UNIVERSITY OF CAPE COAST

EFFECT OF NITROGEN FORMS AND RATES ON YIELD AND PERFORMANCE OF YOUNG AND MATURE COCOA TREES IN TWO AGRO-ECOLOGICAL ZONES IN GHANA

DANIEL NANA YAW GYEBI

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BY

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Thesis submitted to the Department of Crop Science of the School of Agriculture, University of Cape Coast, in partial fulfillment of the requirements for the award of Master of Philosophy degree in Crop Science

JULY, 2021

DECLARATION

Candidate's Declaration

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

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

Name: Daniel Nana Yaw Gyebi

Supervisors' Declaration

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

Principal Supervisor's Signature:................................... Date:........................

Name: Prof. Michael Osei Adu

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Name: Dr. Kofi Atiah

ABSTRACT

Cocoa affectionately called ‘golden pod’ is one of the few valuable tropical crops. Undoubtedly, cocoa is the most inevitable agricultural produce among several other crops produced in Ghana. It is the stronghold of Ghana’s economy, being second leading foreign exchange earner after gold, worth about 30 percent of all revenue from export and responsible for about 57 percent of overall agricultural export. More notably, the cocoa sector offers jobs to about 2 million Ghanaians. Despite the significance of cocoa to the economic stability and as a key export crop for Ghana, yields of cocoa beans are stagnating well below average yields worldwide. Nitrogen (N) plays a critical role in the growth and development of crops. There have been several assertions by industry players on the impact of nutrient nitrogen on cocoa growth and productivity, yet there is limited empirical evidence on the impact of N on the productivity of cocoa in Ghana. Though some studies have focused on the impact of one of the nitrogen forms (i.e. either ureic, ammoniacal or nitric) on cocoa in Ghana, there is yet a comprehensive study to investigate the impact of all three forms of nitrogen on the growth and productivity of cocoa. In this project, two representative cocoa farms from two Agro-Ecological Zones (Coastal Savannah and Evergreen Forest) were evaluated for the impact of N forms (urea/ammonium/nitrate), N rates (low/optimum/high), and nutrient N recycling through litter fall production on the growth, development and productivity of young and mature cocoa trees. A multi-stage random sampling technique was used to collect data on soil-plant nutrition practices among cocoa farmers whilst a randomized complete block design

(RCBD) was used for the on-farm experiment. The survey revealed that 79.2% of the respondents used inorganic fertilizer on their farms with a small proportion (20.8%), using organic fertilizer. Farmers used both liquid (foliar) and granular forms of inorganic fertilizers with the majority of such applications (72.5%) being done in liquid forms because the type of granular fertilizers used lacked N. The results from the on-farm trials showed increased levels of essential soil nutrients on fertilized plots than unfertilized plots. Cocoa yield increased with an increasing rates of N. Young cocoa trees were responsive to N supplied as nitrates whereas mature cocoa trees responded positively to N supplied in the form of urea. Additionally, young cocoa trees were more efficient in N use than mature cocoa trees whilst N resorption for mature cocoa trees was greater than N resorption recorded for young cocoa trees in both Agro-Ecological Zones. N content in the litter tissue of young cocoa trees was higher than that found in mature cocoa trees. Finally, at increasing N application rates, litter fall production, and litter tissue N content increased. The study concludes that although the yield effect was short term, there is the potential benefit to cocoa plants regardless of the age and location when N in the form of nitrate is added to fertilizers for young plants whilst urea could be incorporated into more mature cocoa plants nutrition in both Agro-Ecological Zones of Ghana. The most promising nitrogen (N) rates for an effective cocoa yield in terms of the pod and dry bean yield should be pegged at 20 to 30 kg N/ha. The incorporation of N in the formulation of granular inorganic fertilizers is recommended.

KEY WORDS

Agro-Ecological Zones

Cocoa

Cocoa farms

Fertilizer application

Nitrogen-based fertilizers

Nitrogen Use Efficiency

Nitrogen Resorption

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DEDICATION

To my irreplaceable loving mother, Regina Blay, and my elder sister, Grace Akosua Gyebi

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LIST OF ABBREVIATIONS

AEZ	Agro-Ecological Zone
ANOVA	Analysis of Variance
BAB	Bibiani-Anhwiaso-Bekwai Districts
CHED	Cocoa Health and Extension Division
CNRA	Center National de Recherche Agronomique
CRIG	Cocoa Research Institute of Ghana
CSZ	Coastal Savannah Zone
DW	Dry Weight
EFZ	Evergreen Forest Zone
FAO	Food and Agriculture Organization
FP	Farmer’s Practice
FW	Fresh Weight
GDP	Gross Domestic Product
GSS	Ghana Statistical Services
GLSS	Ghana Living Standard Survey
IFDC	International Fertilizer Development Center
ISO	International Standards Organization
MAS	Month After Set-up
MoFA	Ministry of Food and Agriculture
Nd	Nitrogen in well-developed cocoa leaf
Ns	Nitrogen in senescence cocoa leaf
NUE	Nitrogen Use Efficiency

NUEc	Nitrogen Use Efficiency of Cocoa
NUE_{ES}	Nitrogen Use Efficiency at the ecosystem
RCBD	Randomized Complete Block Design
SOC	Soil organic carbon
SOM	Soil organic matter
THLDD	Twifo-Hemang Lower Denkyira District
UCC	University of Cape Coast

CHAPTER ONE

INTRODUCTION

1.1 Background to Study

Cocoa *(Theobroma cacao),* is a valuable tropical crop. It is the most essential agricultural commodity among several other crops produced in Ghana. Cocoa is second to gold in terms of Ghana's foreign exchange. It is worth about 30 per cent of all revenue from export and responsible for not less than 57 per cent of overall agricultural export (World Bank, 2007; FAOSTAT, 2015). More importantly, the cocoa sector employs about 2 million Ghanaians directly and indirectly (Breisinger *et al*., 2008).

Despite the significance of cocoa to economic stability and as a key export crop for Ghana, yields of cocoa are below average yields worldwide **(**Aneani and Ofori-Frimpong, 2013). Earlier research conducted hints of an imbalance of soil nutrients and soil fertility degradation as the key contributing factors to this challenge (Appiah *et al*., 2000; van Vliet *et al*., 2015). As such, one of the best approaches to tackling this challenge is the application of fertilizer on cocoa farms. However, farmers cultivating on African soils generally utilize no or little fertilizer on their farms compared to farmers in other parts of the globe. Therefore, soils found in Africa are virtually nutrients deficient (van Vliet *et al.*, 2015).

Nitrogen is one of the fundamental essential macro-nutrients required by plants in large amounts for growth and development (Leghari *et al*., 2016). Nitrogen assumes a basic function in photosynthesis, in that it is related to

Rubisco, a carboxylating protein of photosynthesis and part of chlorophyll arrangement (Waring and Schlesinger, 1985). According to McGuire *et al*. (1995), the variation in nitrogen concentration of leaf tissue usually depicts the variation in the concentration of enzymes. However, there are several factors that determine the nitrogen concentration of leaves, including soil nitrogen mineralization and nitrification rates, soil C/N ratio, plant species, temperature, and irradiance (Yin, 1994; MaGill *et al*., 1996; Ollinger *et al*., 2002). As such, canopy foliage N concentration was attributed to nitrogen availability, plant species traits, and climate (Pan *et al*., 2004).

Nitrogen, though most abundant in the atmosphere, is limiting to plant. However, the conversion of N_2 to NH_3 makes nitrogen readily available to plants. Moreover, nitrogen is derived from both organic and inorganic sources. For this reason, nitrogen, with the aid of microorganisms and spontaneous chemical reaction, undergoes cycling (Schlesinger and Bernhardt, 2013). Naturally, lightning and symbiotic plant bacteria aid in the breaking of the dinitrogen bond-forming N_2. In this modern era, anthropogenic N fixation has contributed immensely to the availability of N in ecosystems, migrating N from the atmosphere into the soil with the largescale production and use of inorganic fertilizers (Fowler *et al*., 2013). For the reaction between hydrogen gas (H_2) and N_2 to successfully produce ammonia (NH_3) high amount of energy is required (Schlesinger and Bernhardt, 2013). In addition, the burning of fossil fuels coupled with global agricultural production of leguminous crops like cowpea, soybean, alfalfa, and clover have increased the input of nitrogen to the soil and atmosphere, making the nitrogen cycle unbalanced (Vitousek *et al*., 1997).

Inorganic fertilizers used in farming are usually in the form of urea (46% N), ammonium (21% N), and nitrates (26% N) (Leghari *et al*., 2016). Though urea contains a high amount of nitrogen, all plants make use of nitrogen in the form of NO_3^- and NH_4^+. For this reason, nitrogen from all sources needs to be converted into these forms for ease of accessibility and uptake by plant roots. Leghari *et al*. (2016) identified diffusion, root interception and mass-flow as the major pathways by which crop plants absorb nutrients. The latter happens to be the pathway used mostly when nitrogen fertilizers are applied to the soil, even though the root interception process also helps to supply nitrogen to plant but under specific conditions (Leghari *et al*., 2016). Hence, for nitrogen to be adequately supplied to plants, it must be in the right form at an optimum rate, applied at the right time using the most efficient methods of application to curb nitrogen losses due to its volatility (Leghari *et al*., 2016).

Meanwhile, there have been several assertions by cocoa farmers and some extension officers on the need to apply nitrogen-based fertilizer to impact the growth, development and productivity of cocoa trees (Ahenkorah and Akrofi, 1968; Aneani and Ofori-Frimpong, 2013; van Vliet *et al*., 2015). Some researchers have added their voices to this assertion (YARA, 2012; van Vliet *et al*., 2015), yet there is no empirical evidence to prove it. Though some studies have focused on the impact of one of these nitrogen forms such as urea, ammonium and nitrate on cocoa in Ghana (Appiah *et al*., 2000; Aneani and Ofori-

Frimpong, 2013; van Vliet *et al.*, 2015), there is yet a comprehensive study to investigate the impact of all three forms of nitrogen on the growth, development and productivity of cocoa. Therefore, this information has become imperative since nutrient nitrogen can be sourced from either of these forms.

Plant N use efficiency is influenced by several factors including, phenology, crop characteristics, soil properties and climatic factors (Dong *et al.*, 2015). Very conducive soil and climate promote the growth and development of plants because N use efficiency reaches its peak (Dong *et al*., 2015). Plants found in areas deficient in nutrients are more efficient in nitrogen use whereas crop plants found in fertile areas are less efficient in nitrogen use (Vitousek, 1982; Tateno and Kawaguchi, 2002).

1.2 Statement of the Problem

Cocoa trees in Ghana are usually aged and have lost their productive capacity, and yet, are grown on soils that are mostly deficient in nutrients. Many studies have shown that continuous decline in the fertility of soil coupled with drastic depletion of essential plant nutrients have been the key contributing factor accounting for the decrease in crop yields on African soils including Ghana (Adejobi *et al*., 2011). One of the measures to mitigate this ordeal is the application of inorganic fertilizers to replenish the soil as the continuous cultivation and harvesting of cocoa annually result in loss of nutrients from the soil in cocoa plantations. Ogunlade *et al*. (2009) revealed that over 85 per cent of cocoa farmers in Nigeria do not use fertilizers on their cocoa farms. Ghanaian cocoa farmers have negative perceptions on the use of fertilizers to their farms.

However, the few who do the fertilizer application on their farms either undersupply or oversupply, hence the persistent decrease in cocoa yield (Appiah *et al.*, 2000). Moreover, most farmers believe that cocoa trees do not require nutrient nitrogen so they do not include nitrogen in their fertilizer programme to the extent that nitrogen is lacking in most formulations of fertilizers used in cocoa production (Ahenkorah *et al.*, 1987; van Vliet *et al.*, 2015). Yet, the use of nitrate-based N has been the preferred source of N in cocoa but while there are negative perceptions of cocoa farmers on the use of fertilizers, there is also lack of empirical evidence on the general effect of N on yield of cocoa. There is yet a comprehensive study to investigate the impact of three (3) N forms (i.e. either ureic, ammoniacal or nitric) and rates on growth and productivity of cocoa in Ghana.

1.3 Justification of the Study

The prospects of Ghana being the leading producer of cocoa or maintaining the status as the second-largest cocoa-producing country in the Globe is under serious threat by inherent low soil fertility coupled with aged unproductive cocoa trees (van Vliet *et al.*, 2015). To make soils under cocoa plantations regain their fertility and ensure aged cocoa trees become productive, there is a need for farmers to adopt good agronomic strategies and a key among them, is fertilizer application. Research has shown that the application of fertilizer to the soil leads to improved soil fertility thereby increasing crop yield. As such, individual nutrient elements when supplied in their right proportions under a favourable soil condition increase the productivity of the soil.

Meanwhile, assertions by most cocoa farmers and some players in the cocoa value chain, that cocoa trees do not require nutrient nitrogen but if applied could have no/or negative influence on cocoa growth and productivity persists. Lately, notwithstanding, the thought that P is the most restricting element, and that N is not basic for cocoa yield in Ghana, has been challenged (Acquaye, 1963; van Vliet *et al.*, 2015). Preliminary investigations led by the Cocoa Research Institute of Ghana (CRIG) showed high profitability when N was applied. This led to amending of fertilizer recommendations to incorporate N (Afrifa *et al.*, 2009). Unfortunately, the non-accessibility of experimental proof to back these cases has left the issue hanging. Albeit a few studies have been carried out, the deficit is that they continue to focus on one type of nitrogen, for example, urea, ammonium, or nitrates on cocoa farms in Ghana. There is yet a comprehensive study to investigate the impact of three (3) N forms (ureic, ammoniacal and nitric) and rates on growth and productivity of cocoa in Ghana.

On completion of this research work, empirical evidence on the impact of nitrogen forms and rates on the yield and performance of young and mature cocoa trees would be provided. The spotlight is on young and mature cocoa trees because one of the integral factors which cannot be overlooked when it comes to the uptake of nitrogen and efficient use of nitrogen in a plant is the age of the plant (Leghari *et al.*, 2016). In several instances, cocoa correlates negatively to N application (Wessel, 1971; Ahenkorah *et al.*, 1987). Later, Appiah *et al.* (2000) reported that young seedlings responded positively to N application, while mature cocoa showed no response regardless of shading. These and many other contradictory research findings in literature create room for further studies, in that, the forms and rates of nitrogen used vary between studies. Hence, the need for more comprehensive, scientific and rigorous trials to investigate the impact of all three forms of nitrogen at varying rates. The findings could be used to develop a fertilizer programme, which when implemented might result in high on-farm cocoa yield to reduce the current yield deficit in the country, as well as enhance the productivity of cocoa, thereby, increasing the income of cocoa farmers in the selected regions and Ghana as a whole.

1.4 Objectives

1.4.1 General Objective

To provide empirical evidence for the effect of nitrogen forms and rates on the yield and performance of young and mature cocoa trees.

Specific Objectives

1. To assess soil-plant nutrition practices among cocoa farmers in two agro-ecological zones.
2. To ascertain the impact of nitrogen forms and rates on yield and productivity of young and mature cocoa trees.
3. To determine nitrogen use efficiency (NUE) and nitrogen resorption of young and mature cocoa trees.
4. To estimate nitrogen recycling through litter fall production.

1.5 Test of Hypothesis

1. H_0: Cocoa trees do not require nutrient nitrogen.

   H_1: Cocoa trees require nutrient nitrogen.

2. H_0: No significant differences exist in nitrogen uptake by cocoa trees in terms of nitrogen forms.

   H_1: Significant differences exist in nitrogen uptake by cocoa trees in terms of nitrogen forms.

3. H_0: No significant differences exist in nitrogen uptake by cocoa trees in terms of fertilizer application rates.

   H_1: Significant differences exist in nitrogen uptake by cocoa trees in terms of fertilizer application rates.

4. H_0: Nitrogen recycling through litter fall is negligible.

   H_1: Nitrogen recycling through litter fall is not negligible

1.6 Thesis Organization

This thesis comprises six chapters. The first chapter is the introduction which gives a brief background of the study, a description of the problem which the research intends to remedy and provides insight into the justification for the study. It also covers the ultimate goal of the study as well as a set of objectives that will aid in the attainment of this goal. In the second chapter, literature is reviewed on the overview and relevance of nitrogen as a plant nutrient, the nitrogen cycle, nitrogen use efficiency, nitrogen resorption, cycling of nutrient in cocoa plantations and the impact of nitrogen on the yield of cocoa. Approach to litter fall production determination as well as nutrient recycled from a litter produced, litter decomposition and theories behind the concepts utilized in the study are also covered in chapter two. Chapter three, which is the materials and methods gives a comprehensive explanation of each method adopted in the study.

The results from the study are presented and interpreted alongside personal description in chapter four. Chapter five constitutes the general discussion of the findings of the study comparing and contrasting existing results from related researches done by others and found in the literature. Lastly, chapter six gives a summary and synthesis of the entire work as well as conclusions drawn from the findings of the study concerning set objectives.

CHAPTER TWO

LITERATURE REVIEW

2.1 Botany and Physiology of Cocoa

Cocoa (*Theobroma cacao)* is originally an understorey rainforest tree (Läderach *et al.*, 2013). Most cocoa systems have been established as agroforestry systems in the shade of large forest trees, but more recently, monocrop plantations have been introduced and advocated (Gockowski and Sonwa, 2011). Under cultivation, cocoa is a rather small tree of about 3-10 m, although under natural heavy shaded conditions, it can be 20-25 m in height (Almeida and Valle, 2007). Trees grow rapidly during the first 3-4 years after which growth is steadier. The tree forms a first 'jorquette' at a height of 1-2 m, where five 'fan branches' grow out sideways. Buds below the jorquette may grow out upward as 'chupons' and are capable of forming a new jorquette above the previous one, thus increasing the height of the canopy in a step-wise process. Basal chupons may also form at the base of the trunk and replace the main trunk if this is severely damaged.

The root system consists of a large tap root of 0.8-1.5 m (although it may be deeper in deep soils and may not form in heavy clay soil) and a lateral root system in the topsoil which is responsible for most of the uptake of moisture and nutrients (Hartemink and Donald, 2005). Leaf production occurs in flushes in which terminal branches produce 3-6 pairs of leaves after which the bud remains dormant for a period until a new flush occurs. A flush usually coincides with leaf fall of older leaves as the nutrient demand of the new flush is partly met by translocation of nutrients and photoassimilates from the older leaves (Almeida and Valle, 2007). Although flowers are also formed on secondary branches, pods form mostly on the trunk and main branches (Almeida and Valle, 2007; Groeneveld *et al.*, 2010). Trees come into bearing after 2-6 years depending on the variety and location (Wessel, 1971). Glendinning (1960) concluded that cocoa trees come into bearing when they have reached a stem diameter of about 6 cm. Amelonado cocoa may continue to bear fruits for 40 years or more, while hybrid trees should be replaced every 15-20 years (Wessel 1971; Gockowski *et al.*, 2003). The start of the decline of production varies depending on factors such as variety, productivity of the tree, pest and disease incidence, and soil nutrient status.

