0.007 ± 0.003 <sup>b</sup>	0.001
MVA (mm <sup>2</sup> )	0.007 ± 0.003 <sup>a</sup>	0.006 ± 0.002 <sup>a</sup>	< 0.001
MVRD (mm)	0.091 ± 0.018 <sup>a</sup>	0.076 ± 0.016 <sup>a</sup>	< 0.001
MVTD (mm)	0.094 ± 0.019 <sup>a</sup>	0.086 ± 0.018 <sup>a</sup>	< 0.001
NV	73.62 ± 24.71 <sup>a</sup>	80.09 ± 37.29 <sup>a</sup>	< 0.001
VD (N/mm <sup>2</sup> )	0.001 ± 0.001 <sup>a</sup>	0.001 ± 0.001 <sup>a</sup>	< 0.001

CI: Cote d'Ivoire GH: Ghana, TVAP: total vessel area percentage (%), TVA: total vessel area (mm<sup>2</sup>), MVA: Mean vessel area (mm<sup>2</sup>), MVRD: Mean vessel radial diameter (mm), MVTD: Mean vessel tangential diameter (mm) NV: vessel number, VD: vessel density (N/mm<sup>2</sup>)

**Table 20a-b .Variations in anatomical vessel traits across farms of each country**

**20A**

<b>Variables</b>	<b>Ghana</b>					
	<b>5Yrs</b>	<b>CV %</b>	<b>15Yrs</b>	<b>CV %</b>	<b>30Yrs</b>	<b>CV %</b>
TVAP (%)	6.001 ± 1.676	27.9	5.59 ± 2.291	40.9	8.159 ± 2.565	31.4
TVA (mm <sup>2</sup> )	0.357 ± 0.163	45.6	719.01 ± 302.80	420.4	1222.20 ± 376.69	308.4
MVA (mm <sup>2</sup> )	0.005 ± 0.002	32.2	0.006 ± 0.002	39	0.006 ± 0.002	38.2
MVRD (mm)	0.069 ± 0.012	18.5	0.08 ± 0.016	19.6	0.078 ± 0.017	22.1
MVTD (mm)	0.082 ± 0.016	20.1	0.087 ± 0.018	20.3	0.088 ± 0.019	22.3
VN	74.46 ± 33.71	45.3	65.94 ± 30.95	46.9	99.01 ± 38.50	38.8
VD (N/mm <sup>-2</sup> )	0.001 ± 0.001	73.4	0.001 ± 0.00	47.5	0.002 ± 0.001	60

**20B**

<b>Variables</b>	<b>Cote d'Ivoire</b>					
	<b>5Yrs</b>	<b>CV %</b>	<b>15Yrs</b>	<b>CV %</b>	<b>30Yrs</b>	<b>CV %</b>
TVAP (%)	9.025 ± 3.78	41.88	7.314 ± 3.064	41.90	8.676 ± 3.38	67.27
TVA (mm <sup>2</sup> )	744.99 ± 3110.27	417.49	1338.561 ± 3963.48	296.10	108.45 ± 1047.05	308.32
MVA (mm <sup>2</sup> )	0.0075 ± 0.005	62.30	0.008 ± 0.002	27.85	0.007 ± 0.002	0.6
MVRD (mm)	0.088 ± 0.026	29.71	0.096 ± 0.014	14.41	0.089 ± 0.014	8.29
MVTD (mm)	0.094 ± 0.025	27.25	0.101 ± 0.015	15.11	0.089 ± 0.015	8.43
VN	80.72 ± 26.04	32.25	73.71 ± 20.81	28.24	69.55 ± 25.74	50.25
VD (N/mm <sup>-2</sup> )	0.001 ± 0.00	57.78	0.001 ± 0.00	44.80	0.002 ± 0.001	0.09

## CHAPTER V

### 5.0 DISCUSSIONS

This chapter focused on discussing the results obtained from this research work and made comparisons with references to available data from elsewhere. The discussion came out with conclusions and gave possible suggestions and recommendations at the end for future study.

**Discussion on objective 1** Cocoa farmers and stakeholders' perceptions of sustainable cocoa agroforestry system through the cocoa supply chain

The high proportion of male respondents in this study suggests their advantage over females in the acquisition of land or that cocoa farming is male dominated in the two countries. Even though most women who ventured into cocoa farming in Ghana can acquire land through family inheritance it is not as common as men. In Côte d'Ivoire the female respondent were not many as compared to female respondents in Ghana suggesting their right to land acquisition or to head a farm. Also, the higher proportion of women owning cocoa farms in Ghana compared with that of Côte d'Ivoire may be related to cultural differences in the two countries. For instance, among the Akans in Ghana, husbands and wives can have access to land and farm relatively independently even if they are from the same households (Adjei-Nsiah *et al.*, 2007) which may not be the case in Côte d'Ivoire. The farmers are old with an average age range of 44 - 59 for Côte d'Ivoire and Ghana 44 - 62 indicating that most of the cocoa farmers were of economically productive age (Kouassi, *et al.*, 2021; Tauer, 2017; Mburu *et al.*, 2014) with number of children per household ranging from 2 to 5 in Côte d'Ivoire and 2 to 4 in Ghana. The high number of children found in Côte d'Ivoire per household could be linked to the high percentage of male respondents or that most of the respondents were in their reproductive age even though the number did not differ much from Ghana. Most of them were married and had up to senior high school education. The significant land area used in Ghana for cocoa plantation coupled with large size of plantation compared with Côte d'Ivoire could be attributed to fact that farmers in the study area in Ghana were more focused on cocoa production rather than the production of other cash crops such as oil palm and rubber as found in Côte d'Ivoire. It could also be that farmers in Côte d'Ivoire chose to cultivate rubber rather than cocoa which may be related to farm profitability (Breustedt & Glauben, 2007). Several studies (Chatelain *et al.*, 2010; Konate *et al.*, 2016; Ruf *et al.*, 2015) in recent times have also reported of declining farm size and number of cocoa plantations in Côte d'Ivoire which they attributed to the farmers willingness to cultivate rubber plantation due to the financial benefits it provides throughout the year. According to the findings, majority were dependent on cocoa farming only for livelihoods while few were engaged in other activities than cocoa farming for livelihoods and

survivals previous work by (Asamoah *et al.*, 2013 Baah *et al.*, 2012; Gockowski *et al.*, 2011) revealed largest population made up of mainly smallholder cocoa farmers are depending on production- base livelihoods.

Our results of farm history revealed that high percentage of cocoa farmers were landowners this corresponds to percentage of respondents being native residents of the study area even though non-natives residents can also become landowners by purchasing the land. Similar observation was made by (Kouassi, *et al.*, 2021; Ruf & Varlet, 2017) during their studies on the adoption of cocoa agroforestry. The percentage of respondents involved in the application of chemical fertilizer in Ghana as the only source of plant nutrient on their farms, may probably be due to the subsidized fertilizer scheme been implemented by the government of Ghana. However, a larger percentage of respondents from Côte d'Ivoire admitted to not using any soil amendment or chemical application on their farms which implies that the crops depend on the soil system for available nutrients (self-sustaining). The reason they practice this may be related to lack of fertilizer subsidies high cost of chemical fertilizers. Several of them also admitted practicing agroforestry on their farms when asked the type of plantation they have this ascertain work done by (Kouassi, *et al.*, 2021) on barriers to agroforestry adoption he noticed a high percentage of farmers about 50.2 to 82.1% were willing to plant trees on their farms in Côte d'Ivoire. Our study suggest that some cocoa farmers were practicing cocoa agropastoral (cocoa agroforestry/ small ruminants/poultry) on their farm as means of diversification of income and to improve soil fertility status at least 20 % from Côte d'Ivoire and 7.9 % from Ghana.

Agroforestry is part of the package of good agriculture practices that is a safe, healthy and sustainable production condition of cocoa. From this study, many farmers traditionally practice cocoa agroforestry on their farms but their level of knowledge about it was low among the cocoa farmers in the study area of both countries. This may be because of limited training received on agroforestry by cocoa farmers in the two countries as was expressed by the farmers. According to Domínguez & Shannon (2011), farmers manage their lands having four different reasons in mind (i) the economic expectation from the property they are using in this case the land, (ii) how the farmland should look, (iii) ethical reasons and (iv) natural risks. (Michon *et al.*, 1986) has established that agroforestry systems would be interesting to farmers, if the farmer understands and see the importance of diversification, and the corresponding ecological and economic stability and risk minimization offer by the system rather than expected highest possible yield. Apart from lack of knowledge of agroforestry, many other reasons account for the limited adoption and practice of agroforestry such as absence of subsidies, economic viability, soil quality, age of the farmer and land ownerships. Recent studies (García de Jalón

*et al.*, 2018; Kouassi, *et al.*, 2021) have shown that landownership is frequently a barrier to adoption of new technological practices on farm and farmers do not like to plant trees on fertile soils but rather on marginal soil where farming is difficult. This is in line with our observations made from the cocoa farmers farm in Ghana and Côte d'Ivoire where most farmers see agroforestry as non-profitable system imposed on them by the government to practice.

In addition, our results demonstrate that cocoa farmers were not aware of soil organic carbon (Cook & Ma, 2014) or its management (Sánchez *et al.*, 2016). The lack of awareness among farmers in the study communities reflects their level of exposure to the term soil carbon or its management. According to the result the only source of information on soil carbon to these farmers has been Agricultural extension officers and farmer to farmer or through personal observations (that is when the soils are loose, dark and the crops grow vigorously, they consider this to be as a result of dead materials on the soil surface (Kenfack Essougong *et al.*, 2020) Increasing soil organic carbon content under the cocoa production system is important for soil quality and sustainable production (Bünemann *et al.*, 2018). Apart from climate conditions, it is crucial to increase soil carbon on farmers farm for agronomic and environmental purposes (Robertson & Hamilton, 2015; Zhao *et al.*, 2015).

Accordingly, farmers perceived that their management practices could facilitate soil carbon loss from their farms. However, they are mostly not aware of the practices that can reduce its loss although several views were raised by some. Soil carbon management by the cocoa farmers is also a key to achieving sustainable development goals 2, 13 and 15 which are the plans of stakeholders and policy makers (Hamidov *et al.*, 2018; Lal, 2018; Rodrigues *et al.*, 2021), but achieving these goals in our smallholder farmers' farm in Ghana and Côte d'Ivoire is far from reality due to poor knowledge of farmers. The result further revealed a lack of knowledge of biodiversity. Many of the farmers were unaware of biodiversity in both countries and it seemed to be new to them. The high percentage of respondents not having any knowledge of these three sustainable issues (agroforestry, soil carbon and biodiversity) meanwhile they are always cultivating the land, calls for raising awareness as far as cocoa agroforestry upscaling, climate change mitigation and biodiversity conservation is highly concerned.

Besides, larger percentage of farmers have no knowledge of the approaches to be used to achieve sustainable agroforestry system, strategies to reduce soil carbon loss and mitigate climate change, reduce biodiversity loss and improve the soil system under cocoa production, probably due to lack of research providing clear understanding these issues. On the contrary, some farmers were knowledgeable about the strategies to be used to achieve them (Joon *et al.*, 2022). According to Ingram *et al.* (2018), most farmers lack in-depth scientific knowledge

of sustainable soil management. This is in the case of most of our cocoa farmers in Ghana and Côte d'Ivoire. This research suggests that there should be more farmer participatory research in these two countries involving farmers in research concerning sustainable development. Public sector stakeholders from the ministries of Land and Forestry, Food and Agriculture, and Environment, Science and Technology (Table 7 & 8) highlighted the need to demonstrate agroforestry on farmers' fields for farmers to emulate, education on the benefits to landowners and farmers among others.

Generally, there were varying perceptions of how to achieve sustainable agroforestry among stakeholders (farmers, policy makers and researchers) with varying cultural and educational backgrounds. Some farmers express the need for financial support from the government to be able to practice agroforestry on their cocoa farms. Farmers also perceived that if the technical staff from the forestry service and extension officers from the cocoa health and extension division of Cocoa board assist them by training them and they follow advice they would be able to achieve sustainable cocoa agroforestry on their farms which would reduce biodiversity loss and mitigate climate change. Stakeholders' awareness and understanding of the approaches varied from that of the cocoa farmer who is always cultivating the soil (Practice *et al.*, 2020). With these differences in response, it is necessary for stakeholders to come together and collaborate on the best ways to achieve sustainable agroforestry system in these cocoa communities. Sustainable in terms of increasing high value product, improved management costs, and environmental benefits that would really improve the local supply chain of cocoa in Ghana and Côte d'Ivoire. This is also a clear need of reinforcement of network among stakeholders in the two countries who aim to promote and achieve sustainable cocoa agroforestry systems in these countries.

The result of the multinomial logit regression model, has highlighted the significance of demographic factors such as age, gender, education level, ethnic group in cocoa farmers' awareness and perception of sustainable cocoa agroforestry and soil carbon management, biodiversity, and causes of climate change, management practices that can reduce soil carbon loss confirming the findings of previous studies which show how socio-demographic factors influence individual farmers' awareness and perception of the concept such as climate change, and agroforestry (Agwu *et al.*, 2018; Kouassi, Gyau, *et al.*, 2021; Reeg, 2011). The awareness of the respondents of agroforestry, soil carbon and biodiversity were positively influenced by educational level. This implies that farmers with higher educational levels are more likely to get access to information related to agroforestry, soil carbon management and biodiversity in the study area than respondents with low educational background. In addition, farmers'

perception of causes of climate change was positively influenced by the farmers' demographic characteristics such as country and village of a respondent implying communities from different villages have different perceptions on the causes of climate change and one country is more knowledgeable about the causes of climate change. According to this findings, high proportion of awareness of climate change and observed changes in its variable such as temperature, rainfall, drought and flood was obtained this ascertained with the several studies conducted in Africa particularly in West Africa on the awareness climate change and changes observed in temperature, rainfall, drought and flood by farmers and households (Amos *et al.*, 2015; Nzeadibe *et al.*, 2012). Increase in temperature and decrease in rainfall was experienced in many parts of West Africa (Bernard, 2014; Owusu *et al.*, 2019; Soro *et al.*, 2016). The multinomial logit regression model results further revealed that it does not take the respondents educational background or other demographic information to be aware of changes in rainfall, temperature, flood or drought as soon as they belong to a community, village or country they may be experiencing these changes.

More so, awareness of management practice, benefits of conserving biodiversity and storage of soil carbon were negatively influenced by respondents' village and country. In studies on factors and barriers to agroforestry adoption, researchers have shown how socio-demographic background of respondents are potential determinants that influence decision making of farmers to adopt or practice new innovations and technologies (Danquah *et al.*, 2015; Nkamleu, 2005, Kouassi *et al.*, 2021; Clearfield and Osgood, 1986). In this study age of farmer, residential status, country, village and gender had no influence on the farmer's awareness or knowledge about agroforestry and soil carbon management in their farms. This clearly shows that awareness and adoption are different concepts when it comes to farmers' decision making to adopt or practice any new technology. Our study suggests that it does not take age, gender, country, village, or residents to be aware or knowledgeable about a concept or term, but education does. Therefore, farmers, particularly farmers in the study area, need education to be aware of technologies they have already been practicing on their farms.

**Discussion on Objective 2.** Amount of soil carbon sequestered and concentration of soil nutrient across cocoa agroforestry farm (year) and soil depths

Cocoa production has been of great economy importance to the leading producers particularly Ghana and Côte d'Ivoire. Understanding the response of soil properties to the impact of these systems is necessary for the implementation of effective strategies to improve the management of plant nutrients and carbon sequestration of the system. The surface soils are modified directly by cultivation therefore the most relevant to assess management's impact on nutrient status and other soil properties. There were statistical differences in soil physico-chemical properties based on farm location (5, 15 and 30 years old) in Ghana and Côte d'Ivoire. According to (Field *et al.*, 1998), soil bulk density is an indicator of soil compaction and soil health and affects infiltration, water holding capacity, root growth, plant nutrient availability and soil microorganism activity that influence key soil processes and productivity. Ideal bulk density for plant growth ranges  $<1.10 \text{ g/cm}^3$  of Clays ( $> 45\%$  clay) to  $< 1.60$  Sands, loamy sands (Field *et al.*, 1998). In agreement with a previous study, the bulk density of the soil increased with increasing soil depth especially in the soils of Ghana. This could be associated with the high organic carbon content which enhances aggregation and root penetration at the surface soil (Gebrekidan *et al.*, 2013; Wu *et al.*, 2018; Kaur *et al.*, 2020). At lower depth, an increase in bulk density in all the farm was observed, due to decreasing organic matter content with soil depth (Toru and Kibret, 2019).