2.1.1 Cocoa in Ghana

Theobroma cacao is a native of the Amazon region of South America. It is a perennial plantation, a tree crop which belongs to the family *Sterculiaceae*. There are over 20 species in the genus *Theobroma*, yet the cacao tree is the only one economically cultivated and widely recognized. According to Opeke (2005), there are three main cultivated sub-species namely; Criollo, Forastero, and Trinitario. Out of these, forastero is present on over 80 per cent of all cocoa plantations.

Cocoa was first brought into Ghana by the Bassel Missionaries in 1857 (Grossman-Greene and Bayer, 2009). The Dutch, Swiss, and English though actively involved in diverse ways, yet Ghanaian history gives credit to Tetteh Quarshie, a Ga blacksmith from Christiansburg whose noble act led to the cultivation of cocoa on a commercial scale in Ghana (Tetteh, 2019). Thus, after he arrived from Fernando Po, he established a cocoa nursery (of about 300 healthy trees) in Mampong-Akuapem and sold pods and seedlings at maturity to local farmers for onward proliferation and development (Grossman-Greene and Bayer, 2009; Adu-Gyamfi *et al*., 2020). These trees served as the foundation for cocoa production in Ghana (Grossman-Greene and Bayer, 2009). From Akuapem, cocoa farming proliferates to Ashanti, Brong-Ahafo, Central, and Western regions. The foremost export from Ghana took place in 1891 and only 36 kg of the cocoa bean was exported but the development of the cocoa industry was very rapid such that by 1925, export had increased to 90.7 kg (Adu-Gyamfi *et al*., 2020). Subsequently, Ghana became the leading producer of cocoa, producing about 40,000 tons annually (Grossman-Greene and Bayer, 2009).

Over the years, the majority of farms on which cocoa are cultivated are characterized as smallholder farms owned by peasant farmers found within the major cocoa regions in Ghana. There are no enormous farms claimed by exiles, multinationals, or corporate organizations in Ghana (Grossman-Greene and Bayer, 2009). Nonetheless, several large cocoa plantations exist in some parts of the country.

Meanwhile, Ghana cocoa is considered premium on the world market due to its high-quality cocoa beans which are not solely attributed to taste but also good agricultural practices involved in the production compared with what pertains to other big plantations in other producing countries elsewhere on the globe (Darkwah and Verter, 2014). Ghanaian cocoa farmers deploy traditional methods which are environmentally friendly on their farms (Danquah, 2003).

More to the point, the Ghana COCOBOD scrutinizes the inception of novel agrochemicals to deal with any probable induction of new crop contaminants from time to time into the cocoa industry (Danquah, 2003).

2.1.2 Significance of Cocoa to Ghana's Economy

For Centuries, cocoa has been one of Ghana's most valuable resources which earns the West African country foreign exchange. It is an important contributor to the Ghanaian Economy Gross Domestic Product (GDP), food security, livelihood, and food supply at both local and global levels as it provides carbohydrates, fats, and minerals like potassium. Also, revenue generated from the export of cocoa has since served as a derivation of funding to the government for the implementation of major developmental projects in the country. Grossman-Greene and Bayer (2009) stated that the Nkrumah led administration government policies geared towards Ghana industrialization was chiefly based on cocoa revenue. Following suit, the construction of Ghana's second major hydroelectric power generation dam at Bui is widely believed to have received financial sponsorship based on some collateralization of the country's cocoa of some kind.

Despite this, sky-scraping annual production of cocoa in Ghana implies adequate resources or revenue to fund the central government policies and developmental projects. Canatus and Aikins (2009), posit that the cocoa industry is the mainstay of Ghana's economy; since the commencement of commercial cocoa production in Ghana, cocoa prices serve as the basis for increased production (Danquah, 2003; Grossman-Greene and Bayer, 2009).

The World Bank, notwithstanding, accepted that cocoa can keep on assuming a significant part in Ghana's monetary development toward being a Middle-Income Country status (Breisinger *et al.*, 2008; World Development Report by World Bank, 2007). Once more, it is accepted that Ghana's cocoa production is beneath the worldwide average, recommending the potential for efficiency driven development (Breisinger *et al.*, 2008; FAO, 2005; ICCO, 2007). New scientific proof stresses medical advantages for cocoa consumers which possibly can additionally support demand (Breisinger *et al.*, 2008; FAO, 2005). Moreover, the Government of Ghana has demonstrated its readiness to bring through its proceeds with progression of purchasing organizations to add to yield and efficiency development (Breisinger *et al.*, 2008; Varangis and Schreiber, 2001; Laven, 2007). Cocoa in reality assumes a huge part in Ghana's economy and utilizes numerous small-scale farmers (Breisinger *et al.*, 2008). Cocoa production hit an untouched high of 3.6 million metric tons in long term with West African nations including Ghana representing more than 70% of world production (ICCO, 2007).

Ghana planned to increase its production by 1,000,000 tons per annum and due to a combination of factors as mass spraying programmes, fertilizer credits, government-backed rehabilitation programmes, partial liberalization, the establishment of price stabilization policy, higher producer prices; the country has been the most successful of all cocoa exporters (Breisinger *et al.*, 2008; FAO, 2005, Laven, 2007). Cocoa production more than doubled from 395,000 tons in 2000 to 740,000 tons in 2005, contributing 28 per cent of agricultural growth in

2006 (Begotic *et al*., 2007; Breisinger *et al*., 2008). This makes the sector's performance more impressive following the country's earlier elasticity in production (Abdulai and Rieder, 1995). The lift prompted an expansion in agricultural GDP from 13.7 percent in 2003/2004 to 18.9 percent in 2005/2006 (Breisinger *et al.,* 2008). Producer prices rose by about $260 somewhere in the range of 2000 and 2006. The FAO and Ministry of Food and Agriculture (MOFA) gauges that attainable yield for cocoa is around 1-1.5 tons per hectare every year; more than two-fold the normal yields in 2005 (Breisinger *et al*., 2008). In 2005, cocoa beans (24.3%) and cocoa products (3.8 %) together contributed about 28 percent of total exports accounting for about half of agricultural exports (Breisinger *et al*., 2008). Africa processed on average 15 percent of cocoa products. However, Ghana's processed cocoa is below Africa's average ranging from 8 to 12 percent. Domestic food industries that use cocoa as raw material are small hence value addition is low limiting its contribution to economic growth (Breisinger *et al*., 2008).

There is, however, an encouraging development, the value of processed beans went up from US$83.6 million in 2004 to US$152.9 million in 2006 (MoFA, 2007 and Breisinger *et al*., 2007). Levy on export tax on cocoa has, however, declined over the years, reducing from 16 percent in the 1960s to 12 percent in the 1990s and about 5 percent in 2005 (BoG, 2007 and ISSER, 2001 in Breisinger *et al*., 2008). National poverty reduced from 51.7 per cent in 1991 /92 to 39.5 in 1998/99 and then to 28.5 in 2005/2006 (Breisinger *et al*., 2008). Poverty among cocoa farmers is also believed to have reduced drastically; from

60.1 per cent or over 281,600 cocoa farmers in 1991/92 to 23.9 percent or 112,000 cocoa farmers in 2006 (Coulombe and Wodon, 2007; Breisinger *et al*., 2008).

The cocoa sector offers many economic and social advantages to the Ghanaian economy due to the high-quality standard of Ghana’s cocoa. Canatus and Aikins (2009) argue that the cocoa industry is the backbone of Ghana’s economy. Again, contrary to economic indices that label gold as the largest foreign exchange earner, Tutu (2011), cited by the Ghana News Agency (2011), 15th February edition, observed that cocoa is the largest foreign exchange earner for Ghana. He posited that an investment of one dollar ($1.00) in the minerals sector earned two dollars while the same amount of investment in the cocoa sector earned about seventeen dollars ($17.00).

A major problem here is that cocoa production is geographically concentrated and its contribution to poverty reduction is not evenly distributed (Breisinger *et al*., 2008). From Ghana Living Standard Survey-5 (GLSS-5), about two-thirds (2/3) of the country’s cocoa is produced in the forest zone, where rural poverty levels are below the national average and about 30 percent in the Southern Savanna zone (mainly Brong-Ahafo Region) and the Coastal zone takes the rest (GSS Survey, 2005/2006).

In the North where poverty is endemic, natural conditions are not suitable for cocoa production (Breisinger *et al*., 2008). The rural household generates only 30 percent of their Agriculture income from cocoa with the rural poor getting about 10 percent of income from cocoa (Breisinger *et al*., 2008).

2.1.3 Challenges in cocoa production

The comparatively low cocoa productivity experience in several cocoa producing countries and in Ghana precisely could be ascribed to some challenges encountered in cocoa production, which include poor farm management practices, cultivating low-yielding varieties, pest and diseases incidence, erratic precipitation pattern and low level of modern technologies adoption among cocoa farmers and decline in soil fertility.

Decline in soil fertility is a serious issue affecting the sustainability of cocoa production in West Africa. Degraded soils can no longer sustain satisfactory cocoa productivity, and leading to the migration of farmers often from a particular area once the soil has become depleted. In Ghana, the large shift in cocoa cultivation from the Eastern to the Western region has been largely due to soil degradation. This shifting agricultural pattern increases pressure on remaining forests. Thus, while excessive or inappropriate application of fertiliser has well documented environmental side effects (e.g., leaching, water pollution), neglect of soil maintenance also has serious environmental consequences. Strategies to maintain soil quality on cocoa farms are integral to sustainability

2.1.4 Cocoa Production Systems

Cocoa production in Ghana has been done in two principal Agro-Ecological Zones: the moist semi-deciduous forest (Eastern, Ashanti, Brong-Ahafo, and Central Regions) and high rainforest (Western and Western-North Regions) Agro-Ecological Zones. The cocoa area is generally comprised of smallholder farms. As indicated by Dawoe (2009), 66 per cent of farms falls between ½ a hectare and 8 hectares though 18.9 per cent of cocoa farms are more prominent than 20 hectares. The generally thick woodland that portrayed the underlying development of cocoa in Ghana kept up the regular environment reasonable for cocoa development. Under it, there is a steady steep slope of the forestland locale created. It likewise monitored somewhat numerous environment capacities and the remainder biodiversity of the first timberland. Woodland biological systems, for example, those in the semi-deciduous and high rainforest Agro-Ecological Zones give a wide scope of administrations to ranchers and mankind. These incorporate producing and looking after soils, putting away and cycling basic nutrients, water-related administrations, for example, support by hydrological cycles and counteraction of floods, water quality improvement, looking after biodiversity, carbon sequestration, and controlling atmosphere. In Ghana, those administrations are compelled by fast deforestation, at the pace of 2% every year with a development of the region planted and a move from additional to less concealed cocoa cultivating plans.

As of late, the shaded cocoa systems have been altered with the end goal that at a spacing of 2.4 m by 2.4 m to 3.6 m by 3.6 m, plant populace between 900 trees for each hectare and 1300 trees for every hectare in the blended of 10 to 15 medium-sized trees per hectare is feasible.

2.1.5 Hi-Tech Cocoa Production in Ghana

This program was introduced by the Government of Ghana through the COCOBOD as part of the strategies geared towards boosting annual cocoa production in the country. Application of fertilizers, the supply of improved cocoa seedlings, and other agrochemicals on cocoa farms were included in the Hi-Tech cocoa production program. This initiative offered cocoa farmers the opportunity to access farm inputs and logistics such as fertilizers, agro-chemicals, farm tools, and equipment as well as some essential services like weeding, pruning, labour assistance in terms of chemical and fertilizer administration. As a measure of success, the program recorded about fifty thousand cocoa farmers as beneficiaries in the first year, this figure doubled by year 2. According to Dormon *et al.* (2004), cocoa farms that were enrolled in the program saw a tremendous boost in cocoa productivity.

Despite these successes, Wienco Ghana limited which happens to be a private company dealing in fertilizer established the 'Cocoa Abrabopa Scheme'. Cocoa farmers formed groups in major cocoa growing areas and by extension the Cocoa Abrabopa Association. Members of this association are entitled to a credit facility of Ghc318.10 worth package that comprises adequate cocoa inputs to cater for not less than two acres of mature cocoa farm, due for repayment after the farmers harvested their produce. Quartey (2007) reported that the package was made up of several agrochemicals, six bags of 590 Kg Asaase Wura special cocoa fertilizer, one Matabi pneumatic sprayer, and extension services to signed-on farmers.

2.2 Background and relevance of nitrogen

2.2.1 Nitrogen

A non-metallic element symbolized by N with 7 as its atomic digit. Nitrogen is found within the group of 15 elements on the periodic table. Daniel

Rutherford, a Scottish Physician, first did the discovery and isolation as far back as the 17th century. However, in 1790 the nomenclature 'Nitrogene' was suggested by French Chemist Jean-Antoine-Claude Chaptal upon finding it to be a component of nitric acid and nitrates. Since then nitrogen has been identified as the most common element in the universe. Two atoms of nitrogen bind in forming dinitrogen (N_2) a colourless and odourless gas that constitutes 78 per cent of the atmosphere. This chemical element is considered as the fundamental nutrients very essential to the existence of all living organisms (Bernhard, 2010). Nitrogen is found in the molecular structure of DNA, RNA, proteins, chlorophyll, and adenosine triphosphate (ATP) (Bernhard, 2010; Leghari *et al*., 2016).

Despite the atmospheric abundance of N_2, it is rarely available to green plants in this form leading to limitations on primary productivity (Schlesinger and Bernhardt, 2013). However, the conversion of N_2 to NH_3 makes N readily available to plants. Based on the diverse utilization of N by organisms, it undergoes several alterations naturally (Bernhard, 2010). This transformation is made possible due to the actions and interactions of microorganisms essential to productivity in the biosphere. This makes up the nitrogen cycle.

2.2.2 The Nitrogen Cycle

Nitrogen cycling involves the conversion of N in diverse forms via physical, chemical, geological, and most especially biological processes. The N cycle can occur in a natural setting or can be influenced by mankind's activities (Sergei, 2015). In normal environments, N enters the soil through an organic or substance N obsession, wet and dry deposition from barometrical NO and deterioration of plant and animal matter. Little natural compounds can be absorbed straightforwardly by plants (Näsholm *et al*., 1998) or they can be mineralized to NH_4^+. Complementing this natural phenomenon is the Haber-Bosch process which is being used in the fertilizer industry to manufacture nitrogenous fertilizers for agricultural purposes (Galloway and Cowling, 2002).

The Cycle begins with the fixation of N, which is characterized by the usage of molecular nitrogen (N_2) by bacteria. The process is catalyzed by enzymes with a high affinity for molecular oxygen (O_2) to produce Ammonia. Ammonia is transformed into proteins, nucleic acids (DNA), and other nitrogen-containing organic molecules (Sergei, 2015). The decomposition process is influenced by numerous environmental factors such as soil moisture, temperature, pH, the C: N ratio, and the type of organic materials in the residue (Bernhard, 2010). In the cycle, microorganisms respire through denitrification in the absence of or in an event of limiting oxygen. Particularly, bacteria prefer nitrate utilization at the expense of oxygen to perform their metabolic functions. By so doing, nitrate (NO_3^-) is reduced to NO_2^- and then to gaseous forms including N_2O and N_2 as shown in Fig 1·

Despite this, nutrient nitrogen availability in soil is related to the proportionate occurrence of mineralization and immobilization. There is a surplus of N for crops and other organisms when mineralization is greater than immobilization whereas when immobilization is more prominent than mineralization, the soil is depleted in N (Robertson and Groffman, 2007). According to Schimel and Bennett (2004), terrestrial nitrogen cycling naturally depends on the depolymerization rate, since the conversion of N from amino acids to NH_4^+ is more rapid compared with converting proteins to NH_4^+ (Jones and Kielland, 2002; 2012).

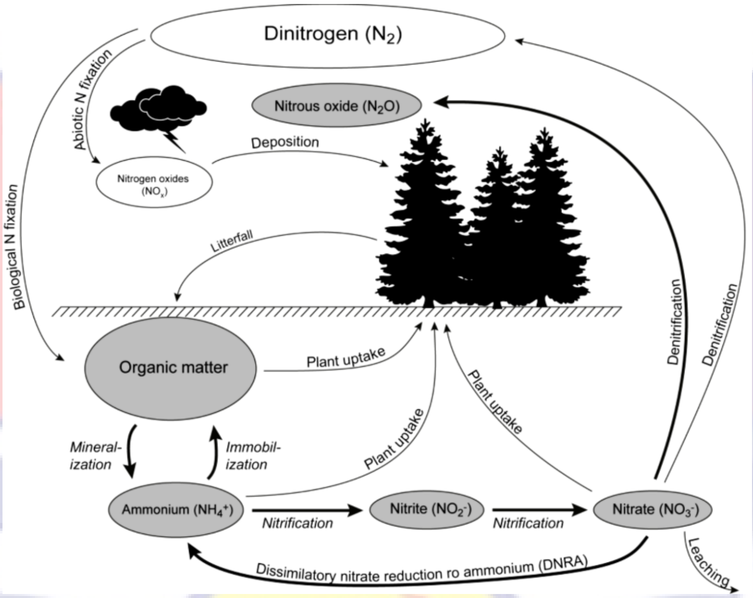

Figure 1: The Major pathways and processes in nitrogen cycling (Adopted from Björsne, 2018)

2.2.3 The Plant Nutrient (Nitrogen)

The supply of nutrients is paramount to the enhancement of crop plant growth and development. Nitrogen is among the few elements considered essential nutrients (Vicente *et al.*, 2014). Specifically, nitrogen boosts leaf area development, succulence enhancement, and other physiological processes of several crops, hence crucial in agriculture (Vicente *et al.*, 2014). All N absorbed in the soil is either ammonium (NH_4^+) or/and nitrate (NO_3^-) (Coraspe-Leon, 2009), therefore, the total uptake of N usually consists of a combination of these forms. About 80 per cent of the total cations and anions which enable a plant to absorb NO_3^- and NH_4^+ have a great impact in controlling the pH of the rhizosphere (Coraspe-Leon, 2009; Vicente *et al*., 2014). The optimum N for normal plant growth varies between 2% and 5% of the dry weight of the plant (Castaño *et al*., 2008). According to González-Raya *et al*. (2005), the core source of N for most crop species is NO_3^-, but this depends on the plant species and some factors like the pH, the temperature, the carbohydrate content in roots (Mengel and Kirkby, 2001). NO_3^- absorption also varies with the variety and light intensity as might be found in lettuce and other vegetables (Rodrigues, 2002).

Physiologically, N promotes leaf area and leaf area index (LAI), which may be due to the higher number and size of leaves (Vicente *et al*., 2014). It intensifies the green colour of the leaves and is a constituent of essential cellular components such as amino acids, proteins, and nucleic acids (Bernhard, 2010). Nitrogen also regulates the uptake of P, K, and other nutrients by plants, and improves the succulence of many crops (Sedano-Castro *et al*., 2011). Considering that water is the main factor limiting the development of plants and is the only substance capable of integrating the growth and metabolic activity at the cellular level, the role of N as an osmotic agent, which allows retaining the water in the vacuoles, has been considered as important to its nutritional function (Mcintyre, 1997; Cárdenas-Navarro *et al*., 2004).

According to Tóth *et al*. (2002), plants that are deficient in nitrogen become chlorotic in the middle leaves. Also, there is a decrease in lignin which is a substance used by plants as a physical defence against pests and diseases (Vicente *et al*., 2014; Rubio *et al*., 2005). It has been observed that excessive applications of N may decrease the concentration and toxicity of phenols used by plants against invading pathogens (Vicente *et al*., 2014; Rubio *et al*., 2005). An excessive application of ammonium nitrogen may undesirably distress plant growth, causing a hasty crop development coupled with rapid stem elongation that makes plants too soft, and may even block the absorption of Ca (Alarcón, 2002). Both the shortage and overabundance of NO_3^- have undesirable impacts on plants (González-Raya *et al*., 2005; Jauset *et al*., 2000; Vicente *et al*., 2014). Rubio et al. (2005) demonstrated that both the shortage and overabundance of NO_3^- affect the incidence of late blight in potato. The lack of N can stimulate reproduction by oospores of oomycete and can animate over the top vegetative development of the plant and the arrangement of a great microclimate for the improvement of the microbe inside the plant foliage, other than the negative impact on the yield and nature of tubers (Rubio *et al*., 2005; Bélanger *et al*., 2002).

2.2.4 Impact of Nitrogen on Cocoa

As with most crops, cocoa plants need nutrient nitrogen (N) in appreciable quantities. Nitrogen provided as ammonium promotes canopy development, but mature cocoa trees may only react to N when they are pruned and thinned (Jadin and Snoeck, 1985). The addition of urea formulated N stimulated young cocoa seedlings growth and jorquette formation (in interaction with K and Mg application), coupled with early closure of cocoa canopy (Wessel, 1971).

It has been suggested that the impact of nitrogen application is best felt in young cocoa trees (Appiah *et al*., 2000). Again, some studies carried out in Ghana concluded that young cocoa trees are sensitive to nitrogen and potassium fertilizers, especially when fertilizers are placed in the holes created for planting

(Wessel, 1971). Wessel (1971) observed progressive cocoa yields increase as rates of nitrogen ascend. Nonetheless, the impact of N at the highest rate was felt only as a result of phosphorus application (Wessel, 1971). This is to say that exchanges between N and P treatment have been experienced time after time (Ahenkorah and Akrofi 1968; Wessel, 1971; Ahenkorah *et al*. 1987). As such, the inability of cocoa trees to respond to nitrogen could be attributed to the limitation of phosphorus. Thus, where P is readily available, N may be lacking thereby increased demand for nitrogen base fertilizer (Wessel, 1971).

Wessel (1971) revealed that NPK fertilizer applied in the planting hole before transplanting of young cocoa seedlings depressed the growth of the plants in the initial growing season. Subsequent fertilizer application in split dosages and bands around the plants resulted in positive impacts (Wessel, 1971). Again, some studies carried out in Ghana concluded that young cocoa trees are sensitive to nitrogen and potassium fertilizers, especially when fertilizers are placed in the holes created for planting (Wessel, 1971).

The Cocoa Research Institute of Ghana (CRIG) and its partner, the Center National de Recherche Agronomique (CNRA) situated in Côte d'Ivoire currently do not right include N application for their public fertilizer programmes, albeit the two organizations are associated with experiments to evaluate its significance (van Vliet *et al*., 2015). This is on the grounds that at the time the programmes were set up, cocoa seedlings were developed under shade on generally rich soils that had not been under development for quite a while, clarifying the absence of reaction to nitrogen application (van Vliet *et al*., 2015). It is considerably more challenging to distinguish N inadequacies and the need for N fertilizer on cocoa farms by basic soil test since plants fascinate N from the soil as the mineral ammonium and nitrate particles. In that capacity, the powers of ammonium and nitrate inside a soil at some random time are the finished result of the dynamic harmony of mineralization and immobilization of nitrogen from litter and soil organic matter, plant take-up and losses through leaching, volatilization, and denitrification as perceived by van Vliet *et al*. (2015). This portrays instability or fluctuations in soil nitrogen subsequently serves as a constraint to soil test investigation as a sole marker of N insufficiency.

Meanwhile, Jadin and Snoeck (1985) stated that soil is deemed low in nitrogen when total N ranges from 1 - 2 per cent and then added that N application is only desirable when Total Exchangeable Bases is very high (TEB, 2 cmol/kg) > 8.9*N per cent. This was evident in Snoeck *et al.* (2010) which observed that 11 per cent of cocoa-producing regions in Ghana possess such characteristics. Wessel (1971) however suggested 1.5 per cent Total N as the lower limit of sufficiency, while Snoeck *et al*. (2010) only deemed soils insufficient where total nitrogen was below 0.6%.

2.2.5 Impact of nitrogen forms on cocoa

2.2.6 Nitrogen Resorption

The phenomenon where nutrients are mobilized from foliage tissues before the onset of abscission as well as senescence and redirected to meristematic tissues in plants is termed nutrient resorption. This is one of the major ways used by green plants in nutrient conservation. Resorption takes place during the life span of the leaf, most especially at shade formation (Ackerly and Bazzaz, 1995; Hikosaka, 1996). The phenomenon decreases the loss of nutrients as litter fall on the ground (Bormanon *et al*., 1977; Dawoe *et al*., 2010). Averagely, plants siphon roughly 5 – 80 per cent N by resorption (Wright and Westoby, 2003). Proportionally nutrients siphoned from foliage represent the efficiency of resorption which differs vastly between species and the condition of the surroundings. Studies carried out by Aerts and Chapin (2000) report of not less than 5 – 80 per cent of nitrogen contained in leaf and 0 – 95 per cent may be resorbed. As such, in infertile habitats, N in senescence leaf is decreased to lower levels as compared to fertile habitats (Wright and Westoby, 2003; Dawoe *et al*., 2010).

2.2.7 Nitrogen Use Efficiency

In a broader sense, nutrient use efficiency explains how judicious crop plants utilize nutrients. The efficient use of nutrients by crop plants is simply the inverse of nutrient concentration in senescence leaf. Consequently, plants found in areas deficient in nutrients are more efficient in nitrogen use whereas crop plants found in fertile areas are less efficient in nitrogen use (Vitousek, 1982; Tateno and Kawaguchi, 2002). Nitrogen use efficiency as an index may ease the explanation for species distribution across landscapes that vary in soil fertility and other resources (Vitousek, 1982; Schlesinger *et al*., 1989).

2.3 Soil Fertility Dynamics in a Cocoa Plantation

2.3.1 Cycling of Nutrient under Cocoa Plantation

Nutrient cycling simply refers to the constant mobility of nutrients between compartments in a given ecosystem. After earlier work done by Nye and Greenland (1960) on the pools and flows of nutrients in shifting cultivation systems, studies involve the cycling of nutrients have been progressing steadily. More so, the key channels of nutrient cycling have been identified to comprise stores and flows as well as gains and losses within an ecosystem (Young, 1989; Attiwill and Leeper, 1987). Nutrient pool in cocoa plantation exists both above-ground, in tree and crop biomass, below ground in plant residues, soil fauna, and soil organic matter available in a solution of soil. Flows within the system (recycling) include plant residues decomposition and soil organic matter and plant uptake. Thus, gains encompass N fixation, the addition of fertilizer, rainfall, and dry depositions. On the other hand, losses occur via leaching, erosion, and product removal (Young, 1997). Nutrient in fine roots turnover, pruned branches, and litter fall constitute recycled.

Research has shown that trees/shrubs through diverse means apportions extra N underneath the ground (Hobbie, 1992), interdependent exchanges with N fixing bacteria (Vitousek *et al.* 1987) or through different proneness to N deposition (Lovett and Lindberg, 1986), cause distress to rhizosphere with both roots and canopies. Conversely, Lovett *et al.* (2004), identified the chemical composition of leaf litter to be one of the best regulators. But there is a significant variation between broadleaved litter and coniferous species regarding their structure and composition. Thus, litter from broad leaved species possess rapid decomposition rate (López *et al.*, 2001), whereas those from coniferous soil has a higher soil organic matter and litter content, as a result of slower decomposition (Vesterdal *et al.*, 2013) and higher concentrations of humic acids and polyphenols (Northup *et al*., 1998).

2.3.2 Nutrients Inputs and Litterfall

In areas grown to plantation crops like cocoa, usually soils in such areas are intensively weathered and nutrient deficient so the production of litter serves as a basis for nutrients to be mobilized from vegetation to soil (Dawoe, 2009). An immediate resource of nutrients in a cocoa plantation is litter. However, the recycling and return of plants nutrient, as well as dead organic matter via litter fall pathway, is a gradual process (Martius *et al*., 2004). As such, nutrient transfer per annum is a function of nutrient concentration in litter fall and litter fall produced. According to Isaac *et al.* (2005), litter fall ranges from 2.9, 6.9, and 10.4 Mg ha^{-1} yr^{-1} for 2, 15, and 25-year-old cocoa trees, respectively. Also, cocoa plantation recorded a mean litter fall of 6.9 Mg (Owusu-Sekyere *et al*., 2006). Elsewhere in Nigeria, a value of 11.2 Mg ha^{-1} was reported from a work done on a 22-year old cocoa plantation (Opakunle *et al*., 1989). In addition to this, a review article on nutrient cycling in cocoa plantation concluded that the per annum average litter production of cocoa trees of different ages was 10 Mg ha-1yr^{-1} (Hartemink, 2005).

2.3.3 Decomposition of Litter

The breakdown of litter is referred to as decomposition. This complex process occurs when soil micro-organisms interact with their physical environment. The quality of the decomposed material is defined by the proportion of nitrogen, lignin, and condensed and dissolvable polyphenol present (Swift *et al*., 1979; Dawoe *et al*., 2010). Indigenously, the determination of litter fall rates is done using an airtight mesh bag for ease of materials recovery as well as modification of microclimate under which organism function efficiently. But the disadvantage is that humidity in litter bags is very high so conducive for microbes' action unlike the natural ecosystem (Vossbrinck *et al*., 1979).

Despite this, there is the tendency of under-estimation or over-estimation of decomposition rate depending on the sizes of mesh used. Despite its shortfalls, its relevance in the determination of nutrients as well as in comparative studies cannot be overlooked (Coleman *et al*., 2004). In the Sefwi Wiawso district in the Western-north region of Ghana, a study was done on a cocoa plantation and decomposition rates between 0.484 and 0.784 per month were recorded (Isaac *et al*., 2005).

2.3.4 Nutrient Balances in Cocoa

In a review article written on the cycling of nutrients in cocoa plantation and calculated nutrient balances from experimental data in the absence of inorganic fertilizer, Hartemink (2005) found the nutrient balance to be negative for all essential nutrients (Dawoe *et al*., 2010). For instance, the input and output balances of N, P, and K respectively were -25, -4, and -15 kg ha^{-1} yr^{-1} for Malaysia and -15.5, -2.8, and -44.0 kg ha^{-1} yr^{-1} for Cameroon. With fertilizer application, the balances in Venezuela and Costa Rica were -14.0, 24.7, and 10.6 kg ha^{-1} yr^{-1} and 100.7, 14.4, and 7.1 kg ha^{-1} yr^{-1} respectively (Dawoe *et al*., 2010).

These negative values recorded simply means that these essential nutrients were lacking or reducing (Gichuru *et al*., 2003). For this reason, Defoer *et al*. (2000) did indicate that available stocks or active soil nutrients should be the basis for nutrient balance assessment.

Furthermore, it was discovered that in cocoa systems, nitrogen detached by cocoa beans (yield) is lower than in litterfall. For Cameroon, N in the litter is generally multiplied by the sum of N in beans, however in Malaysia, the proportion is fivefold (Dawoe *et al*., 2010). His decision at that point was that if around 6000 kg N ha-1 is available in the soil, N detached by the yield is usually under 0.5 per cent. The expansion of N by wet and dry deposition was discovered to be genuinely high and gone from 1/6 to nearly ½ of the yearly nitrogen evacuation (Hartemink, 2005). In this way, nitrogen resorption in senesced leaves and nitrogen fixation in the leaf are critical to replenish soil lost nutrient on a cocoa plantation with nutrients from litter since litter is a central nutrient asset (Dawoe, 2009; Martius *et al*., 2004).

2.4 Fertilizer and Cocoa

Since the arrival of cocoa to Ghana, the crop is known to be cultivated on cleared virgin forest lands. These lands are noted for their inherent richness in soil nutrients which promote the growth, development, and yield of the cocoa trees without the addition of external nutrients to the soil (van Vliet *et al*., 2015). However, over the years the replenishment of cocoa soils has become necessary because forest lands used for cocoa production are either in limited supply or have had their nutrient base worn out as a result of continuous cultivation on yearly basis. As such, the use of fertilizer is it organic or inorganic has been identified as an agent for sustainable cocoa production together with the resurgence of soil fertility in forest areas. (van Vliet *et al*., 2015)

Despite this, several natural and manufactured fertilizers from diverse sources have been recommended for cocoa production. These fertilizers include Asaase Wura, Cocofeed, Cocoa Master, Cocoa Sett, Sidalco liquid fertilizers, Nutrismart, Natural Asontem, poultry manure, and cocoa pod husk. Although these have been tested and proven positive, Afrifa, *et al.* (2000) observed that they have unique characteristics. Thus, some are granular, liquid, have high P and K but lack nitrogen in the formulations (Cocofeed - N: P: K 0:30:20 and Asaase Wura - N: P: K 0:22:18), and others contain all the nutrients at varying concentrations of the nutrient elements.

Nonetheless, due to each distinct characteristic, the mode of application, as well as the rate of application and time of application, varies between them so must be considered. This implies that some could be by broadcasting or band placement, and foliar application. Most granular fertilizers are applied at 375 kg ha^{-1} by broadcasting at the onset of the rains whereas all liquid fertilizers are applied once monthly at a rate of 100 mL ha^{-1} (Afrifa *et al*., 2000).

2.4.1 Fertilizer Usage and Impact on Cocoa Production

In recent times, countless experiments concerning the impact of fertilizers on cocoa production have been carried out both on-farm and off-farm. Most often than not diversification in ecological zones, type of fertilizer, treatments, farm size, and cocoa exist (Ruf and Bini, 2012). Conceivably the most cited studies are the longstanding experiments spearheaded by Ahenkorah, Akrofi, and Adri, of the Cocoa Research Institute of Ghana (CRIG) in 1974. In that experiment, nitrogen response was occasionally significant though habitually negative. Correspondingly, the upsurge in the quantity of K applied was followed by Acquaye *et al*. (1965) and Ahenkorah and Akrofi (1968). In all instances, nitrogen was in ureic form, excluding the trial in 1956 referred to by Ahenkorah *et al*. (1974), where N was smeared as ammonium phosphate. Also, Evans and Murray (1953) administered nitrogen to their plot as ammonium sulphate.

According to Jadin and Snoeck (1985), the application of fertilizers to smallholder farmers' fields in Côte d'Ivoire resulted in a drastic increment in cocoa yield. With the aid of a soil diagnostic method, calculation was done to vary the number of nutrients added between the respective fields. Other fertilizer trials have also resulted in large yield increases due to fertilizer application (van Vliet *et al*., 2015).

Appiah *et al*. (2000) discovered cocoa yields of 97%, 29.6%, 24.3%, and 16.9% greater for four consecutive years in farms on which fertilizer was applied as treatments, in contrast to unfertilized farms. Gockowski and Sonwa (2011) in their review discovered normal cocoa yields in Ghana to be more than twofold those of Ivoirian farmers which they credited generally to more fertilizer use in Ghana. Wessel (1971) announced positive reactions to fertilizer application, despite the fact that the degrees of reaction differed from location to location, with no reaction at certain locations. Reactions to fertilizer additionally differed consistently.

As indicated by Wessel (1971), yield increments because of fertilizers came about because of increments in the quantity of pods as opposed to the unit content. Others additionally discovered expanded pod tallies (Asomaning *et al*., 1971). In spite of the fact that Asomaning *et al*. (1971) discovered fertilizer application to bring about slight increments in bloom production and slight abatements of Cherelle wilt, they credited expanded yields generally to expanded pod setting.

2.4.2 Instituting Fertilizer Scheme

In general, there are several mechanisms or approaches involved in establishing an efficient fertilizer programme for crop production. As such, the four basic approaches mostly utilized to establish fertilizer recommendations in cocoa production are nutrient balance analysis, soil analysis, leaf tissue analysis, and fertilizer response trials.

The underlying principle for nutrient balance analysis is a replacement. Thus, nutrients supplied to the soil through the application of fertilizer in crop production are meant to replace lost nutrients. As such, to determine nutrients lost via plant uptake, harvested parts of the crop are analyzed for their nutrient composition. Goh (2005) argued that nutrients immobilized in the tree for growth are also included in the balance most especially for plantation crops. Despite being straightforward and alluring, the following limitations exist;

1. Crop nutrient composition must be verified at least for each major production since it is influenced by environmental conditions and management practices.

2. To obtain high level of accuracy for nutrient balances, it is advisable to include losses of nutrient via leaching, as well as nutrient inputs through nitrogen fixation or atmospheric deposition, but not rely on fertilizer inputs and crop removal solely.
3. The core worry is that nutrient removal has minute bearing on the crops' nutritional requirements to attain adequate yields (De Geus, 1973).

Secondly, based on the notion that the availability of nutrients in soil corresponds to the output of a crop, soil testing is done. Thus, soil test analysis indicates soil nutrients available in the soil. Hochmuth *et al*. (2014) hinted that in an event where nutrients may be inadequate, fertilizer application serves as a compliment. However, the feasibility of soil analysis depends on the mobility of nutrient elements in the soil. As such, soil nutrients elements that are less motile like P, K, Mg, Ca, and micronutrients are commonly tested. According to Hochmuth *et al*. (2014) N undergoes several transformations making it greatly unstable. Both available N and total N content in the soil within a specific period could have a miniature bearing on consequent nitrogen availability to the crop. Manifestations of mineralization have been sought, but the pronouncement of a significant gauge of N availability utilizing soil analysis remains challenging (Geypens and Vandendriessche, 1996; Smethurst, 2000).

Consequently, fertilizer recommendations dependent on soil tests are made autonomously for every nutrient. Regardless of nutrient intuitive effects on plant development (Fitts and Nelson, 1956; Anderson and Nelson, 1975) and the foreseen response to a specific nutrient may happen when there is no limitation of different nutrients (Janssen, 1998; Johnston, 2005). Considering this, the Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) framework presented by Janssen (1990) could be normalized to fluctuate yields and developing conditions (Sattari *et al*., 2014), including plantation yields, for example, banana (Nyombi *et al*., 2010) and coffee (Maro *et al*., 2014) so as to develop fertilizer schemes.

Additionally, plant tissue analysis might be utilized to decide fertilizer prerequisites, particularly for plantation tree crops (Jones, 2012). As a rule, leaves are utilized in the examination, albeit different tissues may likewise be utilized (Foster and Prabowo, 2002). The measure of nutrients in the leaf is a proportion of the real nutrient up-take of the plant and may show a solid connection with yields (Foster and Prabowo, 2002). As the sum and mass division of nutrients in leaves change contingent upon variables, for example, season, physiological leaf age, and position on the plant, normalized examining procedures are required for a particular yield, and testing requires skills (De Geus, 1973; Smilde, 1985; Walworth and Sumner, 1987).