Soil texture plays an important role in agriculture (Lal, 2007) because it determines soil characteristics that affect plant growth. In addition, soil texture determines the extent of root litter decomposition and rhizospheric microbial respiration (Silver *et al.*, 2005). In this study, the investigated soils were characterized by sandy clay loam soils for the 5-, 15- and 30-year farms in Ghana while in Côte d'Ivoire, it was sandy loam soil in the 5 years old farm, loamy sand in the 15 years old farm and sandy clay loam in the 30 years old farm. The farms in Côte d'Ivoire have relatively high sand content. Sandy soils tend to have lower water-holding capacities and can have negative impact on plant growth (FAO, 2005). Soil pH values in the soils of Ghana were found to be higher than in Côte d'Ivoire suggesting the severe soil disturbances in these farms of Côte d'Ivoire as disturbances can cause inevitable changes in soil pH or lack of soil organic matter. In this study, soils of Côte d'Ivoire are considered to be strongly acid soils and moderately acid to neutral in Ghana according to USDA description of soil pH range. The relatively high surface total nitrogen accumulation in these farms were as a result of litter decomposition and nutrient recycling or addition of inorganic fertilizers on the

surface (Boutton and Liao, 2010; Mao and Zeng, 2010). General patterns about the available nitrogen and potassium varied completely among the farms. This may be due to variation within sites, and soil type. Higher total and plant available phosphorus recorded at 0-15 cm soil depth in all farms in both countries. The higher concentration in the surface soil may be due to uplift of nutrient by the deeper root of associated trees particularly in Ghana.

Soil pH is a key component of soil fertility. The values of pH were analyzed to further consider its relation to organic carbon, available nitrogen, phosphorus, potassium (OC, N.P.K). Significant and negative correlations patterns were observed between soil pH and these soil properties. Surprisingly, pH influenced soil organic carbon in the soils of Ghana particularly at soil depth 0-15 cm than in Côte d'Ivoire, implying that as pH increases, organic carbon content also increase which may be due to decomposition of organic matter in the surface soil than in the 15-30 cm but might be equally driven by nutrient availability, and environmental factors (Stock *et al.*, 2019; Chen *et al.*, 2020; Zheng *et al.*, 2019). The result revealed that available nitrogen was constant across all the farms in Ghana as soil pH increases. This suggests that at a certain pH value nitrogen is not readily available in these soils. A negative correlation was obtained between pH and available nitrogen in Côte d'Ivoire. Meaning that the pH 4.5 of soils of Côte d'Ivoire does not support nitrogen availability and thus decreases at both soil depths in the 5- and 30-year-old agroforestry farms. However, in the 15 year old farm at 0-15 cm soil depth available nitrogen increased at pH value increase. (Jackson, 1973; Athokpam, *et al.*, 2013). Similarly, as soil pH increases, soil available phosphorus was at constant in farms (5, 15 and 30 years) old in both countries. Suggesting that phosphorus availability in these soils does not increase with pH values. But phosphorus availability was influenced by soil pH at both depths in the 30 years old farm. Further results indicated that available potassium was constant or decreased as soil pH increases. Comparable results were obtained by (Singh and Mishra, 2012). The two sites recorded highest TOC, TN,  $\text{NH}_4^+\text{-N}$ ,  $\text{NO}_3^-\text{-N}$  and POXC in the surface horizon and then decreased sharply with soil depth. The higher status of mineral nitrogen ( $\text{NH}_4^+\text{-N}$  and  $\text{NO}_3^-\text{-N}$ ) in these soils may be due to high nitrification. The presence of high  $\text{NH}_4^+\text{-N}$  and  $\text{NO}_3^-\text{-N}$  in these soils indicates their inter-relationship in N-transformation in the soil. The result conforms with that of Walia *et al.* (1988) and Hu *et al.* (2017), who showed that soil  $\text{NO}_3^-$  and  $\text{NH}_4^+$  concentrations decreased with increasing soil depth in all afforested stands. The increase in soil total organic carbon might have enhanced the N availabilities and soil N minerals  $\text{NO}_3^-$  and  $\text{NH}_4^+$  across the different soil depths. Killham (1986), showed that microorganisms such as heterotrophic organisms use organic substances as both a carbon and an energy source and

can obtain part of energy from oxidation of  $\text{NH}_4^+$  or organic nitrogen compounds. Example of such microorganisms are fungi. This might count for the reason why fungi population was higher in the 30 years old farm at 15-30 cm in Côte d'Ivoire (Fig 25). The permanganate oxidizable carbon (POXC) fraction, determined by the chemical SOM fractionation method, is one of the most reliable indicators used for soil health assessment, including the evaluation of short- and long-term impacts of soil management (Skjemstad *et al.*, 2006; Culman *et al.*, 2012; Hurisso *et al.*, 2016). It has been demonstrated that labile SOC fractions such as POXC control microbial community structure and composition rather than SOC content under changes in soil type and land use (Morrow *et al.*, 2016). In this study, it might be the reason why total soil microbial population was higher in the surface soil (0-15 cm) particularly in Ghana soils.

This section discussed the effect of cocoa agroforestry management on soil organic carbon sequestration at soil depth, farm (5, 15 and 30 year) and site level. Soil carbon is an important soil property influenced by many factors including land use types and soil depth (Tesfaye *et al.*, 2016). Soils from this study have statistically higher soil organic carbon content (SOC g/kg) in the topsoil 0-15 cm depth and lower in the 15-30 cm depth in both countries which may be due to increase decomposition rate taking place in the topsoil. Our results agree with several previous studies (Yang *et al.*, 2013; Zhao *et al.*, 2014; Han, Li & Tang, 2015) who observed a decrease in TOC and TON contents along with soil depth. The soil carbon sequestration density (SOCD) of these soils also decreases with soil depth across farms in both countries. This suggests that the amount of organic matter in the soil influences the carbon mineralization processes and this has a direct influence on the amount of nutrient in the soil. Our result is supported by previous studies which have shown that soil bulk organic carbon concentrations and other soil properties can have significantly different values depending on the land use types and sampling depth (Liu *et al.*, 2018; Hopkins, 2006; Fu *et al.*, 2004). However, the presence of organic carbon in the sub surface soil (15-30 cm) even though not in a large quantity could be an indication for preserving soil organic carbon in soil for long time (Harper and Tibbett, 2013).

Comparatively, at farm level, the results of this study revealed higher soil organic carbon density (SOCD) in the 15- and 5-year-old farm in Côte d'Ivoire and in 15- and 30-year-old farm in Ghana. These differences may result from changes in soil surface, litter composition and decomposition rate of organic matter (Liu *et al.*, 2018; Yu *et al.*, 2022). The amount of organic carbon of these farms may be closely related to the composition of plants, which also may depend on the type of aggregate present in the soil (Yu *et al.*, 2022). The variations in SOCD

between farms could also be attributed mainly to management practices different farmers employed at farm level.

In general, some of the investigated cocoa agroforestry farms were characterized by small number of forest trees related to cocoa trees and shade density, thus, the litter composition was poor leading to less amount of SOCD sequestered in these farms. This confirmed study by many authors who observed higher soil organic carbon in cocoa agroforestry compared to monoculture (Häger, 2012; Dawoe *et al.*, 2014). The positive correlation between soil organic carbon and P (C-P) than carbon and nitrogen (C-N), indicate that phosphorus availability is highly dependent on amount of organic carbon present in these soils, especially in Ghana soils (Fig. 23). All of these reflect the linear interactions among the soil nutrients in the studied soils. Suggesting that it is not enough to clarify the soil quality variation only based on studies on the soil nutrient contents in these systems, the interactions among soil nutrients must be considered. Previous work by (Wang *et al.*, 2018), supports this finding which showed that, the soil C/P indicates the ratio of carbon to total phosphorus present in organic matter or other substrates, which is also an important indicator for the mineralization and storage of soil phosphorus. The contents of soil nutrients are the important parameters of soil quality and the composition of organic matter (Huang, 2000)

Based on the PCA results of the entire soil sample, soil physical, and chemical properties varied between soil depths and sites (Ghana and Côte d'Ivoire). This may be due to the influences of inherent parent rock, climate, vegetation, and management practices, or higher accumulation of organic matter at surface soil depth (Fig. 24). The linear regression model indicates that pH has significant influence on soil organic carbon, phosphorus, nitrogen and potassium in the entire soil rather than generalized additive model (Fig. 26). Soil nutrient elements are closely related and interact in the ecosystem (Zhu *et al.*, 2013).

**Discussion on objective 3.** Soil microbial populations communities across cocoa agroforestry farm (year) and soil depth

Microscopic analysis of the soil samples revealed a generally high presence of arbuscular mycorrhizal and mycorrhizal colonization in all the farms and soil depths (Stutz and Morton, 1996; Sieverding, 1991) reflecting the mycotrophic nature of the cocoa plantations. The result showed that the fungal spores were statistically different only at the site level and soil depth after ordination non-Metric Multidimensional scaling (NMDS) but were similar to all farms in both countries. The results implied that different management and soil chemical properties might have led to the diversity of spores in the two different countries. For instance, soils with low pH are dominated with fungi than bacteria because fungi can tolerate a wide pH range (Koide and Mosse, 2004; Jeffries and Barea, 2001; Edy *et al.*, 2019). While farm practices such as the type and amount of fertilizers, pesticides and fungicides applied are likely to be the most significant factors influencing the soil fungal spore or microbial communities in general on these farms, other major factors that could regulate the variation in fungal spores in this study is likely the soil type, soil moisture, temperature, rainfall, and plant communities and soil chemical properties (Johnson *et al.*, 2006; Davison *et al.*, 2015). The similarity found in the spores across the farms may be due to the mixed vegetations and host (cocoa) preferences of Arbuscular Mycorrhizal Fungi (AMF) (Smith and Read, 1997).

Fungi and bacteria have a symbiotic relationship where each microorganism benefits from the presence of the other. When bacteria break down plant matter, they produce molecules that are toxic to themselves. Fungi protect bacteria from these toxic molecules in exchange for food and shelter (Braham *et al.*, 2018). When the populations of these symbiotic microbial partners are out of balance, there is increased potential for pathogenic fungi or bacteria to infect the plant. Many studies have shown the important role soil microorganisms play in ecosystem processes such as decomposition, carbon cycling, nutrient cycling, and soil aggregate formation (Dangi *et al.*, 2018; Nannipieri *et al.*, 2017; Chaudhry *et al.*, 2012).

Analysis of soil bacteria and fungi (yeast) population show a depletion of fungi in soils of Ghana and an increase population of bacteria compared with soils of Côte d'Ivoire. Soil bacteria population in this study decreased with increasing soil depth in both countries particularly in Ghana in each of the three farms (5, 15, and 30 years) suggesting that bacteria is the dominant group of microbes in surface and subsurface soil in the farms of Ghana. This may be due to the availability of organic carbon, and favourable pH range of the soil of Ghana compared to Côte d'Ivoire. This confirmed previous studies who saw a decrease in microbial population with soil

depth in both agricultural land and forest (Gomoryova *et al.*, 2020; Stone *et al.*, 2014). According to Stone *et al.* (2014), there is a strong relationship between microbial community and organic carbon, and carbon availability decreases along soil profile causing bacteria population to decrease. However, this study shows a higher bacterial population relative to fungal population in the 30 years old cocoa farm in Côte d'Ivoire at both soil depths and even higher in the 15-30 cm depth where soil carbon storage is low and lower in 0-15cm where soil carbon storage is higher.

The differences observed in soil depth are likely due to agricultural practices among the farmers in the two countries. Although some residues may be buried during land preparation or harvest which will also be a significant source of carbon at higher soil depth. Fungi population count on the other hand, was similar at the different soil depths in Ghana but higher in Côte d'Ivoire soils. Primarily, fungi population increases along soil depth. Suggesting that the population of fungi was higher at lower depth 15-30 cm than in the upper depth 0-15 cm. This finding disagreed with Bhattacharya and Jha (2011) who found that fungal population was always higher in surface soil and decreased with increasing depths. According to other previous studies, fungi can reside in deeper layers of the soil profile and contribute to key processes, such as soil formation, nutrient cycling, form associations with plant roots to enhance water and nutrient uptake by plants (Schultz *et al.*, 2013; Lamit *et al.*, 2017; Tojuet *et al.*, 2016).

Total microbial population count was generally influenced by soil depth and the population was mostly higher in the 0-15 cm depth than in 15-30 cm. The sudden decrease in the total population at 15-30 cm may be attributed to the exhaustion of the easily available soluble organic nutrients.

This study shows a higher bacterial population in the 15 and 30 year old plantation in Côte d'Ivoire than the other farms and in the 5 and 15 year old farm in Ghana. These could probably be due to nutrient and pH status of the three farms. Farms with nutrient-poor conditions would turn to have low proportion of microbial populations compared to farms with high nutrient. These results agree with previous studies of Yang *et al.* (2013), Fierer *et al.* (2007) and Smit *et al.* (2007). Also, bacteria population can dominate agricultural soils with low soil carbon storage content. Fungi population was higher in the older farm (30 years) than the younger farms in both countries. We observed that the 30 years old farm in both countries were not frequently managed particularly in Côte d'Ivoire (i.e., minimal disturbance of the soil and almost left to fallow) as compared the 5 and 15 year old farm hence the higher population of fungi in this 30 years old cocoa farm. Previous works by Wal-drop *et al.* (2017); Jangid *et al.*

(2011) and Drenovsky *et al.* (2010), observed that frequent management of agricultural soil often disrupts soil fungal networks thereby decreasing the fungal population (abundance) relative to bacteria in agricultural soils.

Microbial biomass is a measure of potential microbiological ecosystem functioning (Rath *et al.*, 1998). From this study it was clear that soil microbial biomass carbon and nitrogen were generally affected by soil depth and that MBC and MBN were higher in the surface soil layer. This can be attributed to a relatively high input of fresh and readily decomposable organic matter (Fauzi *et al.*, 2006). Previous work by Parham *et al.* (2002), revealed that soil microbial biomass content decreased with increasing soil depth in all soils tested with an expectation of higher microbial biomass carbon in 20-30 cm manure treated soil than in the 10 -20 cm soil. Also, this study is supported by other studies (Xu *et al.*, 2017; Peng and Wang, 2016; Zhao *et al.*, 2016; Chen *et al.*, 2015). Concurrently, at farm level the MBC was higher in the 5 and 30 year old farm and MBN in 15 and 30 year old in both countries. The results indicate the impact of each system on the microbial population and microbial biomass carbon and nitrogen content. The litter produced, the moisture content, the carbon level and nutrient availability and the microorganisms available to produce dissolvable organic carbon (DOC) depends on the plantation system and farm management practices (Lyu *et al.*, 2019; Phillips *et al.*, 2014). This study is also in conformity with Ramesh *et al.* (2013), who found increase in MBC under tree-based agroforestry system which was related to greater soil moisture and soil microbial diversity.

The results showed positive correlation between bacteria and fungi in the 15 and 30 year old farm in Côte d'Ivoire and negative correlation in farms of Ghana. Suggesting the relative abundance of bacteria versus fungi population in the soils of Côte d'Ivoire (Shi *et al.*, 2018). But the higher population of bacteria in soils of Ghana over fungi population may be attributed to the additions of chemical fertilizer to the soil which increase the nutrient status of the soil. Kang *et al.* (2005), and Kirk *et al.* (2004) also reported the increase in bacterial population in response to chemical fertilizers which may be related to a better nutrient status of the soil. In addition, bacteria and fungi exhibited significant relationships with soil carbon and nitrogen. In our study, the correlation between bacteria and soil total carbon and nitrogen was positive especially in soils from Ghana. This could explain the microbes' demand for resource or increase in response to resource availability in these soils (Kaiser *et al.*, 2014; Schneckner *et al.*, 2015; Wei *et al.*, 2017).