Also, nutrient substance of the cocoa leaf relies upon numerous variables separated from the adequacy of accessible nutrients in the soil, therefore with respect to nutrient insufficiencies might be deceiving when just dependent on soil testing. Since leaf nutrient content depends, among others, on leaf age, the improvement of new leaves and natural fruit bearing, light force, and occasional impacts (Acquaye, 1964). Notwithstanding, he keeps up that, this does not in any capacity nullify the handiness of foliar analysis in cocoa nourishment. Wessel

(1971) presumes that leaf investigation is principally helpful for recognizing and distinguishing articulated nutrient inadequacies. De Geus (1973) likewise recognizes and acknowledges the different restrictions of procedures for leaf examination and the understanding of its results. He also comments that if a checked lack exists, the little concentration in the leaf will supersede issues of testing and show the sort of fertilizer needed to address the inadequacy.

All the same, different researchers have referenced the utilization of leaf investigation for distinguishing nutrient lacks in cocoa. Nelson *et al*. (2011) for their examination in Papua New Guinea allude to Wessel (1985) as their wellspring of basic qualities, which are the best bet. Aikpokpodion (2010) additionally utilizes both soil and leaf tests to investigate nutrient elements in cocoa soils. The basic qualities utilized for centralizations of nutrients in leaf tests are 0.9% N, 0.2% P, 2.0% K, 0.6% Ca, and 0.5% Mg, which is substantially less for N yet bigger for Ca and Mg (Aikpokpodion, 2010).

Once more, an error is found among soil and leaf K concentrations, this time with K fixations in leaves almost continually being beneath the basic worth, while those of the soils had K fixations well over the basic convergence of K in cocoa soil utilized (something contrary to what Nelson *et al*. (2011) found). For different nutrients, the outcomes for correlation of both leaf and soil concentrations with basic qualities were practically identical, with N and Ca fixations being sufficient in both leaf and soil, and P and Mg contents being generally deficient. Of various fertilizer systems suggested by different researchers, nations, and associations, it is muddled what logical examination has been led to show up at them. It appears this exploration is restricted. At times, there is separation among areas or soils, however, frequently proposals are summed up for an entire nation, notwithstanding the variety of conditions under which cocoa is produced.

2.5 Soil Organic Matter

2.5.1 Soil Organic Matter

Soil organic matter (SOM) which forms a more noteworthy portion of soil ordinarily contains a high measure of nitrogen. Organic matter is liable for the structure of the soil, guides air circulation, and decides the water holding limit of the soil and exchangeable nutrients (Wood, 1985a). This suggests that its availability is critical as far as soil fertility is concern (van Noordwijk *et al.*, 1997).

Actually, a huge amount of soil organic matter is seen inside the soil. Despite the fact that under cocoa plantation the soil substance of total N, available P, CEC, and the entirety of exchangeable bases concerning certain pH limits associated with the organic matter substance of the soil emphatically (Wessel, 1971). In any case, this could be misleading whenever summed up. The soil organic matter definitely lessens because of disintegration, diminished litter flexibly, and expanded mineralization in the uncovered soils. As such sufficient organic matter is accessible when a shut overhang is framed and can be kept up for an extensive stretch when yields are little and the canopy remains unblemished (Cunningham and Arnold, 1962; Wessel, 1971).

Ahenkorah *et al*. (1974) contended that around 40% – 60% soil carbon decline was observed in the 0-15 cm layer of soil on a fifteen years' cocoa farm. Misfortunes were bigger when C fixations in developed cocoa plots were contrasted with plots at planting after forest land clearing (Ahenkorah *et al*. 1987). Ofori-Frimpong *et al*. (2007) discovered misfortunes in a comparative reach when contrasting forest land with unshaded cocoa (4.0 to 1.7% in the 0-15 cm layer). Ahenkorah *et al.* (1987) found that about 44.5 t/ha of soil organic matter was lost in 16 years, and Ahenkorah *et al*. (1974) discovered misfortunes of 55 t/ha in a long time from the soil (0-15 cm) in Ghana. In Nigeria, soil C was discovered to be almost 3% under forest land while it was below 2% under cocoa plantation (Hartemink and Donald, 2005).

2.5.2 Soil Organic Carbon and Nutrient Changes

After texture, acidity and salinity, organic carbon content is the variable having the best effect on soil properties. Long-term experiments show that the content of soil organic carbon (SOC) is the result of a balance between the inputs and outputs of organic carbon (Johnston *et al*., 2009; Lützow *et al*., 2006). The principal C inputs are plant roots and root exudates, over the ground plant build-ups and excrements or other organic by-products. Outputs are the decomposition of organic matter by soil microorganisms and fauna leading to the evolution of carbon dioxide to the atmosphere (or Methane under anaerobic conditions), leaching of soluble organic C compounds, and particulate losses through erosion.

Decomposition is regularly the prevailing yield measure and is constrained by clay content, temperature, dampness substance, and oxygen accessibility inside the soil. Soils with a higher content of clay-sized particles, or higher cation exchange capacity, normally move towards a higher equilibrium content of organic C than sandy soil due to their greater capacity for stabilizing microbial metabolites. The complete SOC content of the soil under indicated the management practices can frequently be anticipated with some achievement utilizing a few momentum models (Smith *et al.*, 1997). However, further exploration is needed for certain circumstances including peat soils, recreating effects of decreased culturing and the elements of divisions inside the aggregate.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Experimental Sites

This research work was conducted in both the Central and the Western-North Regions of Ghana. The Central Region is one of the emerging cocoa-producing regions in Ghana. The Western-North Region is known to be the largest cocoa producing region in Ghana accounting for about 50 per cent of the cocoa produced yearly. One administrative district from each of the respective regions was selected for an on-farm farmer participatory study. Communities within the district known to be prominent in cocoa production were selected. The Twifo Hemang Lower Denkyira District (THLDD) and the Bibiani-Ahwianso-Bekwai District (BAB) of the Central region and the Western-North Region, respectively, were selected.

3.1.1 Description of the Districts

THLDD is located within latitude 5’50° N, 5’51° N and longitude 1’50° W, 1’10° W and shares borders with Upper Denkyira East Municipality at the North, to the South, with Abura Asebu Kwamankese, Cape Coast Metropolis and Komenda-Edina-Eguafo-Abirem Municipality, to the West with the Wassa Mpohor East District and lastly to the east with Assin North and Assin South Districts. THLDD has a total land area of about 1,199 km^2 containing 1,510 settlements, with a total population of 166,224 and growth rate of 4.1 per cent. The majority of the people are farmers who are into either food crops production or cocoa production (MoFA, 2019).

The Bibiani-Anhwiaso-Bekwai District (BAB) is one out of the 13 administrative districts found in the Western-North Region of Ghana. The district is a major contributor to cocoa production in Ghana (Vigneri, 2008). The district is located inside scope 6° N, 3° N and longitude 2° W, 3° W. It covers a territory of 873 km^2 representing 8.6 per cent of the absolute land zone of the district. Bibiani, the district capital is 88 km from Kumasi in the Ashanti Region and 356 km from the regional capital, Sekondi (Bibiani-Anhwiaso-Bekwai District, 2005). The district is bordered on the North by the Atwima Mponua District in the Ashanti Region, South by the Wassa Amenfi in the Western area, West by the Sefwi Wiawso District in the Western Region and East by the Denkyira North and Amansie East in the Central area and Ashanti District. The district has human population of around 123,727 with 48.8% and 51.2% being male and female, respectively (GSS, 2012).

3.1.2 Climates of Study Districts

The BAB district is favoured with the most suitable climate for the cultivation of most crops, most especially cocoa production because it is within the equatorial climate with an amount of 1200 mm - 1500 mm precipitation per annum. This occurs between March-August and September-October and the peak periods are June and October which makes it bimodal. However, the dry season is mostly November-January (BAB, 2005). During the year, the mean temperature is about 26°C. There is a high relative humidity averaging between 75% in the afternoon and 95% at night and early morning (BAB, 2005).

On the other hand, THLDD lies within the semi-equatorial zone characterized by a bimodal rainfall pattern peaking in June and October, and with an average annual rainfall of 1750 mm. It has a fairly high uniform temperature ranging between 26^{o}C in August and 30^{o}C in March. The relative humidity is around 70 – 80 % during the dry season and 75 – 80 % during the rainy season (MoFA, 2019).

3.1.3 Agro-Ecological Zones and Vegetation

The THLDD is made up of semi-deciduous forest which has been partly disturbed by the activities of farming, mining as well as logging. Also, forest reserves such as the Kakum National Park, Bimpong Forest Reserve, Pra Suhyen Forest Reserve, Minta Forest Reserve, and Bonsaben Forest Reserve altogether cover about 24 % of the entire land area of the district (MoFA, 2019).

The BAB district falls within the Equatorial Rain Forest Zone which is characterized by the moist-deciduous forest which is dominated by Celtie-Triplochiton Association. Naturally, vegetation or tree species found in this area include, Nyamedua, Sapele, Mahogany and Odum (BAB, 2005).

3.1.4 Soils of Study Districts

The THLDD has five main types of soils namely; Nsaba-Swedru Compound, Nta-Offin Associates, Asuanzi-Kumasi Associates, Bekwai-Nzema-Oda Compound, and Juaso-Manso-Kyekyewere-Kakum Compound. The Watreso town is characterized by Asuanzi-Kumasi Associates. The Watreso town was chosen for the on-farm trial because it is one of the major cocoa-producing communities in the THLDD and part of the Dunkwa cocoa district according to

COCOBOD. These are soils developed over Tarkwaian rocks, which are moderately drained and are suitable for the cultivation of tree crops like cocoa and forestry products. They also support food crops such as plantain, maize, banana, cocoyam and cassava. However, they are low in soil nutrients and require nitrogen and phosphorus fertilizer application (THLDD, 2019)

On the contrary, soils commonly found in the BAB district are forest Ochrosols and forest Oxisol. The rich forest Ochrosols and forest Oxisols soils are known to be very suitable for the cultivation of arable crops such as maize, rice, cassava, cocoyam and vegetables; and plantation crops such as cocoa, coffee, oil palm, citrus fruits, etc.

Aside from the agricultural use of land in the BAB district, these soils allow for land use systems as natural forests and sources of minerals with higher economic value. The Oxisol soils are known to contain gold and bauxite mineral deposits making mining the most essential and profitable venture economically in the district (BAB, 2005).

3.2 Experimental Setup and Design

3.2.1 Farms Selection

The selection of farmers and their farms were based on some well-defined recommendation domain criteria (University of Reading Statistical Services Centre - URSSC, 1998). The recommendation domain described a set of farmers with similar land or field features and access to similar resources. The features and resources such as soil type, cocoa genotype(s) under cultivation, climate, topography, a canopy cover of shade trees; and agro-economic features such as access to resources and marketing opportunities, tenants, and owners, etc., were considered. Site selection was also based on farm size, age of plantation, or trees (young and mature). Thus, cocoa trees between 5 and 9 years old and cocoa plantation above 10 years old represented young and mature, respectively. Distance between farms and above all farmer's willingness to have a trial on his farm was strongly considered.

Within each region, stratified multistage sampling was used, with a cocoa farming community as the primary unit and farming household and hence, farms as secondary units. Accordingly, two representative farms were selected from each region and from the relevant groups of farms or farmers who fulfilled the basic requirements of the recommendation domain and were eligible for the trial. Farms in each region were selected such that they were at least 2 km apart.

The Instrument Used and its Structure

A semi-structured questionnaire was used to collect primary data, based on a wide range of themes to assess soil-plant nutrition practices for cocoa in two Agro-Ecological Zones. The questionnaire was structured to include both open-ended or close-ended questions. Before the administration of the questionnaire, pretesting was done at Jukwa to validate the content to achieve the set objectives of the study (Whitehead, 2000). Questionnaires were administered in the local language by one-to-one discussions with individual farmers. Questions were categorized into three sections; (1) demographics of cocoa farmers (age, sex, educational background, annual income); (2) soil-plant nutrition practices for cocoa (fertilizer application rate, type of fertilizer, frequency of application, impact of nitrogen), and (3) willingness of farmers to allow on-farm trials (land size, duration permitted, monetary compensation, etc.) (see Appendix A).

3.2.2 Nitrogen (N) Treatments

Inorganic commercial fertilizer as nitrogen sources were used in the trial. N treatments were N applied as ureic-nitrogen ($(NH_2)_2CO$), ammonium-nitrogen (NH_4-N) or nitrate-nitrogen (NO_3-N) in the rate of: (i) 20 kg ha^{-1} (low); (ii) 30 kg ha^{-1} (medium) or (iii) 40 kg ha^{-1} (high). Additionally, control treatments of no N fertilizer application and farmers' practice fertilizer application were also included.

Even though this work was done on farmers' fields, control treatment of no N fertilizer application was crucial and justifiable irrespective of its detrimental effect, because the overarching objective of this study was to assess the gain from adding fertilizers (URSSC, 2000). Moreover, since this is an on-farm trial, a second control treatment of a farmer's normal practice (FP) was critical. Local farmers' usual cocoa farming practices are characterized by specific organic and inorganic fertilization which were elicited from response to questions on application rates and frequency of fertilizer application on respective farmers' fields, in the questionnaire. Using these rates and how frequent a farmer applied fertilizer on his or her farm, the farmer's practise (FP) N application rates were arrived at. Hence, the experiment was a "2 x 2 x 3 x 5" factorial treatment structure resulting in 60 treatments with four factors, namely Agro-Ecological Zone, farm age, N-form and N-rate.

The fertilizer application was done once in June 2019. However, fertilizer application was carried out in the Western-North Region one week after the application was completed on selected farms in the Central Region to allow for logistics. On the field, fertilizer treatments were administered on each 49m^2 plots size with a maximum of seven cocoa trees selected on each plot. The base of individually selected trees was cleared off litter with a cutlass to have access to the root zone to ease application. Individual treatments were then applied in the ring drawn within the root zone of selected trees and covered with soil to prevent losses through volatilization.

3.2.3 Experimental Design

The experimental design was Randomized Complete Block Design (RCBD) with four replications. Treatments were randomized within farmers' plots. As such, farmers' knowledge about the variation in their fields was exploited to determine the location of the plots and blocking scheme (two blocks per farm) and to avoid using particular patches of the field where necessary. These blockings were further aided by labelled plates with distinct colours. Plot size or the number of trees per treatment depended on the characteristics of each farm and was done in consultation with the respective farmers. Though farm size varied, each experimental plot measured 7 m by 7 m with at most seven (7) trees per plot and in all a total of sixty (60) plots on each farm because each treatment was replicated four times. The boundaries of the plots were marked with nylon ropes to delineate them from other portions of the farms.

3.3 Data Collection and Procedures

3.3.1 Sampling of Soil

Before the application of treatments, soil samples were collected from each site for the determination of the physicochemical properties of the fields. At each farm, soil samples were collected up to a depth of 30 cm, properly mixed to ensure representativeness and bulked into polythene bags (sampling bags). Upon arrival at the laboratory, the soils were air-dried individually under shade for six days after which each sample was crushed and sieved through a 2 mm sieve in preparation for analysis of their physicochemical properties at the University of Cape Coast Soil Science laboratory.

After fertilizer application, sixty (60) soil samples from each farm were also collected on a plot/treatment basis using a soil core down to 0 -15 cm and 15 -30 cm soil depth three times, at 2, 4 and 6 months after setup (MAS) during the entire duration of the experiment. This periodic sampling of soils was performed specifically for soil mineral nitrogen content determination, soil organic carbon, and pH.

The total soil N content was determined by the Kjeldahl method. Soil organic carbon contained in each soil sample was determined by the Walkley-Black method (1935). Also, a standard pH metre was used in determining soil pH, respectively.

Procedure for Soil Nitrogen Determination

Soil samples weighing between 0.5 – 0.52 g were transferred into well-labelled oven-dried digestion flasks and 0.2 g of selenium catalyst then a burette was used to add 3 mL of concentrated H_2SO_4 to each flask in preparedness for digestion. These flasks were gently heated on a bloc digester until the temperature gradually increased to 380^o C for about 120 minutes of digestion. Samples were allowed to cool until just warm and then diluted with distilled water to about 100 mL before distillation. At the distillation phase, a steam distillation apparatus was set up and allowed for steam to pass through it for 30 minutes, after which the apparatus was flushed to get rid of impurities that could contaminate the samples. Then 5 mL of boric acid indicator solution was pipetted into each 100 mL conical flask which was placed under the condenser of the distillation apparatus. Through the trap funnel, a 20 mL aliquot of the sample digest was transferred to the reaction chamber and then 10 mL of alkali mixture was added to commence distillation after which about 50 mL of distillate was collected. To reduce experimental error, the apparatus was rinsed thoroughly with distilled water after each sample distillation. Immediately after each distillate collection, this was titrated against 1/140 M HCl from green to wine red and titre values were recorded which were used in calculating the total nitrogen content.

% Nitrogen = Titre value of sample (ml) × Normality of acid (0.02) × 1.401 Weight of sample (g)

Procedure for Soil Organic Carbon and Organic Matter Determination

Organic carbon was determined by following the procedures of Walkley and Black, 1935. The soil sample was weighed in duplicates ranging from 0.50 – 0.52 g and transferred into a 500 mL Erlenmeyer flask. Using a pipette, 10 mL of $K_2Cr_2O_7$ solution was added to each sample and then swirled gently after which 20 mL concentrated H_2SO_4 was added whilst being swirled gently for about 60 seconds and allowed to stand for half an hour. The addition of concentrated H_2SO_4 was to cause heat to be evolved to drive the reaction to completion. After 30 minutes of standing, the content was diluted with distilled water up to the 200 mL mark and then swirled again to ensure thorough mixing. Subsequently, 10 mL of H_3PO_4 and 0.2 g NaF were added to complex Fe^{3+}. Before titration, 1 mL of diphenylamine indicator was added before titration. Titration was done with a 0.5 M Ferrous ammonium solution to a green endpoint, and the titre value was recorded for each sample including the blank which contained all the reagents except soil (Walkley and Black, 1935).

Procedure for Soil pH Determination

10+/- 0.1 g air-dried soil samples were weighed into a bottle and then 25 mL of distilled water was added. The sample was transferred to a mechanical shaker for shaking for 15 minutes. The electrode was then inserted into each soil suspension and the pH was recorded for each sample. This was done in duplicates.

3.3.2 Sampling of Leaves

Matured fresh green leaves were detached manually from branches of cocoa trees within each experimental plot. These leaves were sampled at 2, 4 and 6 months after setup (MAS) for the entire duration of the experiment (June 2019 to June 2020). At each sampling time, four representative leaves were taken from at least four representative cocoa trees found on each plot and put into a brown envelope and sealed. These leaves upon reaching the laboratory were weighed on an electronic balance and each fresh weight (FW) was recorded. Leaves were then dried in an oven at 70^o C for two days after which they were weighed on an electronic balance and each dry weight (DW) was recorded. Samples were milled using a mechanical miller, into powder and kept in zip lock bags in readiness for chemical analysis.

Cocoa leaves observed to be at the senescing stage characterized by yellowish colour were sampled manually by shaking of cocoa trees within each experimental plot on which treatment was applied. These leaves were sampled at 2, 4 and 6 MAS. At each sampling time, four representative leave samples were taken from at least four representative cocoa trees found on each plot and put into a brown envelope and sealed. These leaves upon reaching the laboratory were weighed on an electronic balance and each FW was recorded. Leaves were then dried in an oven at 70^o C for two days after which weighed on an electronic balance and each DW was recorded. Samples were milled into powder and kept in zip lock bags in readiness for chemical analysis.