Knowing the types of microbes associated with a particular agroecosystem is crucial for taking appropriate management measures that promote crop production and carbon storage. The full-

length ITS sequence data from the combined UNITE-INSDDc dataset generates fungal sequences were classified into 008 operational taxonomic units (OTUs) using a 97% sequence similarity criterion (Tedersoo *et al.*, 2021). The dominant fungal community common to the cocoa agroforestry farms in Ghana and Côte d'Ivoire were dominated by the phyla *Ascomycota* and *Basidiomycota*. This finding is in line with other studies in both managed and natural forest systems (Tedersoo *et al.*, 2014, 2021; Zhang *et al.*, 2017). Previous studies in arid ecosystems showed that *Ascomycota* is the most dominant phyla, which may be due to the number of gene and trait they possessed to thrive in harsh environments and resist damage caused by antibiotics (Egidi *et al.*, 2019; Baldrian *et al.*, 2021) than other fungal phyla. *Ascomycota* are also known to be associated with nutrient and carbon metabolism due to its more genes. This could be the reason why *Ascomycota* become more dominant in managed systems such as cocoa agroforestry system that have low resource availability in terms of nutrients.

At the level of genera, phylotypes representing *Penicillium* were among the most dominant members of the fungal communities in these soils. *Penicillium* plays critical roles in decomposing and cycling organic matter and nutrients (Nath *et al.*, 2012). The fungal genera *penicillium* and *Humicola* can be selected as the key fungal species that can contribute to the cocoa production in these countries. *Penicillium* was found to exhibit plant growth-promoting (PGP) activity through indole acetic acid (IAA) and siderophore production, as well as P solubilization (Nath *et al.*, 2012; Radhakrishnan *et al.*, 2013).

#### **Discussion on objection 4.** Radial growth and anatomical response of *Theobroma cacao* to climate change

Tree-ring analysis allows to reconstruct historical growth and physiological responses of trees which can be used as key ecological indicators of environmental and climatic changes (Fan and Bräuning, 2017; Zhang 2015; Fritts, 1976). In the tropics, such information is greatly important both in understanding past climate variability and modeling tropical forests' response to future climate changes (Gebrekirstos *et al.*, 2014; Hiltner *et al.*, 2016, 2018) as well as for taking management interventions. As such, ecological information such as diameter growth rates, tree ages, regeneration and survival which are required for planning sustainable forest management can be obtained from tree rings relatively faster and with longer timescale than with alternative sources of information like Permanent Sample Plots (PSPs). Previous studies have shown that tropical dendrochronology has already been used to reconstruct past climate variability, to analyze life-time growth patterns, to estimate tropical tree age, to predict tropical forests' response to future climate changes, and to answer other ecological questions and their application in forest management (Rozendaal and Zuidema, 2011; Gebrekirstos *et al.*, 2014).

Cocoa tree in this study presented distinct growth ring boundaries. This distinctiveness of growth rings was also found by previous works on other West African trees (Boakye *et al.*, 2016; Sanogo *et al.*, 2016). Gebrekirstos *et al.* (2014), asserted that the presence of anatomically distinct, annual growth rings is the prerequisite for the development of correctly dated ring-width chronologies.

These findings are in line with study done by Alice Gargano (2020), during her master's degree on Ivorian cacao trees showed that cocoa trees form rings clearer in some regions than others. Tree growth rings are signs of the seasonality of tree growth and indicate how tree productivity relates to environmental factors (Worbes *et al.*, 2017). Growth rings are formed annually in tropical trees, when they shed leaves in the dry season such pattern in seasonality experienced by tree may induce complete cambial dormancy resulting in anatomically distinct tree-ring formation (Worbes, 1999; Gebrekirstos *et al.*, 2008; Spann *et al.*, 2016).

The cumulative ring width increment and mean radial growth of cocoa in each farm and between sites (Ghana and Côte d'Ivoire) showed an increasing growth trend with age. This is consistent with tree-ring series that showed lower initial growth rate and an increase as the cocoa tree aged. This suggests that tree growth is slow at younger age phase, but as they grow older above 30 years growth begins to decrease as seen in Fig. 30b for Côte d'Ivoire. This low growth rate at the initial production stage and continuous increase but irregular growth in the

following stage may be due to disturbance, competition to resources and CO<sub>2</sub> fertilization. It could also be that the cocoa crop at the initial production phase tries to acclimatize to the new environment (exposure to sunlight, root development, search for soil available nutrients and water to survive) after transplanting it. Therefore, implying that canopy formation soil water and nutrient availability may be a limiting factor that are necessary for radial growth at juvenile stage. Suggesting also that agroforestry trees must be established in field before cocoa seedlings are planted.

Previous study showed that cocoa plants are resistant to relatively high temperatures up to an average of 30-32 °C and a minimum of 18-21 °C. Alvim (1957), observed from his study that the growth of cocoa trunk positively correlated with temperatures rather than rainfall and diminished during periods of intense leaf flushing. Using tree-ring analysis in this study has shown positive correlation between mean ring width and annual mean temperature in Ghana and Côte d'Ivoire respectively, indicating that tree radial growth increases with increasing temperatures. It also suggests that increased temperature has an important role in the start of cambial activity (growth) (Chowdhury *et al.*, 2016; Sinha *et al.*, 2017) in both countries.

However, the correlation between annual rainfall and mean ring width was very weak suggesting that cocoa stem growth seems to be more affected by rainfall. This variation can affect cocoa yields because cacao trees appear to be extremely sensitive towards soil water deficiency.

According to the correlation analyses by Alice Gargano (2020), cacao tree rings seem to correlate with precipitation. This may imply that the correlation is weak, or no correlation was obtained between tree ring and precipitation.

The weak correlation observed in this study could be because of the reduction in monthly precipitation and this may induce cambial dormancy and tree-ring formation as suggested by Worbes (1999); Trouet *et al.* (2012). Previous study showed that dry periods with less than 100 mm per month for at least five months would limit the growth of cacao trees (Schroth *et al.*, 2016). Ideal climatic conditions are where the annual rainfall ranges between 1500 mm and 2000 mm and is well distributed throughout the year.

Regarding the cocoa growth and anatomical traits, the study suggests that cocoa trees form annual growth ring across all the farms in the two sites. Generally, larger vessels (area, length, and width) were obtained in tree ring of this study across the farms in both countries. However, anatomical features varied from one to another in terms of size, area, length and width, number and density across the various farms. This variation may be due to xylem hydraulic adjustment to rainfall and temperature variability in the two countries Ghana and Côte d'Ivoire. Previous

studies have reported about xylem hydraulic adjustment to rainfall and temperature (Lambers *et al.*, 2008; Fichtler and Worbes, 2012) and might be because growth of cocoa is highly dependent on rainfall or soil water availability (Schroth *et al.*, 2016). In the meanwhile, water availability is an important growth limiting factor for cocoa production. This implies that lower water availability or higher evapotranspiration can reduce vessel size but increase vessel density to ensure hydraulic safety (Fichtler and Worbes, 2012). However, under humid conditions trees increase xylem size and reduce vessel density to increase hydraulic efficiency as observed in this study. This suggests that vessel density is actively controlled by trees to cope with drought stress (Islam *et al.*, 2018). The study on tree ring and wood quantitative anatomy indicated disturbance signal in the wood annual rings and its eco-physiological response to climate variability.

## GENERAL CONCLUSIONS AND PERSPECTIVES

The present research falls under the context of global environmental changes that requires empirical evidence likely to meet the sustainability of land use and livelihood objectives through the agroecosystem. The study was focused on cocoa agroforestry system at farm level with the general aim to assess its effect on soil properties including soil microbial population and community, MBC and MBN, soil nutrient concentration and soil carbon sequestration, and the growth response of cocoa to climate variability in two regions of West Africa.

First, the study interviewed cocoa farmers on their perceptions of strategies to achieve sustainable agroforestry, reduce soil carbon and biodiversity loss and climate change mitigation through the cocoa supply chain. This interview includes relevant stakeholders who are key players to sustainable land use in the cocoa sector in Ghana and Côte d'Ivoire. Secondly, the study compares soil properties of three cocoa agroforestry farms (5, 15 and 30 years) and at two soil depths in Ghana and Côte d'Ivoire. The survey revealed a lack of sufficient knowledge about agroforestry, soil carbon management, and biodiversity conservation among the smallholder cocoa farmers in these countries. However, the farmers were very much aware of the drivers of climate change and mentioned deforestation and agriculture as the main drivers of it. They reported noticeable changes in climatic variables such as temperature, rainfall, drought, and flood and believe that climate will adversely affect their crops if they do not follow advice. Similar findings have already been reported that climate change will adversely affect cocoa production and reduce suitability areas.