3.3.3 Sampling of Litter fall

To track litterfall for efficient collection, litter traps (1 x 1 m, 50 cm above the ground) (Fig. 2) made from PVC pipe and net were installed in a manner to capture litter from at least four targeted cocoa trees in each plot to collect litter at two-monthly intervals for the period. Care was taken to ensure that only litter from cocoa trees fertilized was collected. These litters were sampled at 2, 4 and 6 MAS. At each collecting time, all cocoa litter found in the litter trap on each plot was hand-picked, put into a well-labelled brown envelope, sealed, and carefully packed into sacs. These were transported to the laboratory where each sample was weighed on an electronic balance for the FW. Litters were then dried in an oven at 70° C for two days after which it was weighed on an electronic balance to record each DW. Samples were cut into pieces and later milled into powder and kept in zip lock bags for subsequent chemical analysis.

Figure 2: Litter traps installed to collect litter at two-monthly intervals for the period.

3.3.4 Cocoa Yield Determination

Cocoa yield data were determined by recording the weight of pods harvested from fertilized plots throughout the season (approximately 4 months) after fertilizer application and by weighing the dried beans from each plot after fermentation (Asare *et al*., 2019). Briefly, mature cocoa pods from each treatment plot were harvested starting from October to December during the harvesting period and composited on a plot basis to constitute a treatment yield. The weight of pods on each plot at each harvest was recorded, after which the beans were fermented in air-tight sacs for 5 – 6 days as recommended by the Cocoa Research

Institute of Ghana (CRIG). The fermented beans were then sun-dried and weighed. Yield data recorded on plots were extrapolated to kg ha^{-1} for easy interpretation (Asare *et al*., 2017).

3.3.5 Measurement of Plant and Nutrient Uptake Parameters

To measure nitrogen uptake and nitrogen use efficiency of well-developed, senesced cocoa leaves and litterfall, tissue analysis was conducted using the Kjeldahl method which was adopted by Triadiati *et al*. (2007) in determining leaf nitrogen concentration.

Subsequently, nitrogen use efficiency parameters including the nitrogen use efficiency of the cocoa plants (NUEc), the nitrogen use efficiency at the ecosystem scale (NUE_{ES}) and the proportional nitrogen resorption were derived according to formulae 1 - 3, respectively as described in Triadiati *et al*. (2007) as follows:

The nitrogen use efficiency of the cocoa plants (NUE_C) was derived by:

$$NUE_c = \frac{1}{nitrogen\ concentration\ in\ senescent\ leaf\ (\%)} \qquad \text{(Eqn. 1)}$$

The nitrogen use efficiency at the ecosystem scale (NUE_{ES}) (i.e.: NUE at the plot level) was derived by:

$$NUE_{ES} = \frac{Litterfall\ production (g\ m^{-2} y^{-1})}{N\ content\ in\ litterfall (g\ m^{-2} y^{-1})} \qquad \text{(Eqn. 2)}$$

The proportional nitrogen resorption was derived by:

$$Resorption\ (\%) = \frac{Nd - Ns}{Nd} \times\ 100\% \qquad \text{(Eqn. 3)}$$

Where Nd: Nitrogen in well-developed leaf, Ns: Nitrogen in senesced leaf.

3.4 Statistical Data Analysis

Data derived from soil physicochemical properties, the nitrogen content of leaf tissues, nitrogen resorption, and nitrogen use efficiency were analyzed using the Genstats software (19th Edition) package. Analysis of variance (ANOVA) was used to test the significance of the effects of treatments. The least significant difference (LSD 5%) was used to compare the different treatments where there were significant differences in the means. Primary data collected through questionnaire administration was coded and entered into Statistical Package for Social Science (SPSS version 16) and then analysed into frequencies and percentages.

CHAPTER FOUR

RESULTS

4.1 Soil-plant Nutrition Practices among Cocoa Farmers

Findings from the survey conducted are presented in Tables 1 - 3 which cover farmers' socio-economic data and soil-plant nutrition practices among cocoa farmers in both Western-north region (Evergreen Forest Zone) and Central region (Coastal Savannah Zone). A total of one hundred and twenty (120) cocoa farmers were interviewed from both Agro-Ecological Zones. Majority of the respondents were males and were distributed amongst various age groups with 56.7 per cent within the age bracket 30-50 years. A greater percentage (72.5%) of the cocoa farmers were literate with 87 (68.3%) having gone through basic education and 5 per cent with tertiary education. Most of the respondents (80 farmers) representing 66.7 per cent have been in farming over a decade while a smaller number, 13 and 27, representing 10.8 and 22.5 per cent, respectively, have less than 5 years and between 5-10 years of cocoa farming experience. Slightly higher than half (67.5%) representing 81 of the farmers earn between GHc 2500 to GHc 5000, whiles 18.3 per cent earn more than GHc 5000 annually and just a handful (5%) earning less than GHc 1000 annually. Farmers had one or more farms and had the same or different varieties of cocoa growing on these farms (Table 1).

Table 1: Demographics of interviewed cocoa farmers

VARIABLE	POPULATION (N)	PERCENTAGE (%)
Gender		
Male	92	76.7
Female	28	23.3
Age		
Less than 30 years old	7	5.8
Between 30 and 50 years old	68	56.7
51 years old and above	45	37.5
Education		
Educated	87	72.5
Uneducated	33	27.5
Educational level		
Basic	82	68.3
Secondary	32	26.7
Tertiary	6	5.0
Farming experience		
Less than 5 years	13	10.8
Between 5 and 10 years	27	22.5
10 years and above	80	66.7
Yearly income		
Less than GH¢1000.00	5	4.2
Between GH¢1000 and GH¢2500.00	12	10.0
Between GH¢2500 and GH¢5000.00	81	67.5
GH¢5000.00 and above	22	18.3
Total number of respondents	**120**	

Farmers indicated that they use both organic and inorganic fertilizers but to varying degrees. Approximately 79.2% of the respondents used inorganic fertilizer on their farms with a small proportion (20.8%) using organic fertilizer. Farmers who applied organic manure sourced it from manure dealers, COCOBOD (green OK), poultry farms and farmers' farm. The inorganic fertilizers were recommended to farmers by Agricultural Extension officers (46.7%), COCOBOD (12.5%), colleague farmers (15.8%) and agrochemical dealers (25%) (Table 2). Farmers use inorganic fertilizer in both liquid (foliar) and granular forms with the majority of such applications (72.5%) being done in liquid forms. On the frequency of fertilizer application (organic and inorganic), more than half of the farmers interviewed (65% for organic; 58.7% for inorganic) indicated application frequencies more than once a year (Table 2).

On the blend of fertilizers used by the cocoa farmers, the survey revealed that the use of granular NPK was on the decline whilst a greater percentage of farmers who indicated 'others' did so by foliar means which largely comes from Sidalco foliar fertilizer (74.2%), lithovit foliar (56.9%), Asaase wura (43.7%). Other variant fertilizers used were coco feed (31.8%) and a compound blend of NPK 15:15:15 (17.9%) (Table 3).

Table 2: Soil-plant nutrition practices among cocoa farmers

GROUPS	POPULATION (N)	PERCENTAGE (%)
Fertilizer applied (120)		
Organic	25	20.8
Inorganic	95	79.2
Source of fertilizer Organic		
COCOBOD	74	61.7
Farmer's farm	7	5.8
Poultry farm	23	19.2
Manure dealer	16	13.3
Inorganic		
Agriculture extension agent	56	46.7
COCOBOD (CHED)	15	12.5
Friends	19	15.8
Agrochemical dealer	30	25
Kind of inorganic fertilizer applied		
Liquid	63	72.5
Granular	57	27.5
Frequency of application		
Organic		
Once annually	42	35
More than once annually	78	65
Inorganic		
Once annually	52	41.3
More than once annually	74	58.7
Total number of respondents	**120**	

Table 3: Specific types and mostly used fertilizers

TYPES OF FERTILIZER	POPULATION (N)	PERCENTAGE (%)
Organic (n = 108) *		
Poultry manure	29	26.8
Green OK	44	40.7
Cocoa pod husks	35	32.5
Inorganic (n = 151) *		
Asaase wura	66	43.7
Coco feed	48	31.8
Sidalco	112	74.2
Lithovit foliar	86	56.9
NPK	27	17.9

***Respondent selected multiple options**

4.2 Soil Chemical Attributes

Soil chemical properties of the sites before treatments application are presented in Table 4. In all the parameters measured, the soil under cocoa plantations in the selected farms and Agro-Ecological Zones were very low in essential nutrients. However, soil pH for both the topsoil and the subsoil sampled recorded higher value which was observed to be fairly optimum in most cases. Nonetheless, soil from the Forest Zone was more acidic compared to the soil from the Coastal Savannah (Table 4).

Table 4: Results of initial Soil chemical properties

Agro-Ecological Zone	Farm	pH (H_2O)	Total N (%)	Ava. P (ppm)	Exc. K (ppm)	CEC (cmolkg^{-1})	O.C (%)
Coastal Savannah	Mature	7.4	0.12	10	55	13.4	0.97
	Young	7.8	0.07	7	75	17.7	0.82
Evergreen Forest	Mature	4.6	0.03	4	38	5.0	0.51
	Young	5.5	0.06	5	24	7.1	0.89

Table 5 shows the results from soil analysis done on soil samples collected at harvest after application of fertilizer treatments on both mature and young cocoa farms across the two Agro-Ecological Zones. There was an improvement in most of the parameters measured. Also, there was slight increase in the level of the essential nutrients under cocoa plantations in the selected farms and Agro-Ecological Zones. However, soil pH values were observed to be fairly optimum in most cases. Nonetheless, soil from the Forest Zone was more acidic compared to the soil from the Coastal Savannah (Table 5).

Table 5: Results of final Soil chemical properties

Agro-Ecological Zone	Farm	pH	Total N (%)	Ava. P (ppm)	Exc. K (ppm)	CEC (cmolkg^{-1})	O.C (%)
Coastal Savannah	Mature	6.5	0.19	12	62	15.4	1.0
	Young	6.2	0.31	9	95	19.7	0.95
Evergreen Forest	Mature	5.6	0.13	7	34	6.2	0.61
	Young	4.5	0.21	9	27	9.1	1.09

4.3 Cocoa Yield

4.3.1 Weight of Pods per Plot (kg/m^2)

The weight of pods per plot recorded was significantly higher ($p < 0.05$) in the Coastal Savannah Agro-Ecological Zone than that of the Forest Zone (Fig. 3). There was a highly significant difference ($p < 0.001$) in the weight of pods produced between the mature cocoa farm and young cocoa with higher values derived from young cocoa farms in both Coastal Savannah and Evergreen Forest Zones (Fig. 3). Yet, the young farms in the Coastal Savannah recorded the highest value (28.33 kg/m^2) (Fig. 3a) whereas the mature farm in the Coastal Savannah recorded the lowest value (15.8 kg/m^2). In the Forest Zone, the weight of pods per plot was significantly different ($p < 0.05$) between the mature and young farms, where the mean values were 17.74 kg/m^2 and 19.46 kg/m^2, respectively (Fig. 3b).

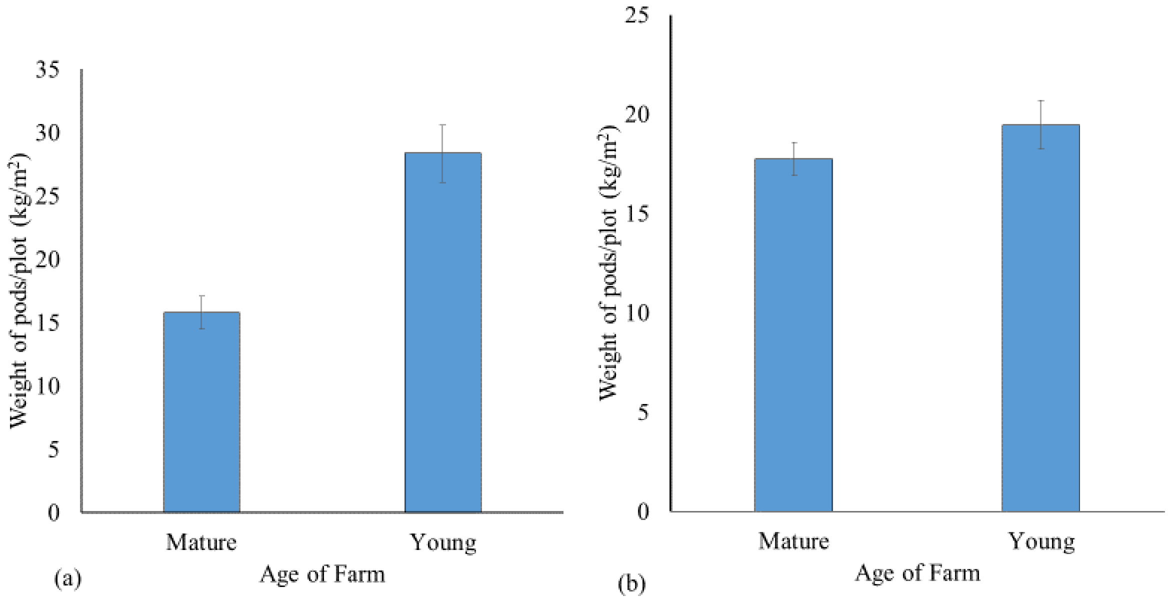

Fig 3a: Coastal Savannah

Fig 3b: Evergreen Forest

Figure 3: Cocoa pod yield of mature and young cocoa trees in the Coastal Savannah and Evergreen Forest Zones**.**

Analysis of variance showed a significant difference ($p < 0.05$) in the weight of pods per plot recorded at the various zones. There was a significant difference ($p < 0.05$) in the weight of pods per plot amongst the nitrogen forms in the Coastal Savannah (Fig. 4a). Likewise, in the Forest Zone, the weight of pods per plot recorded was highly significantly different ($p < 0.001$) amongst the nitrogen forms (Fig. 4b). The highest mean pod weight per plot was recorded for nitrate in the Coastal Savannah (24.61 kg/m^2) (Fig. 4a), which was significantly different from that of the Forest Zone (20.52 kg/m^2) (Fig. 4b). In the Coastal Savannah, the mean pod weight per plot for ammonium was 16.7 kg/m^2 which was lower than 17.18 kg/m^2 recorded in the Forest Zone (Fig. 4), whilst in the Coastal Savannah, the mean pod weight per plot for urea treated field was 23.6 kg/m^2 which was higher than 18.07 kg/m^2 recorded in the Forest Zone (Fig. 4).

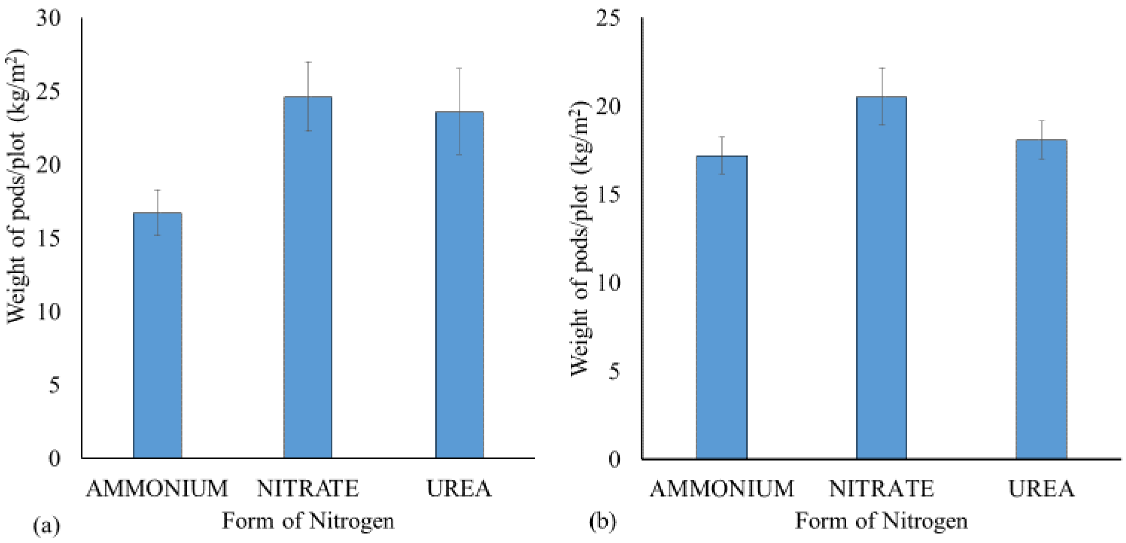

Fig 4a: Coastal Savannah

Fig 4b: Evergreen Forest

Figure 4: Cocoa pod yield in terms of nitrogen forms in the Coastal Savannah and Evergreen Forest Zones.

Figure 5 shows the effect of nitrogen rates on the yield of cocoa for both the Coastal Savannah and Evergreen Forest Zones. For the Coastal Savannah (Fig. 5a), there was no significant difference ($p = 0.366$) in weight of pods per plot between the fertilizer application rates. On the contrary, for the Forest Zone (Fig. 5b), there was a significant difference ($p < 0.001$) in the weight of pods per plot between the fertilizer application rates. In general, cocoa pod yield increased at an increasing level of N rates (Fig. 5). Yet, cocoa farms fertilized according to farmers practice (FP or 10 N kg/ha) in the Forest Zone recorded the highest mean cocoa pod yield (20.46 kg/m^2) as compared to 19.61 kg/m^2 recorded for trees fertilized at 40 N kg/ha. On the other hand, in the Coastal Savannah trees fertilized at 20 N kg/ha recorded the highest value (24.83 kg/m^2) (Fig. 5a) whereas trees fertilized at 30 N kg/ha recorded the lowest value (18.61 kg/m^2).

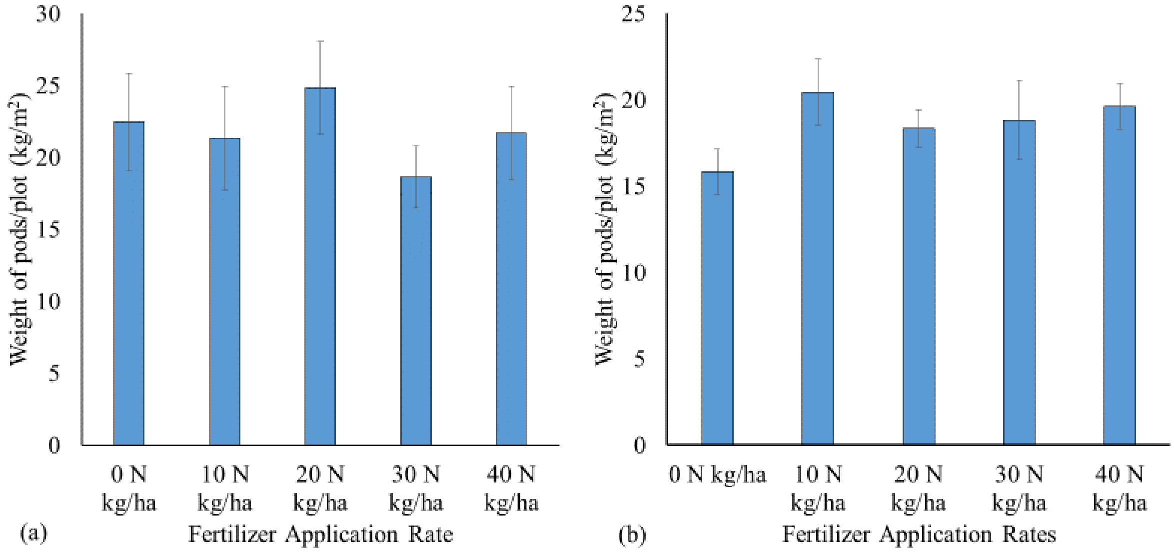

Fig 5a: Coastal Savannah

Fig 5b: Evergreen Forest

Figure 5: Cocoa pod yield at different rates of N fertilizer application in the Coastal Savannah and Evergreen Forest Zones.

Figure 6 shows the variation in cocoa yield recorded for the Coastal Savannah and Evergreen Forest Agro-Ecological Zones. Figure 6a shows the effect of nitrogen forms on cocoa pod yield of mature and young cocoa farms in the Coastal Savannah Agro-Ecological Zone whilst Figure 6b represents the effect of nitrogen forms on cocoa pod yield of mature and young cocoa farms in the Evergreen Forest Agro-Ecological Zone. Analysis of variance revealed a highly significant difference ($p < 0.001$) in the weight of pods per plot recorded for the interactive effect between the age of farm and form of nitrogen for both Agro-Ecological Zones (Fig. 6). For example, young cocoa trees treated with nitrate-based fertilizer recorded the highest yield of 35.73 kg/m^2 (Fig. 6a) whereas mature cocoa trees treated with nitrate-based fertilizer recorded the lowest (13.5 kg/m^2) mean pod weight per plot (Fig. 6a).

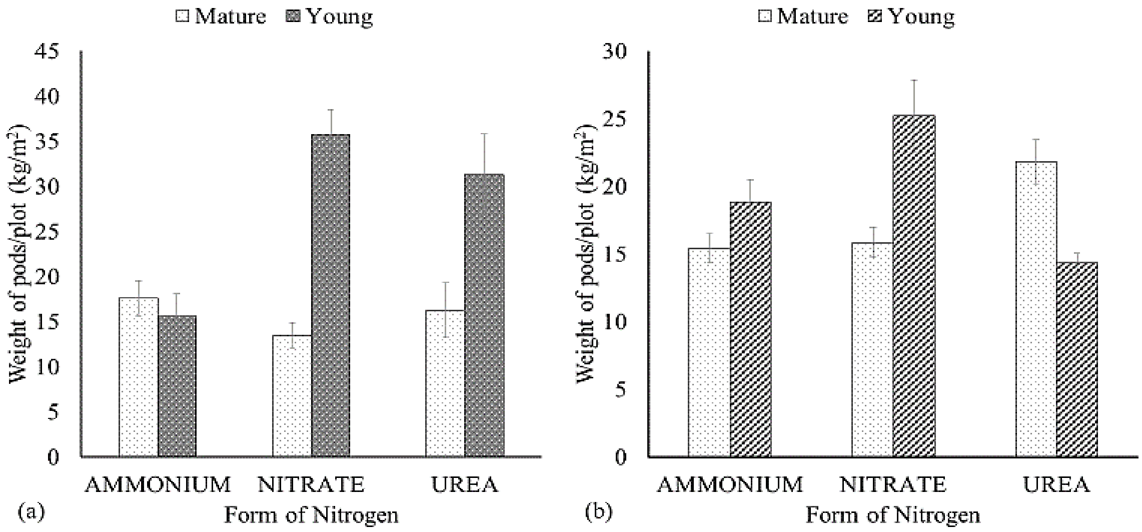

Fig 6a: Coastal Savannah

Fig 6b: Evergreen Forest

Figure 6: Cocoa pod yield of mature and young farms with respect to different N forms in the Coastal Savannah and Forest Zones.

The variation in cocoa yield recorded for the Coastal Savannah and Evergreen Forest Agro-Ecological Zones is shown in Figure 7. The effect of varied N-rates on cocoa pod yield of mature and young cocoa farms in the Coastal Savannah Agro-Ecological Zone is presented in Figure 7a whilst Figure 7b represents the effect of varied N-rates on cocoa pod yield of mature and young cocoa farms in the Evergreen Forest Agro-Ecological Zone. Analysis of variance revealed no significant interaction ($p = 0.681$) between the age of farm and N-rates on the weight of pods per plot recorded in the Coastal Savannah (Fig. 7a). However, the Forest Zone indicated a highly significant ($p < 0.001$) interactive effect of age of farms and N-rates on the weight of pods per plot. Cocoa pods yield recorded in the Coastal Savannah shows that young cocoa trees fertilized at 20 N kg/ha recorded the highest yield of 34.36 kg/m^2 (Fig. 7a) whereas mature cocoa trees fertilized at 30 N kg/ha recorded the lowest mean (14 kg/m^2) (Fig. 7a). Young cocoa trees fertilized at 10 N kg/ha recorded the highest yield of 22.29 kg/m^2 (Fig. 7b) whereas mature cocoa trees fertilized at 30 N kg/ha recorded the lowest mean (16.29 kg/m^2) pod weight per plot in the Forest Zone (Fig. 7b).

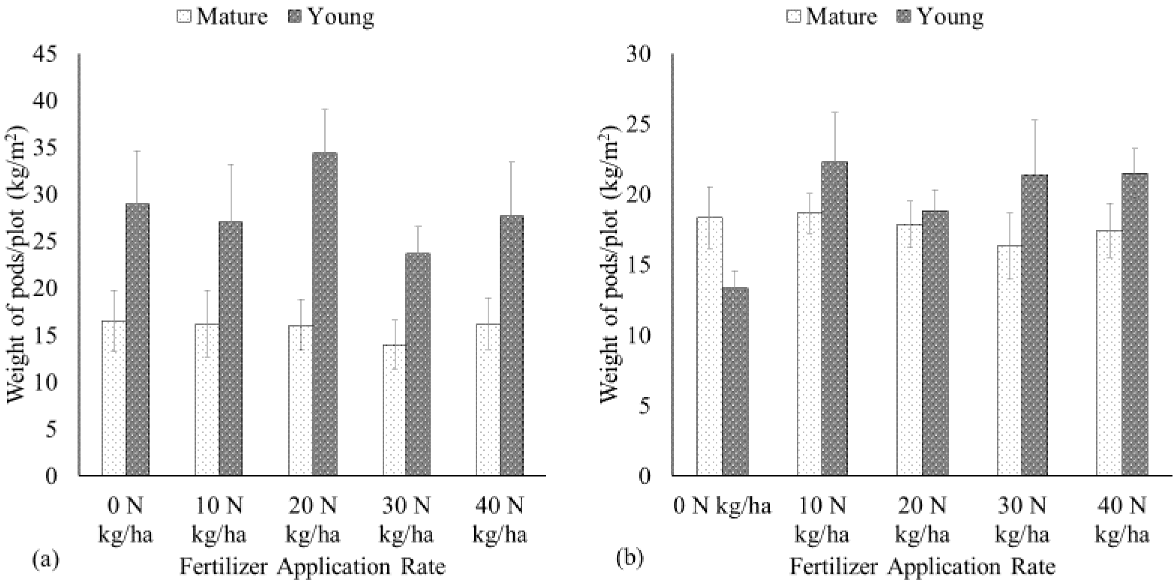

Fig 7a: Coastal Savannah

Fig 7b: Evergreen Forest

Figure 7: Cocoa pod yield of mature and young farms with respect to different N-rates in the Coastal Savannah and Forest Zones.

No significant interaction ($p < 0.926$) existed between N-forms and N-rates on the weight of pods per plot in the Coastal Savannah (Fig. 8a). The weight of pods per plot recorded on farms in the Forest Zone was highly significantly different ($p < 0.001$) in terms of N-forms and N-rates interactive effect (Fig. 8b). The highest mean (28.25 kg/m^2) pods weight per plot was recorded at nitrate applied at 10 N kg/ha in the Coastal Savannah (Fig. 8a), which was significantly different from that of the Forest Zone (24.88 kg/m^2) (Fig. 8b). In the Coastal Savannah, the lowest mean 13.86 kg/m^2 was recorded for ammonium applied at 10 N kg/ha whilst which was the lowest in the Forest Zone (13.81 kg/m^2) was recorded for ammonium applied at 30 N kg/ha (Fig. 8).

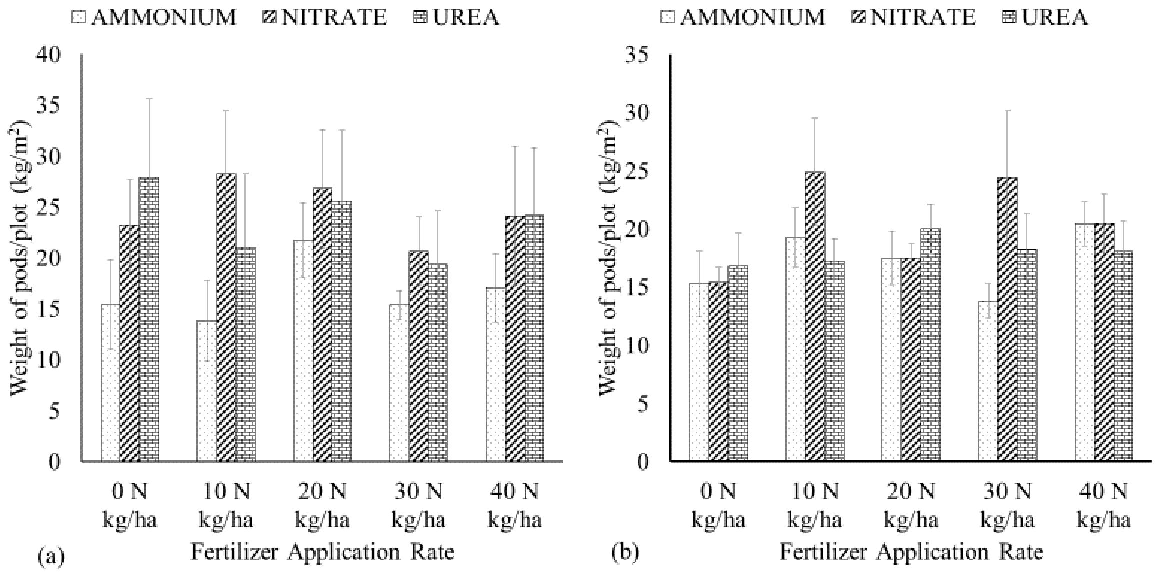

Fig 8a: Coastal Savannah

Fig 8b: Evergreen Forest

Figure 8: Cocoa pod yield recorded at different N-forms and N-rates in the Coastal Savannah and Forest zones.

Figure 9 shows the variation in cocoa yield recorded for both the Coastal Savannah and Evergreen Forest Agro-Ecological Zones. Figure 9a represents the effect of varied N-forms and N-rates on cocoa pod yield of mature and young cocoa farms in the Coastal Savannah Agro-Ecological Zone whilst Figure 9b represents the effect of varied N-forms and N-rates on cocoa pod yield of mature and young cocoa farms in the Evergreen Forest Agro-Ecological Zone. Analysis of variance revealed no significant interaction ($p = 0.094$) between the age of farm, N-forms and N-rates on the weight of pods per plot recorded in the Coastal Savannah (Fig. 9a) whilst in the Forest Zone, the interactive effect of age of farms, N-forms and N-rates were highly significant ($p < 0.001$) on the weight of pods per plot (Fig. 9b). Cocoa pods yield recorded highest values in both Coastal Savannah and Forest Zones on young cocoa farms on which nitrate fertilizer was applied at increasing rates but lowest mean values on mature cocoa farms on which nitrate fertilizer was applied at increasing rates (Fig. 9). However, mature cocoa farms responded positively to the application of urea fertilizer at increasing rates such that cocoa pods yield recorded was higher in both Coastal Savannah and Forest Zones (Fig. 9).

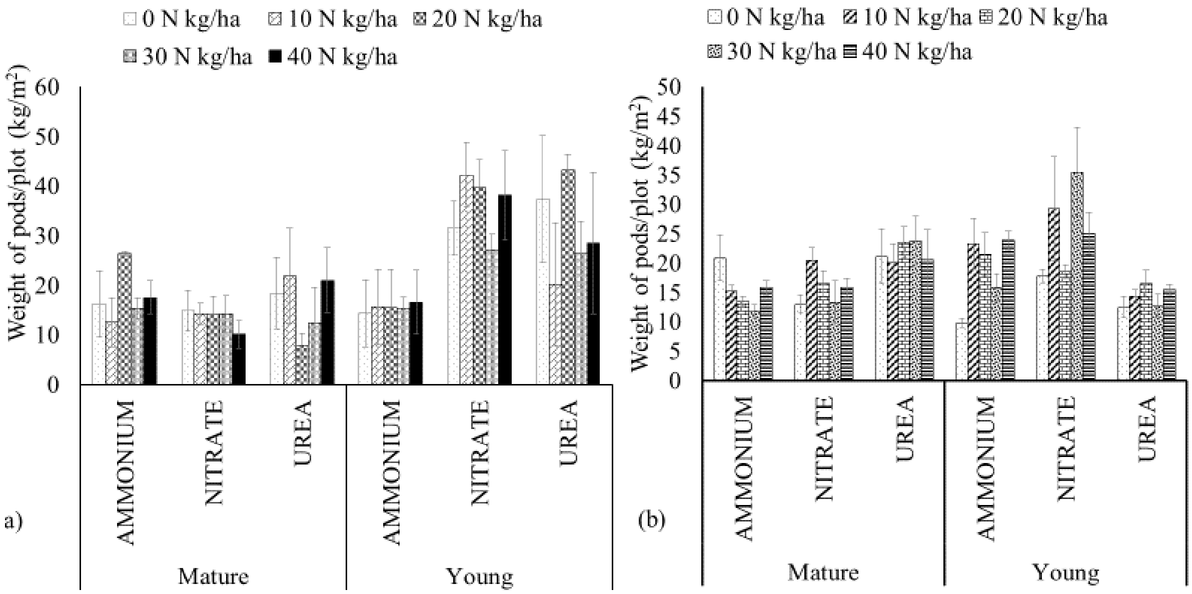

Fig 9a: Coastal Savannah

Fig 9b: Evergreen Forest

Figure 9: Cocoa pod yield of mature and young cocoa trees grown in two Agro-Ecological Zones subjected to different nitrogen forms and rates.

4.3.2 Dry bean weight

The dry bean weight of cocoa was higher in the Forest Zone compared to the Coastal Savannah Zone (Fig. 10). The dry bean weight of cocoa was significantly different ($p < 0.001$) between farms in the Coastal Savannah Zone (Fig. 10a) but the dry bean weight of cocoa did not differ significantly ($p = 0.217$) between farms in the Forest Zone (Fig. 10b). Young cocoa farm in the Forest Zone recorded the higher dry bean yield (4.08 kg/m^2) than that of the mature cocoa farm (3.79 kg/m^2) (Fig. 10b) whilst farms in the Coastal Savannah recorded dry bean yield of 3.06 kg/m^2 and 1.28 kg/m^2 for young and mature cocoa farms, respectively (Fig. 10a).

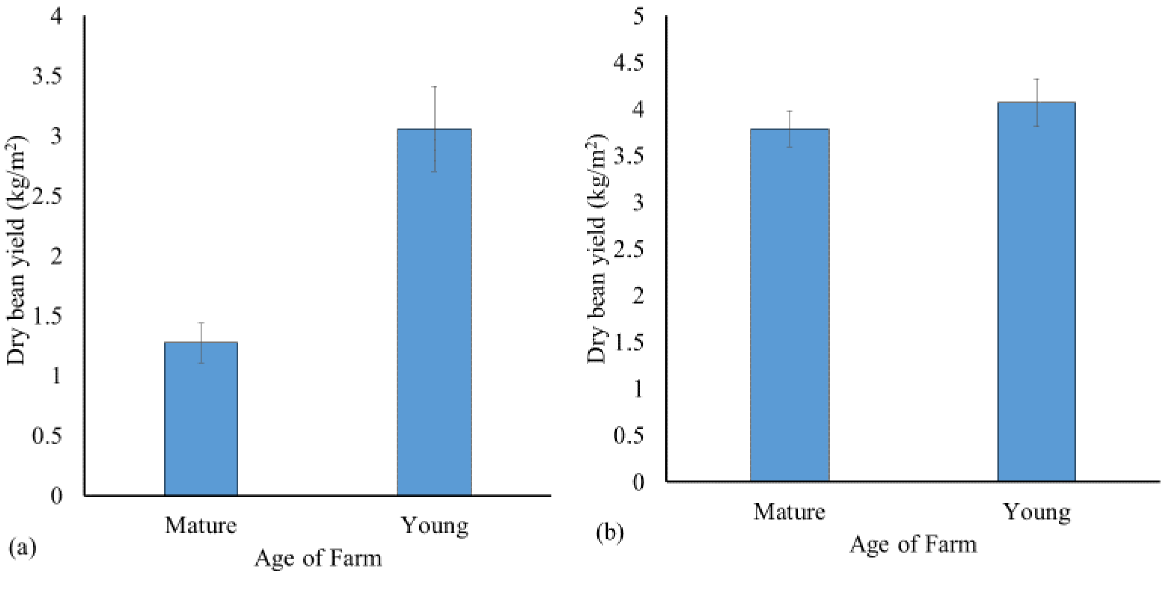

Fig 10a: Coastal Savannah

Fig 10b: Evergreen Forest

Figure 10: Cocoa dry bean yield of mature and young farms located in the Coastal Savannah and Evergreen Forest Zones.

Analysis of variance showed a significant difference ($p < 0.05$) in the dry bean weight per plot recorded at the various zones. There was no significant difference ($p = 0.060$) among the nitrogen forms in the Coastal Savannah (Fig. 11a). Dry bean weight per plot recorded on farms in the Forest Zone was significantly different ($p = 0.036$) in terms of nitrogen forms (Fig. 11b). The highest mean dry bean weight per plot was recorded on nitrate treated field in the Forest Zone (4.38 kg/m^2) (Fig. 11b), which was significantly different ($p < 0.05$) from that of the Coastal Savannah (2.49 kg/m^2) (Fig. 11a). In the Coastal Savannah, the mean recorded for ammonium was 1.61 kg/m^2 which was significantly lower than 3.69 kg/m^2 in the Forest Zone (Fig. 11) whilst in the Coastal Savannah, the mean recorded for urea was 2.23 kg/m^2 which was lower than 3.71 kg/m^2 recorded in the Forest Zone (Fig. 11).