The demographic factors that influence the farmers' perception/knowledge most in this study is education suggesting education is highly need for adoption and promotion of sustainable soil and land management through the cocoa supply chain in Ghana and Côte d'Ivoire. The study highlighted some strategies mentioned by the respondents. However, most of the respondents were not aware of a single practice they can employ on their farm to either mitigate climate change, conserve biodiversity, or reduce soil carbon loss rather they relate climate change mitigation actions to God. Even though there are some existing strategies within the cocoa supply chain such as climate smart agriculture practices, zero deforestation and many more. The results further show differences between stakeholders and the cocoa farmers in their response to how sustainable agroforestry can be achieved.

The cultivation system has a profound influence on soil properties analyzed in this study and appreciable effect was noticed within the various farms (5, 15 and 30 years old) within the two countries. Our comparison of the soil properties to the three different cocoa farms in Ghana

and Côte d'Ivoire is an effective way to illustrate which of these farms had the higher microbial population and sequestered higher soil carbon. The results indicate that 5 and 15 year old farms in Ghana recorded the highest microbial population and sequestered higher amount of soil organic carbon and in Côte d'Ivoire it was 15 and 30 years old farms which could be due to management practices. As there were wide variations between the individual farms (year), in terms of microbial population and biomass, soil nutrient concentration and soil organic carbon sequestration it is possible that farm age in this study, had no influence on the soil properties measured. The positive correlation between bacteria, yeast, total organic carbon and total nitrogen in Ghana and weak correlation in Côte d'Ivoire, show a strong relationship between bacteria and total organic carbon and nitrogen in these soils. The indication that the soil properties are mostly concentrated within the 0-15 cm soil depth (the surface soil), any small exposure through unsustainable management will disrupt these soil properties particularly, microbial community, soil carbon sequestration, cause soil dryness, and nutrient loss. Thus, the need for canopy formation even before cocoa seedlings are transplanted.

The analysis of cocoa wood features revealed that cocoa trees can be successfully used for dendrochronological studies with relevance for the management and restoration of the cocoa agroecosystems of West Africa. This can reveal amount of CO<sub>2</sub> captured by the plants, the deposition of toxic substance such as heavy metals in the cocoa tree, past climate variability, life-time growth patterns, tree age, and predict cocoa trees' response to future climate changes which can affect the growth and yield performance of the cocoa over a period of time. The cocoa tree forms distinct annual growth ring boundaries. The annual increment growth was similar between sites correlating positively with temperature. Yet, variations within the various farms were observed regarding the cumulative ring width increment of the individual trees. These variations have reflected in the quantitative wood anatomy of the cocoa trees which showed variations in vessel traits (vessel number and vessel area and vessel density) across the farms. This indicates that cocoa trees responds to temperature and rainfall variability through the adjustment of these vessel traits, implying that xylem vessel traits are more sensitive to climate variability.

## **PERSPECTIVES AND RECOMMENDATIONS**

Results of the present study provide relevant social and ecological insight on cocoa agroforestry system in West Africa. While it has important significance for the sustainable management of soils under the cocoa production system, similar studies can be carried out on the impact of associated trees on soil moisture and temperature, and their relationship with soil carbon storage in the cocoa production system to elaborate efficient soil management and conservation of biodiversity plans for Ghana and Côte d'Ivoire cocoa sector.

There was high level of lack of sufficient knowledge among the smallholder cocoa farmers of agroforestry, soil carbon and its management, biodiversity conservation and the strategies to be used to achieve them, therefore, this study recommends that effort should be made by government agencies, stakeholders, and NGOs to initiate programs to educate and train the rural farmers particularly cocoa smallholder farmers in West Africa on sustainable soil and land management within the cocoa agroforestry system. The study also calls for the need to increase the level of awareness about ecological benefits of sustainable soil management and restoration and reinforce network among stakeholders in Ghana and Côte d'Ivoire. This will help to promote and achieve sustainable cocoa agroforestry system in these countries. The strategies mentioned by some of the respondents such as cover cropping, biofertilizer application, and the introduction of poultry into their farms can be used as sustainable soil management practices to raise soil organic carbon and nutrient content on the cocoa farms, but this also call for education and awareness raising.

The study revealed high fungi population at increasing soil depth in 30 years old cocoa farm in Côte d'Ivoire, suggesting that cocoa plant health is associated with fungi. Therefore, future research can be considered in the use of fungi of these soils as inoculants for young cocoa seedlings. This may enhance nutrient uptake at an early age.

Future research is needed to further understand why MBC and MBN content varied within farms. With results of soil physicochemical properties, it necessary that future work should be directed to knowing how easily nutrients are leached out, and the rate of GHGs (NO<sub>2</sub> and CO<sub>2</sub>) emissions from these soils. Since the bulk densities are low and the textural class falls within sandy loam and sandy clay loam. This is critically required because cocoa farmers are keen in the application of chemical fertilizers which can be detrimental to the environment, particularly nitrogen and phosphorus. We suggest that the interactions among soil nutrients must be considered in future studies since this affect nutrient availability and uptake. More research is needed on carbon storage in both above and belowground for effective management towards

profitable cocoa production, climate change mitigation and biodiversity conservation. The study of cocoa wood features did not include the study of the amount of CO<sub>2</sub> captured by the cocoa trees from atmosphere using carbon isotopes therefore there can be study on this in future. This work could not provide significant difference between the parameters measured due to small observation size; therefore, we recommend that any future work in this form should consider increasing the sample size.

The results of soil properties and wood anatomical features, suggests sustainable management practices within the cocoa agroforestry system, the reinforcement of soil management and restoration actions are crucial for achieving future agriculture and forest sustainability. In this wise Ghana and Côte d'Ivoire can conserve and protect enough biodiversity on the cocoa farms, reduce soil carbon loss, restore the dead soils, mitigate climate change, and finally have a productive system. Soil management is the key factor to sustain increasing human needs in the near future.

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**APPENDEXES**

Survey Questionnaire (Farmers' Perception)

**Introduction**

I am a Doctorate student from University of Felix Houphouet Boigny, Côte d'Ivoire. I am currently undertaking research on **“impact of cocoa cultivation on soil carbon sequestration and microbial community under climate and land use changes”**. The purpose of these questions is to gather information about farmers' perception on the above subject. You have been selected to provide information about cultivation changes on biodiversity and climate change mitigation in the cocoa agroforestry systems here. Information and responses obtained from this study will be treated confidentially and use for academic purpose only and no commercial whatsoever. Everyone's idea is important and everyone has an opportunity to speak. There are no right or wrong answers; even negative comments are useful in gaining insight about the topic under discussion. Your participation is highly appreciated.

**Name of the interviewer ----- Questionnaire No-----**

**General information**

**Name of region -----, Name of District-----,**

**Name of village -----, Name of respondent-----**

**Geographical data of the Village.....**

**Geographical data of the Field.....**

**a. .** Examine the links between cultivation changes and the farmers' perception about climate change mitigation and biodiversity conservation in the cocoa value chain.