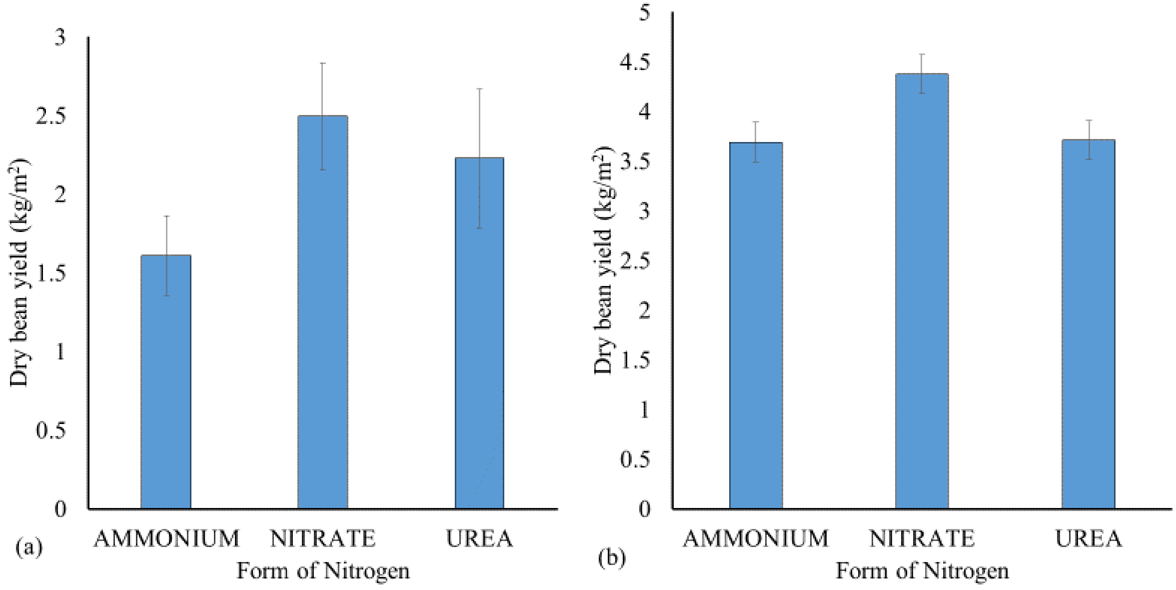

Fig 11a: Coastal Savannah

Fig 11b: Evergreen Forest

Figure 11: Cocoa dry bean yield recorded for different N forms in the Coastal Savannah and Evergreen Forest Zones.

Figure 12 shows the graphical representation of the effect of nitrogen applied at varied rates on dry bean yield of cocoa of both the Coastal Savannah and Evergreen Forest Zones. For the Coastal Savannah (Fig. 12a), no significant difference (p = 0.387) existed in the weight of dry bean per plot concerning fertilizer application rates. In the Forest Zone (Fig. 12b), there was a significant difference (p = 0.007) in the weight of dry bean per plot among the fertilizer application rates. In general, cocoa dry bean yield increased at an increasing level of N rates (Fig. 12). Yet, cocoa farms fertilized according to farmers practice (FP or 10 N kg/ha) in the Forest Zone recorded the highest mean cocoa dry bean yield

(4.73 kg/m^2) as compared to 4.13 kg/m^2 recorded for trees fertilized at 40 N kg/ha (Fig. 12b). On the other hand, in the Coastal Savannah trees fertilized at 20 N kg/ha recorded the highest value (2.66 kg/m^2) (Fig. 12a) whereas trees fertilized at 30 N kg/ha recorded the lowest value (1.81 kg/m^2).

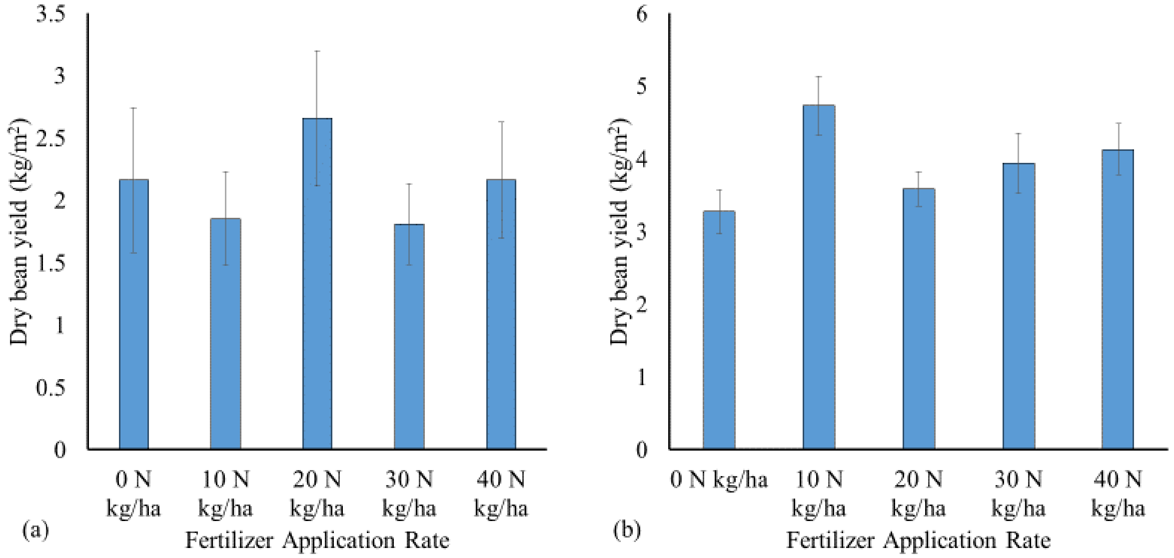

Fig 12a: Coastal Savannah

Fig 12b: Evergreen Forest

Figure 12: Cocoa dry bean yield recorded at increasing N rates in two Agro-Ecological Zones.

There were significant interactions ($p < 0.001$) between N form and age of cocoa trees on cocoa dry bean yield recorded in the Coastal Savannah Agro-Ecological Zone ($p < 0.001$) (Fig. 13a) and the Forest Zone ($p < 0.001$) (Fig. 13b). For instance, young cocoa trees treated with nitrate-based fertilizer recorded the highest yield of 5.03 kg/m^2 (Fig. 13b) whereas young cocoa trees treated with urea-based fertilizer recorded the lowest (3.28 kg/m^2) mean dry bean yield (Fig. 13b).

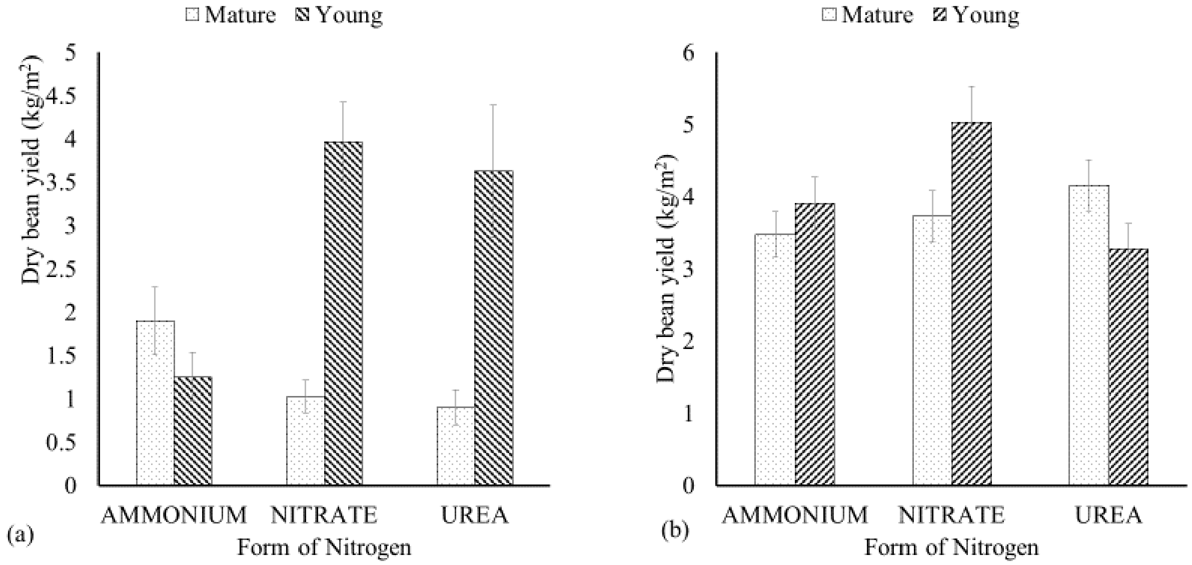

Fig 13a: Coastal Savannah

Fig 13b: Evergreen Forest

Figure 13: Cocoa dry bean yield of mature and young cocoa farms subjected to different N forms in two Agro-Ecological Zones.

There was no significant (p = 0.871) interaction effect on the cocoa dry bean yield for the age of farm and fertilizer application rates for both the Coastal Savannah Agro-Ecological Zone (Fig. 14a) and the Forest Zone (p = 0.149) (Fig. 14b). Generally, cocoa dry bean yield increased at an increasing level of N rates applied (Fig. 14). Yet, young cocoa farms fertilized according to farmers practice (FP or 10 N kg/ha) in the Forest Zone recorded the highest mean cocoa dry bean yield (4.92 kg/m^2) compared to 4.72 kg/m^2 recorded for trees fertilized at 40 N kg/ha (Fig. 14b). On the other hand, in the Coastal Savannah young trees fertilized at 20 N kg/ha recorded the highest value (3.65 kg/m^2) (Fig. 14a) whereas mature trees fertilized at 0 N kg/ha or control recorded the lowest value (1.04 kg/m^2).

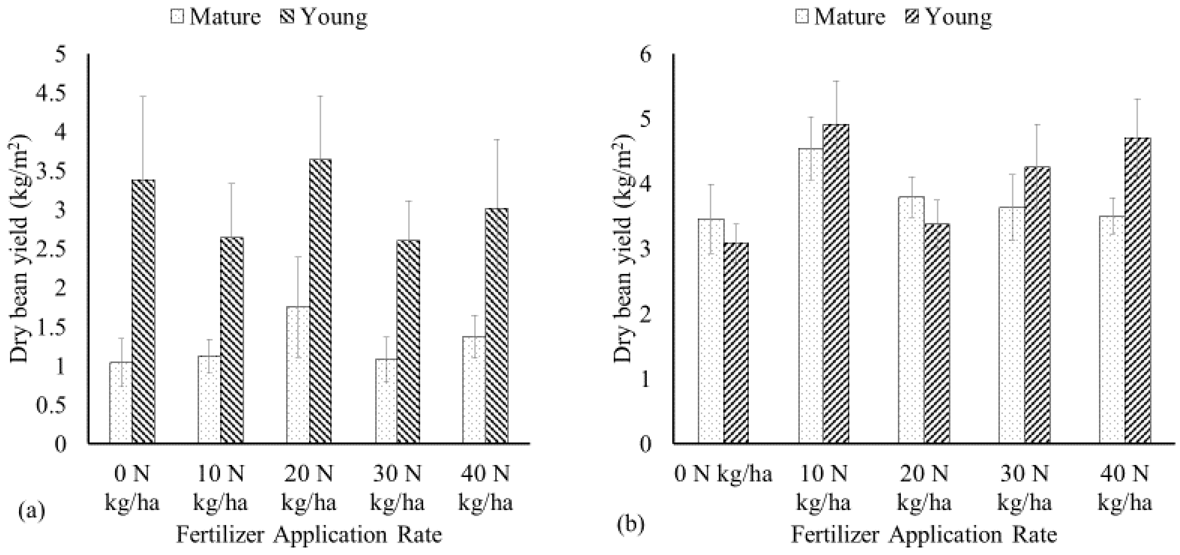

Fig 14a: Coastal Savannah

Fig 14b: Evergreen Forest

Figure 14: Cocoa dry bean yield recorded at increasing N-rates on mature and young farms in two Agro-Ecological Zones.

Significant difference ($p < 0.001$) existed for the interactive effect of N-forms and N-rates on cocoa dry bean yield in the Coastal Savannah (Fig. 15a) but in the Forest Zone, there was no significant ($p = 0.100$) interaction amongst N-forms and N-rates on cocoa dry bean yield (Fig. 15b). However, cocoa dry bean yields differed significantly ($p < 0.05$) between the two Agro-Ecological Zones. The highest mean (3.38 kg/m^2) cocoa dry bean yield was recorded at 0 N kg/ha in the Coastal Savannah (Fig. 15a), which was significantly different from that of the Forest Zone (5.81 kg/m^2) recorded at nitrate applied at 10 N kg/ha (Fig. 15b). In the Coastal Savannah, the lowest mean 0.95 kg/m^2 was recorded for ammonium applied at 0 N kg/ha but 3.13 kg/m^2 which was the lowest in the Forest Zone was recorded for ammonium applied at 0 N kg/ha (Fig. 15).

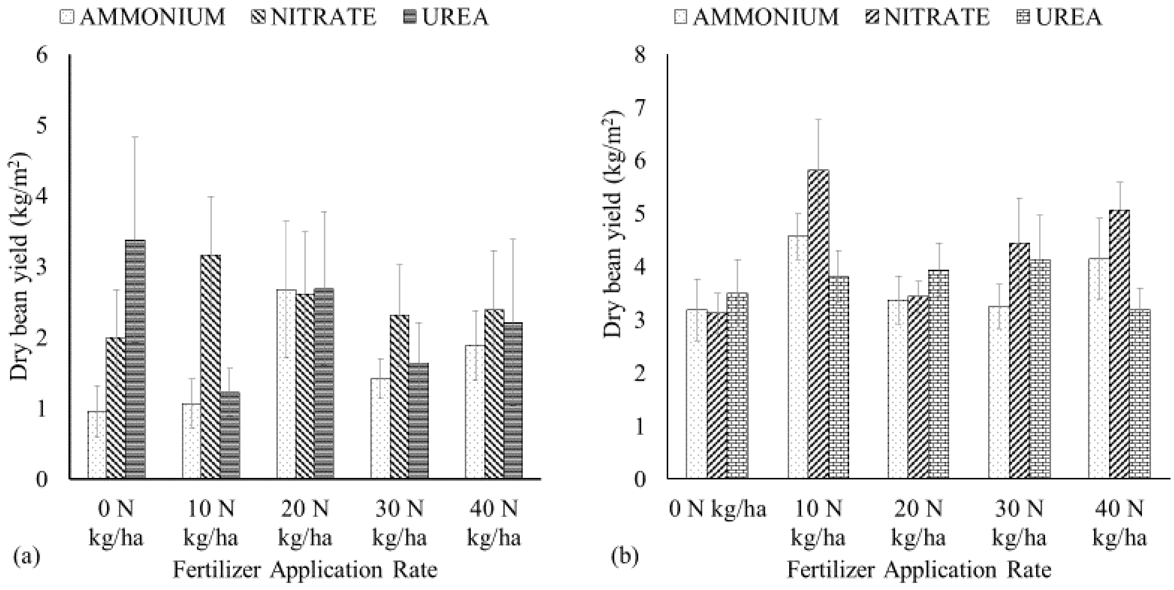

Fig 15a: Coastal Savannah

Fig 15b: Evergreen Forest

Figure 15: Cocoa dry bean yield recorded for different N-forms and at increasing N-rates in two Agro-Ecological Zones.

Dry bean weight values varied between 0.5 kg/m^2 and 6 kg/m^2 (Fig. 16). Analysis of variance for interactive effect of treatments indicated significant effect ($p < 0.05$) of treatments on dry bean yield in the Evergreen Forest Zone (Fig. 16b), but no significant ($p = 0.066$) interactive effect of treatments in cocoa dry bean yield of the Coastal Savannah Zone (Fig. 16a). Mean values for dry bean yield were highest for nitrates, intermediate for ammonium, and lowest for urea in young cocoa farms whilst on mature cocoa farms, dry bean weight values recorded were highest for urea, intermediate for ammonium, and lowest for nitrate (Fig. 16).

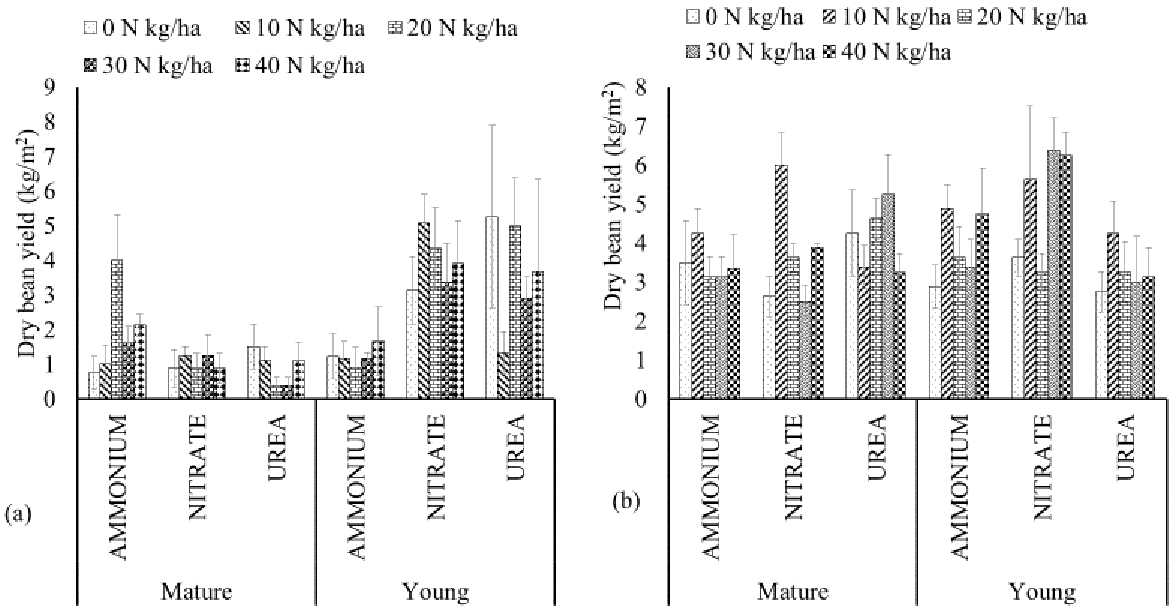

Fig 16a: Coastal Savannah

Fig 16b: Evergreen Forest

Figure 16: Effect of fertilizer treatments on cocoa dry bean yield of mature and young farms at the two Agro-Ecological Zones.

4.4 Plant tissue nutrient analysis

The cocoa plantations used for this on-farm research were smallholder farms located in the Coastal Savannah and the Evergreen Forest Agro-Ecological Zones. These farms had no structured fertilizer application scheme. Means of N-use efficiency (NUEc) and proportional nitrogen resorption recorded from the two Agro-Ecological Zones are presented in Table 6.

Means of N-use efficiency of cocoa and proportional nitrogen resorption both differed significantly ($p < 0.001$) between the farms in the Coastal Savannah such that NUEc recorded for mature cocoa and young cocoa farms were 1.11 and 0.80 whilst % N resorption were 37.63 and 17.79, respectively (Table 6a). The analysis revealed no significant differences among the forms of nitrogen concerning % N resorption though urea recorded the highest mean (29.05 %)

followed by nitrate (27.86 %) and ammonium (25.41 %) as shown in Table 6a. There were no significant differences among the forms of nitrogen concerning NUEc which were 0.93, 0.93, and 0.94, respectively. However, % N resorption increased and differed significantly at increasing N rate of application such that treatment of 40 N kg/ha recorded the highest mean (40.36 %) whilst the control treatment recorded the lowest mean (5.22 %). Yet, in terms of NUEc increasing N rate of application was not significant, even though 40 N kg/ha treatment recorded the highest mean (0.96) whilst the control treatment recorded the lowest mean (0.90). Investigating how the age of cocoa trees influence % N resorption in terms of nitrogen forms, it can be seen that % N resorption of urea (39.88 %) was highest in mature cocoa trees compared to ammonium (36.43 %) and nitrate (36.47 %), respectively whereas % N resorption of nitrate (20.18 %) was highest in young cocoa trees compared to that of urea (18.35 %) and ammonium (14.67 %) (Table 6a).