**I. Demographic characteristics**

1. Code..... Date: ...../...../.....

2. Gender of the interviewee: Male  Female

3. What is your ethnic group: Native  Non-Native?

4. Age of the interviewee (in years) .....

5. Marital status: a) married: b) Single; c) divorced: d) widowed:

6. Highest educational level: Primary  JHS  SHS  Tertiary  None

7. Total number of family members: Male....., Female: .....

8. Number of active household members aged between 15-64 years Male....., Female.....

9. What is your principal activity (a) cocoa farmer (b) business + cocoa farm (c) public servant + cocoa farm (d) others

**II. Information about plantation**

10. Origin of land/land acquisition (a) Owner (b) Rent (c) others

11. Number of cocoa plantations ..... size of farm ..... age of plantation .....

12. What is the history of previous land-use type before cocoa cultivation? (a) Primary forest (b) fallow (c) cropland

13. What variety of cocoa do you grow? ..... Source (a) Neighbour (b) Researcher (c) Bought (d) Other.

14. Do you belong to famers association? (a) Yes (b) No if yes name .....

15. Do you have link with any institution center such as university (a) yes (b) No (c) Not sure

16. Do you have river around or inside your cocoa farm? (a) Yes (b) No

17. Is the river still there or it has died off (a) Yes, it is there (b) No it is died off (c) it has reduced.

18. Any use of pesticides (a) yes (b) No **ii** Herbicides (a) Yes (b) No.

**iii** Fungicides (a) Yes (b) No If yes when do you start using them .....

Chemical	Name	Nature		Freq. of use/year	Main biotic stress	Provider	Picture of container
		Organic	Synthetic				
Herbicide							
Insecticide							
Fungicide							
Virucide							
Others							

19. Soil amendment (a) fertilizer application (b) cover crops (c) self-sustaining

Soil amendments	Name	Nature		Freq. of use/year	Main biotic stress	Provider	Picture of container
		Organic	Synthetic				
1							
2							
3							
others							

20. Type of cropping system? (a) Monoculture (b) Agroforestry

21. Are you practicing agro pastoralism (a) Yes (b) No ..... If yes what type of animals do you have on your farm (a) Poultry (b) Small ruminants (c) Snails

22. Reasons for use. (a) Manure (b) Termite picking (c) weeding (d) Others

23. How often do prune your crops? (a) Ones yearly (b) Twice yearly (c) Thrice yearly (d) I don't prune at all.

24. When you prune where do you normally throw the debris? (a) I leave them on the farm (b) I throw them outside (c) I spread it around the tree (d) I use to burn them.

25. When you want change your plantation what do you do (a) clear forest (b) fallow (c) replant

26. Do you want to change your plantation in future (a) Yes (b) No.? If yes for what use? (a) rubber plantation (b) palm plantation (c) fallow (d) food crops

27. How does increase family size affect your production? (a) Increase farm size (b) maintain farm size but use intensive method (c) others.

28. How does this increase influence the cocoa supply chain? .....

.....

**Part II**

**III. Farmer’s Knowledge about Climate Change**

1. Climate change what do you believe is/are the cause(s)? [1] Deforestation [2] Agricultural [3] God [4] I do not know [5] it doesn’t exist [6] others
2. How will you describe the following climatic variables over the past 10 years?

°N	Climatic variables	Increase	Decrease	No change
	Temperature			
	Rainfall pattern			
	Drought			
	Flood			

3. A 5 Priority list of practices which are optimal for adaptation to the present climate change  
 1..... 2..... 3..... 4.....  
 5.....
4. Do you experience drought in your farm? (a) Yes (b) No (c) Not really
5. Do you also experience run-off, erosion or flood in your farm? (a) Yes (b) No
6. Are the soil so dried during dry season in your farm? (a)Yes (b) No
7. If no, what management practice do apply in your farm?.....
8. How does these changes affect your production? (a) Decline productivity (b) No effect at all (c)
9. How do you mitigate severe drought on your farm?.....  
 .....

**Part III**

**IV. Knowledge about Agroforestry systems and soil carbon management**

1. Are you aware of agroforestry systems? Yes..... No.....  
 if yes, what do you know about it?.....  
 .....
2. Have you ever had any training concerning agroforestry system? (a) Yes (b) No (c) Not really
3. Who was the trainer?  Extension officers  Farmers association  Students  
 Others

4. How is the cocoa agroforestry system affecting your livelihood? (a) Improved (b) still normal (c) the system is not good at all (c) others
5. From your experience do you think this system is better than the old method of cultivation? (a) Yes (b) No (c) Not interesting
6. Are you aware of soil carbon management? (a) Yes (b) No
7. Where do you hear it (a) radio (b) farmer to farmer (c) extension officers (d) others
8. Do you know the source of soil organic carbon? (a) Yes (b) No
9. What is the source of soil carbon? (a) Sun (b) Soil (c) organic matter (e) God
10. How do you think SOC is important to you as a farmer? (a) Regulate climate (b) soil more fertile, (c) More productive (d) All the above (e) none of the above
11. Do you agree with me that soil management plays a critical role in whether the carbon remains in the soil or is released to the atmosphere (a) agree (b) Strongly agree (c) Disagree (d) strongly disagree
12. So what can we do to reduce soil carbon loss in your farm? .....
13. Do you feel your farm practice can help to store carbon in the soil? (a) Yes (b) No (c) I don't know
14. What if the government wants to pay for your effort for practicing a method that enhances soil carbon storage will you continue? (a) Yes (b) No (c) I will try it.
15. Do you think you are working for the government? Or agroforestry system is specifically government's work (a) Yes (b) No (c) the government is forcing us to grow trees (d) others
16. What drives you to change your cultivation pattern? (a) Family size (b) to increase yield (c) control pest and diseases (d) control soil fertility (e) others
17. Have you ever received any incentives for this practice? (a) Yes (b) No (c) government have promised but never come back (d) we hope to start receiving some.
18. What are the benefits derive from agroforestry systems?
  - a. Climate change mitigation
  - c. Biodiversity security
  - d. Household food security
  - e. Diversification and regular incomes

f. All the above

g. None of the above

h. Others

19. How do shade affect your yield? High yield  Low yield  others

20. How many times do you harvest in a year? .....

21. A sustainable agroforestry management how can it be achievable in your own context?.....

22. Can you decide that the price of cocoa should include all the costs of production; economic and environmental? (a) Yes (b) No (c) Not sure. Why?.....

.....  
.....

### **V. Knowledge about biodiversity and climate change mitigation**

1. Why do you keep trees in your farm? Is it for any reason? (a) Biodiversity (b) timber (c) food (d) Fuelwood (e) Others

2. Have you heard anything about biodiversity conservation? (a) Yes (b) No (c) Not sure, if yes what? .....

3. What do you think biodiversity is? (a) God (b) Trees (c) Animals (d) Trees & Animals (e) All living organisms.

4. Is your management practice appropriate to conserve biodiversity? (a) Yes (b) No (c) Not sure How?.....

5. Are you aware of the benefits of conserving biodiversity? (a) Yes (b) No (c) Not sure.

6. What can we do to mitigate climate change and reduce biodiversity loss through the cocoa supply chain?.....

7. Do you know that soils have the capacity to mitigate climate change by sequestering carbon? (a) Yes (b) No (c) I don't know.

8. If yes what can we do to improve our soil system to ensure this climate regulation?

(a)..... (b)..... (c).....

9. Factors affecting the conservation of diverse tree species in the cocoa agroforestry system

(a) Anthropogenic factors (b) Ecological factors (c) Soil factors (d) Climate factors (e) Others

10. How do you think fighting climate change (mitigation options) would affect your business?

.....

11. According to you how can we achieved climate change mitigation and biodiversity security?

- .....
12. What are your views on the research topic? .....
13. Do you think this research will help solve some problems through the cocoa supply chain? (a) Yes (b) No (c) Not sure  
if yes what are your reasons? .....
14. What are your expectations for the study? .....
15. From sustainable and climate change mitigation point of view, do you think there is an area that needs urgent research attention than what this research aims to achieve? .....What are the areas? 1..... 2..... 3.....4.....
16. Are you interested in what we doing and aim to achieve? (a) Yes (b) No (c) Not sure
17. Do you want to collaborate and hear the result and which part of the results?.....
18. Under what conditions do you think we can achieve the ecological, economic and social benefits in the cocoa production sector?
- .....
- .....
- .....
- .....

## Survey Questionnaire (Ministers and Stakeholders)

### Introduction

I am a Doctorate student from University of Felix Houphouet Boigny, Côte d'Ivoire. I am currently undertaking research on “**impact of cocoa cultivation on soil carbon sequestration and microbial community under climate and land use changes in Ghana and Côte d'Ivoire**”. The purpose of these questions is to gather information about Ministers and stakeholders’ perception on the above subject. You have been selected to provide information about cultivation changes on biodiversity and climate change mitigation in the cocoa agroforestry systems here. This research is purposed for academic work only and to help solve some problems in the cocoa supply chain, so please feel free and share your thought with us to improve this research work. Your participation is highly appreciated.

### Demographic characteristics

1. Code..... Date: ...../...../.....
2. Name of the respondent.....
3. Gender of the interviewee: Male  Female
4. Age (in years) .....
5. Marital status: a) married: b) Single; c) divorced: d) widowed:
6. Nationality.....
7. Highest educational level: Primary  JHS  SHS  Tertiary  None
8. Name of workplace.....
9. Current position .....

### Knowledge about Agroforestry systems and soil carbon management

1. Are you aware of agroforestry systems? Yes..... No..... if yes what do you know about it? .....
2. How important is agroforestry systems to you in this era?.....
3. Do you think practicing agroforestry through the cocoa production is necessary for producers..... how?.....
4. What could be the benefit for the cocoa producer?.....
5. What could be the benefit for the country?.....
6. Are you aware of soil carbon management? (a) Yes (b) No
7. Do you know if the soil is capable of mitigating climate change by sequestering carbon? (a) Yes (b) No (c) I don't know.

8. If yes what can we do to improve our soil system to ensure climate regulation?
9. What do you think are the factors affecting the conservation of diverse tree species in the cocoa agroforestry system
  - (a) Anthropogenic factors (b) Ecological factors (c) Soil factors (d) Climate factors (e) Others
10. Do you think government should pay for the effort of farmers for practicing a method that enhances soil carbon storage, is it the best option?.....
11. It's revealed that farmers are not really adopting the agroforestry system due to some factors such as negative cash flow in the early stage of establishment, uncertain demand for agroforestry products, low yields and investment requirements. How do you convince the numerous smallholder farmers to adopt and practice this system of agroforestry?.....
12. Have you ever promoted any training concerning cocoa agroforestry system..... how many times?.....
13. Have your ministry provided any incentive for farmers who practice agroforestry on their farm? Or any target incentive to support best environmental practice in cocoa production areas?.....
14. What are some of the incentives placed on cocoa agroforestry farms?.....
15. Minister/stakeholders' perception or knowledge on cocoa agroforestry farms? How do you think it should be implemented or how should it be designed?.....
16. Is there any existing policy on cocoa agroforestry systems? .....
17. Do you think there is a need to have a policy on cocoa agroforestry implementation?.....
18. What could be the purpose/objective of the policy?.....

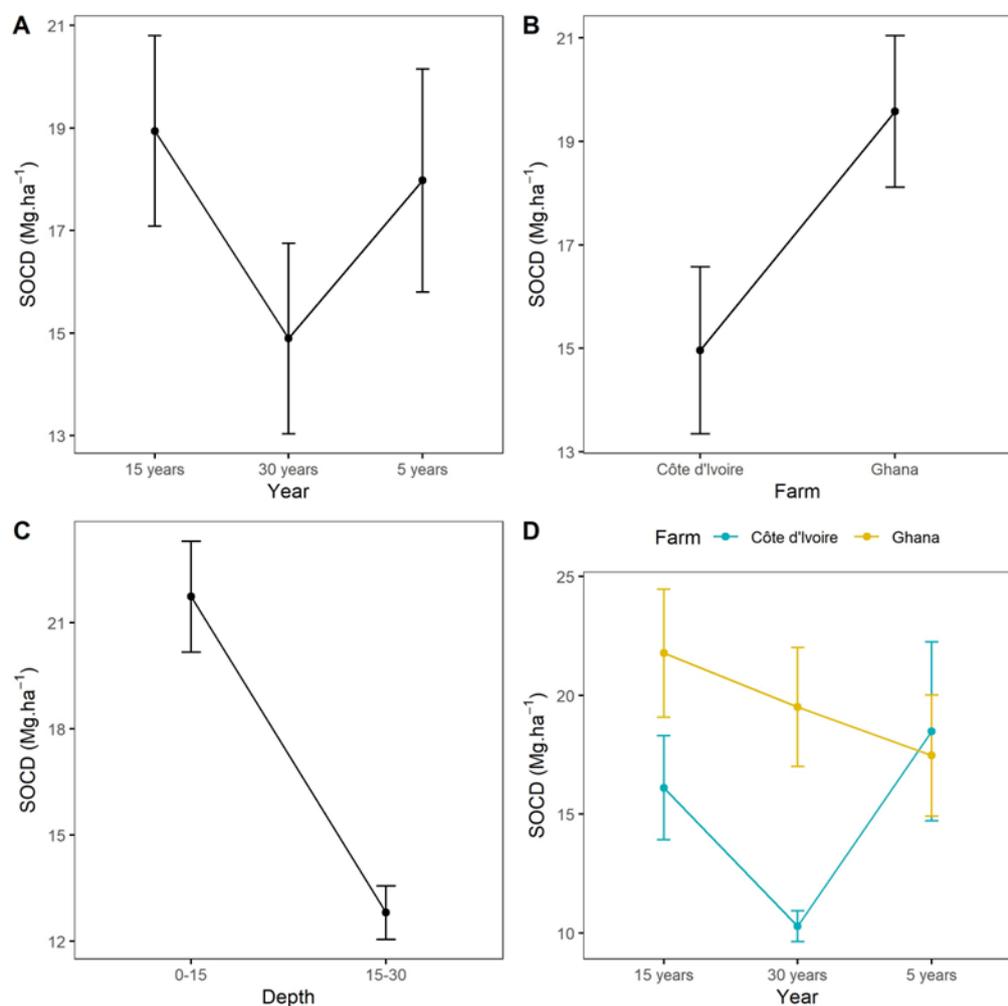
**Biodiversity and climate change mitigation (sustainable system)**

1. How do think implementing climate change mitigation options would affect the cocoa business?.....
2. To what extent has biodiversity conservation been taken serious in the cocoa production system? .....
3. How can you rate farmers performance in terms of biodiversity conservation.....
4. Do you know that conserving biodiversity can help us mitigate climate change? (a) Yes (b) No (c) Not sure.
5. As it stands now, don't you think it is important to integrate land degradation and sustainable soil management into key development and cocoa sector policies, strategies, and action plans? .....

6. From your experience as a minister do you think cocoa agroforestry system is better option to conserve biodiversity? (a) Yes (b) No (c) Not at all
7. What can we do to stop climate change through the cocoa supply chain? .....
- 8, How can we also promote food and biodiversity security?.....
9. Achieving ecological, economic and social outcomes has become a global challenge, according to you what are the possible ways of optimizing the ecological, economic and social outcomes through the cocoa value chain? .....
10. From your perspective how will you describe climate change and how can we achieve climate change mitigation.....
11. What are your views on the research topic? .....
12. Do you think this research will help solve some problems through the cocoa supply chain? (a) Yes (b) No (c) Not sure. What are your reasons? .....
13. From sustainable and climate change mitigation point of view, do you think there is an area that needs urgent research attention than what this research aims to achieve? .....What are the areas?  
1..... 2..... 3..... 4.....
14. What are your expectations for the study? .....
15. Are you interested in what we are doing and aim to achieve? (a) Yes (b) No (c) Not sure
16. Do you think the country can have a specific law for sustainable cocoa production?..... how?.....
17. Do you want to collaborate and hear the result and which part of the results?

### Results of objectives 3

Effect of site, depth and farm (year) on the SOCD in all soil samples of Ghana and Côte d'Ivoire



**Figure 1** Variation in SOC density across (A): cocoa agroforestry farms; (B); Site (CI: Côte d'Ivoire and GH: Ghana); (C): Soil depths and D: farms of each country

**Table 1:** Analysis of Variance (ANOVA-type II) Table for the model minimum adequate SOCD model

Term	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Site	1	192.4	192.39	12.000	1.675e-03
Depth	1	718.3	718.30	44.804	2.423e-07
Year	2	107.2	53.60	3.343	4.938e-02
Site: Year	2	162.1	81.06	5.056	1.307e-02
Residuals	29	464.9	16.03		

**Table 3:** comparison of mean total OC sequestered per farm (years)

<b>Independent variable</b>	<b>Levels</b>	<b>Mean (SD) of TOC</b>	<b>p</b>
<b>Year</b>	15 years	<b>13.4 (4.8)</b>	0.784
	30 years	12.1 (4.6)	
	5 years	13.1 (4.6)	