Table 6a: Nitrogen resorption and Nitrogen use efficiency (NUEc) of cocoa plants grown in the Coastal Savannah Agro-Ecological Zone

Treatment	N Resorption (%)	N NUE_C
Farm		
Mature	37.63	1.11
Young	17.79	0.80
Form		
Ammonium	25.41	0.93
Nitrate	27.86	0.93
Urea	29.05	0.94
Rate		
0 N kg/ha	5.22	0.90
10 N kg/ha	18.53	0.92
20 N kg/ha	28.17	0.92
30 N kg/ha	36.19	0.95
40 N kg/ha	40.36	0.96
Mature		
Ammonium	36.43	1.11
Nitrate	36.47	1.11
Urea	39.88	1.11
Young		
Ammonium	14.67	0.79
Nitrate	20.18	0.80
Urea	18.35	0.82

Table 6b shows the means of N-use efficiency of cocoa and proportional nitrogen resorption recorded on farms in the Evergreen Forest Agro-Ecological Zones. NUEc recorded for mature cocoa trees and young cocoa trees were 1.09 and 0.72 whilst % N resorption were 35.71 and 7.59, respectively (Table 6b). The analysis suggested no significant difference among the forms of nitrogen concerning % N resorption though urea recorded the highest mean (23.13 %) followed by nitrate (20.92 %) and ammonium (19.71 %) as shown in Table 6b. There was no significant difference among the forms of nitrogen concerning NUEc which were recorded as 0.88, 0.84, and 0.88, respectively. However, % N resorption increased and differed significantly at increasing N rate of application such that treatment 40 N kg/ha recorded the highest mean (24.69 %) whilst the control treatment recorded the lowest mean (16.15 %). Yet, in terms of NUEc, increasing N rate of application was significant such that treatment 0 N kg/ha (Control) recorded the highest mean (1.04) whilst the treatment 40 N kg/ha recorded the lowest mean (0.75). The interaction between age of cocoa trees and nitrogen forms indicates that % N resorption of urea (37.86 %) was highest in mature cocoa trees compared to ammonium (33.90 %) and nitrate (35.28 %), respectively, whereas % N resorption of nitrate (8.83 %) was highest in young cocoa trees compared to that of urea (8.33 %) and ammonium (5.65 %). (Table 6b)

Table 6b: Nitrogen resorption and Nitrogen use efficiency (NUEc) of cocoa plants grown in the Evergreen Forest Agro-Ecological Zone.

Treatment	N Resorption (%)	N NUE_C
Farm		
Mature	35.71	1.09
Young	7.59	0.72
Form		
Ammonium	19.71	0.88
Nitrate	20.92	0.84
Urea	23.13	0.88
Rate		
0 N kg/ha	16.15	1.04
10 N kg/ha	20.18	0.98
20 N kg/ha	20.94	0.84
30 N kg/ha	22.35	0.79
40 N kg/ha	24.69	0.75
Mature		
Ammonium	33.90	1.08
Nitrate	35.28	1.09
Urea	37.86	1.10
Young		
Ammonium	5.65	0.75
Nitrate	8.83	0.68
Urea	8.33	0.74

After 4 months of setup (MAS) on mature and young cocoa farms in the Coastal Savannah Agro-Ecological Zone, the means recorded for litterfall, nitrogen concentration and nitrogen use efficiency at the ecosystem scale are presented in Table 7a. Analysis of variance revealed no significant difference ($p = 0.273$) in litterfall production between the mature cocoa farm and young cocoa farm in the Coastal Savannah Agro-Ecological Zone. The mature cocoa trees had a mean litterfall of 54.1 g m^{-2} y^{-1} which was not significantly different from that of young cocoa trees (57.8 g m^{-2} y^{-1}). Litter tissue N content of the mature cocoa trees (0.93 %) was highly significantly ($p < 0.001$) lower than that of the young cocoa trees (1.17 %). The mature cocoa farm had the highest value of NUE_{ES} (58.38 %) whilst the young cocoa farm recorded the lowest mean of NUE_{ES} (49.35 %) (Table 7a).

Forms of nitrogen application did not significantly ($p = 0.198$) influence litterfall production. Despite the lack of forms of nitrogen effect on litterfall production, ammonium had the highest mean litterfall of 58.6 g m^{-2} y^{-1} which was not significantly different from that of nitrate (57.6 g m^{-2} y^{-1}) but greater than that of urea (51.6 g m^{-2} y^{-1}). Litter tissue N content of ammonium treated cocoa trees (1.04 %) was not significantly different ($p = 0.210$) from that of the urea-treated cocoa trees (1.04 %) but lower than nitrate treated cocoa trees (1.07 %). The ammonium treated cocoa farm had the highest value of NUE_{ES} (56.32 %) whilst the urea treated cocoa farm recorded the lowest mean of NUE_{ES} (49.62 %) (Table 7a).

Litter production differed significantly ($p = 0.05$) at increasing levels of N application rates. Treatment 40 N kg/ha recorded the highest mean (66.2 g m^{-2} y^{-1}) whilst the treatment 20 N kg/ha recorded the lowest mean (51.5 g m^{-2} y^{-1}), a value which was lower than the Control treatment (52.1 g m^{-2} y^{-1}). Litter tissue N content of treated cocoa tree was highly significantly different ($p < 0.001$) among N application rates. N applied at 40 N kg/ha recorded the highest mean (1.29 %) whilst N applied at 0 N kg/ha recorded the lowest mean (0.84 %). The 0 N kg/ha treated cocoa farm had the highest value of NUE_{ES} (62.05 %) whilst the 30 N kg/ha treated cocoa farm recorded the lowest mean of NUE_{ES} (46.98 %).

However, Table 7a shows that litter production was not significantly different ($p = 0.257$) between mature and young cocoa farms concerning N-forms. On mature cocoa farm, nitrate had the highest mean of litterfall of 57.2 g m^{-2} y^{-1} which was not significantly different from that of ammonium (52.8 g m^{-2} y^{-1}) but significantly greater than that of urea (52.2 g m^{-2} y^{-1}) whereas on young cocoa farm ammonium recorded the highest mean of litterfall of 64.4 g m^{-2} y^{-1} which was not significantly different from that of nitrate (57.9 g m^{-2} y^{-1}) but greater than that of urea (51.1 g m^{-2} y^{-1}). On the mature cocoa farm, litter tissue N content of ammonium treated cocoa trees (0.94 %) was significantly different ($p < 0.001$) from that of the urea treated cocoa trees (0.91 %) but greater than nitrate treated cocoa trees (0.93 %) as compared to the young cocoa farm where litter tissue N content of nitrate treated cocoa trees (1.22 %) was significantly different ($p < 0.01$) from that of the ammonium treated cocoa trees (1.14 %) but greater than urea treated cocoa trees (1.15 %). With regards to mature cocoa farm, the nitrate treated cocoa farm had the highest value of NUE_{ES} (62.89 %) whilst the urea treated cocoa farm recorded the lowest mean of NUE_{ES} (55.95 %), but on a young cocoa farm, the ammonium treated cocoa farm had the highest value of N NUE_{ES} (56.32 %) whilst the urea treated cocoa farm recorded the lowest mean of NUE_{ES} (44.55 %). (Table 7a)

Table 7a: Mean litterfall, Nitrogen content and Nitrogen use efficiency at the ecosystem scale (NUE_{ES}) recorded at 4 MAS in the Coastal Savannah Agro-Ecological Zone.

Treatment	Litterfall Dw (g m^{-2} y^{-1})	N content (%)	NUE_{ES}
Farm			
Mature	54.1	0.93	58.38
Young	57.8	1.17	49.35
Form			
Ammonium	58.6	1.04	56.32
Nitrate	57.6	1.07	54.01
Urea	51.6	1.04	49.62
Rate			
0 N kg/ha	52.1	0.84	62.05
10 N kg/ha	53.8	0.90	59.72
20 N kg/ha	51.5	1.02	50.57
30 N kg/ha	56.1	1.19	46.98
40 N kg/ha	66.2	1.29	51.23
Mature			
Ammonium	52.8	0.94	56.32
Nitrate	57.2	0.91	62.89
Urea	52.2	0.93	55.95
Young			
Ammonium	64.4	1.14	56.32
Nitrate	57.9	1.22	47.32
Urea	51.1	1.15	44.55

After 4 months of setup (MAS) on mature and young cocoa farms in the Evergreen Forest Agro-Ecological Zone, the means recorded for litterfall, nitrogen concentration and nitrogen use efficiency at the ecosystem scale are presented in Table 7b. Analysis of variance revealed a significant difference ($p < 0.001$) in litterfall production between farms. The mature cocoa trees had a mean litterfall of 79.7 g m^{-2} y^{-1} which was highly significantly different from that of young cocoa trees (115.1 g m^{-2} y^{-1}). Litter tissue N content of the mature cocoa trees (1.21 %) was highly significantly different ($p < 0.001$) from that of the young cocoa trees (1.47 %). The young cocoa farm had the highest value of NUE_{ES} (78.42 %) whilst the mature cocoa farm recorded the lowest mean of NUE_{ES} (65.92 %). (Table 7b)

Forms of nitrogen application did not differ significantly ($p = 0.938$) concerning litterfall production. Nitrate had the highest mean of litterfall of 98.9 g m^{-2} y^{-1} which was not significantly different from that of urea (96.3 g m^{-2} y^{-1}) but significantly greater than that of ammonium (97 g m^{-2} y^{-1}). Litter tissue N content of ammonium treated cocoa trees (1.31 %) was highly significantly different ($p < 0.01$) from that of the nitrate treated cocoa trees (1.35 %) but lower than urea treated cocoa trees (1.36 %). The ammonium treated cocoa farm had the highest value of NUE_{ES} (73.48 %) whilst the urea treated cocoa farm recorded the lowest mean of NUE_{ES} (71.51 %) (Table 7b).

Litter production did not differ significantly ($p = 0.422$) at increasing levels of N application rates. Treatment 20 N kg/ha recorded the highest mean (105.2 g m^{-2} y^{-1}) whilst the treatment 10 N kg/ha (FP) recorded the lowest mean (90.3 g m^{-2} y^{-1}), a value which was lower than the Control treatment (95.3 g m^{-2} y^{-1}). Litter tissue N content of treated cocoa tree was highly significantly different ($p < 0.001$) among N application rates. N applied at 40 N kg/ha recorded the highest mean (1.65 %) whilst N applied at 0 N kg/ha recorded the lowest mean (1.02 %). The 0 N kg/ha treated cocoa farm had the highest value of NUE_{ES} (93.69 %) whilst the 30 N kg/ha treated cocoa farm recorded the lowest mean of NUE_{ES} (59.47 %).

However, Table 7b shows that litter production was not significantly different (p = 0.094) between mature and young cocoa farms concerning N-forms. On mature cocoa farm, urea had the highest mean of litterfall of 86.4 g m^{-2} y^{-1} which was not significantly different from that of nitrate (83 g m^{-2} y^{-1}) but significantly greater than that of ammonium (69.6 g m^{-2} y^{-1}). Yet, on young cocoa farm ammonium recorded the highest mean of litterfall of 123 g m^{-2} y^{-1} which was not significantly different from that of nitrate (114.8 g m^{-2} y^{-1}) but significantly greater than that of urea (107.6 g m^{-2} y^{-1}). On the mature cocoa farm, litter tissue N content of ammonium treated cocoa trees (1.2 %) was not significantly different (p = 0.089) from that of the urea treated cocoa trees (1.22 %) but greater than nitrate treated cocoa trees (1.20 %) as compared to the young cocoa farm where litter tissue N content of nitrate treated cocoa trees (1.49 %) was not significantly different (p = 0.089) from that of the ammonium treated cocoa trees (1.42 %) but greater than urea treated cocoa trees (1.47 %).

With regards to mature cocoa farm, the urea treated cocoa farm had the highest value of NUE_{ES} (70.56 %) whilst the ammonium treated cocoa farm recorded the lowest mean of NUE_{ES} (58 %), but on a young cocoa farm, the ammonium treated cocoa farm had the highest value of NUE_{ES} (86.56 %) whilst the urea treated cocoa farm recorded the lowest mean of NUE_{ES} (72.29 %) (Table 7b).

Table 7b: Mean litterfall, Nitrogen content and Nitrogen use efficiency at the ecosystem scale (NUE_{ES}) recorded at 4 MAS in the Evergreen Forest Agro-Ecological Zone.

Treatment	Litterfall Dw ($g\ m^{-2}\ y^{-1}$)	N content (%)	NUE_{ES}
Farm			
Mature	79.7	1.21	65.92
Young	115.1	1.47	78.42
Form			
Ammonium	96.3	1.31	73.48
Nitrate	98.9	1.35	73.35
Urea	97	1.36	71.51
Rate			
0 N kg/ha	95.3	1.02	93.69
10 N kg/ha	90.3	1.14	79.29
20 N kg/ha	105.2	1.33	79.22
30 N kg/ha	92.5	1.56	59.47
40 N kg/ha	103.8	1.65	62.79
Mature			
Ammonium	69.6	1.2	58
Nitrate	83	1.20	69.02
Urea	86.4	1.22	70.56
Young			
Ammonium	123	1.42	86.56
Nitrate	114.8	1.49	76.84
Urea	107.6	1.47	72.29

Figure 17 shows the interactive effect between the age of farms, forms of nitrogen and fertilizer application rates on leaf tissue N in well-developed cocoa collected from the Coastal Savannah and Forest Agro-Ecological Zones. Invariably at all levels of applied N, Forest Zone had higher N concentration in leaf than Coastal Savannah Zone; however, highly significant differences ($p < 0.001$) existed among the treatments (Fig. 17). Nitrogen-concentration in leaf on mature farms in the two zones followed a similar trend as that of young cocoa farms, but a significant increase for leaf tissue N was observed mostly for the nitrate treatment in young cocoa farms whilst in mature cocoa farms urea treated trees had higher leaf tissue N. Urea applied at 40 N kg/ha recorded the highest value (1.81 %) on mature farm whilst ammonium applied at 0 N kg/ha recorded the lowest (1.07 %) in the Coastal Savannah Zone. With regards to the young cocoa farm, Nitrate applied at 40 N kg/ha recorded the highest value (1.91 %) whilst ammonium applied at 0 N kg/ha recorded the lowest (1.22 %). Elsewhere in the Forest Zone, Urea applied at 40 N kg/ha recorded the highest value (1.71 %) on mature farm whilst ammonium applied at 0 N kg/ha recorded the lowest (1.16 %). In terms of the young cocoa farm, Nitrate applied at 40 N kg/ha recorded the highest value (2.12 %) whilst urea applied at 0 N kg/ha recorded the lowest (1.09 %) (Fig. 17).

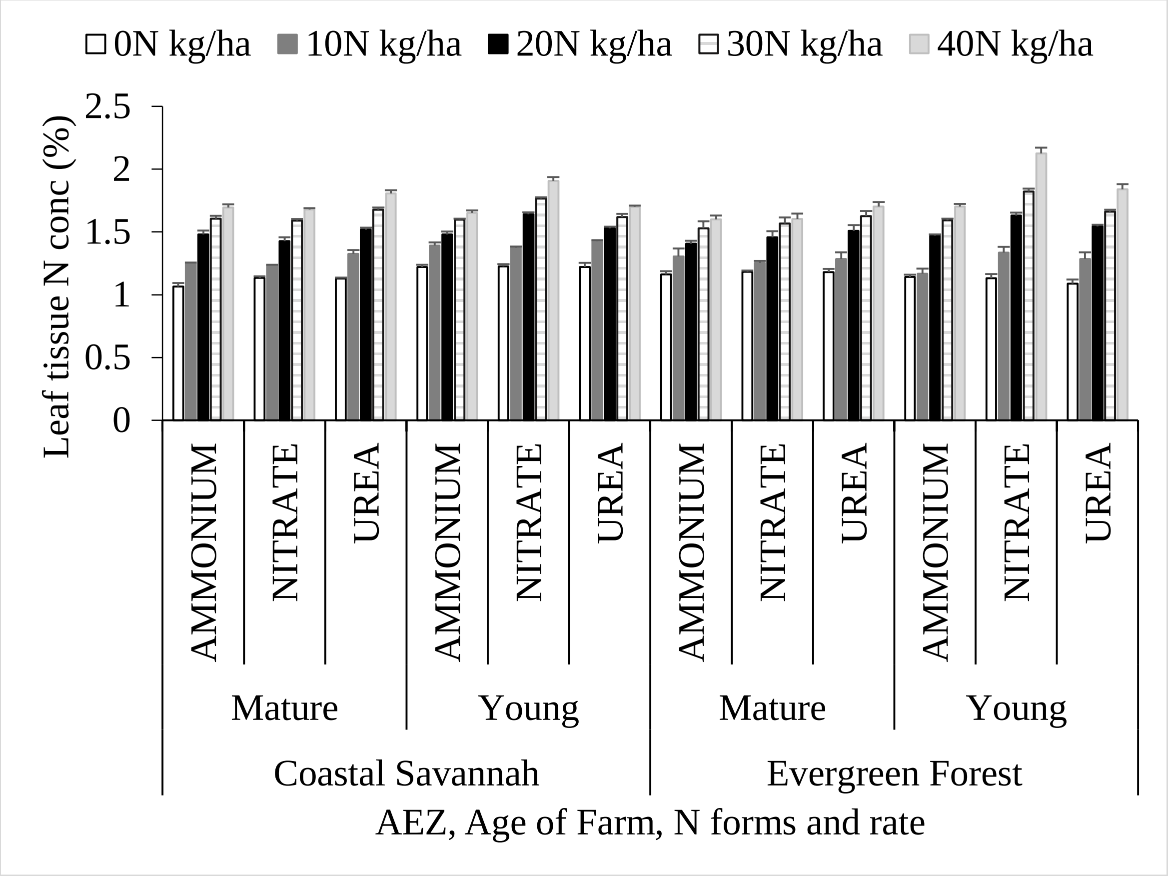

Figure 17: N in the well-developed leaf of mature and young cocoa trees subjected to different N-forms and N-rates grown in two Agro-Ecological Zones.

Figure 18 shows the interactive effect between the age of farms, forms of nitrogen and fertilizer application rates on tissue N in senescence cocoa leaf collected from the Coastal Savannah and Forest Agro-Ecological Zones. Analysis revealed that at all levels of applied N, Forest Zone had higher N concentration in leaf than Coastal Savannah Zone; and highly significant differences ($p < 0.001$) existed among the treatments (Fig. 18). Nitrogen-concentration in leaf on mature farms in the two zones followed a similar trend as that of young cocoa farms, but a significant increase for leaf tissue N was observed mostly for the nitrate treatment in young cocoa farms whilst in mature cocoa farms, urea treated trees had higher leaf tissue N. Urea applied at 0 N kg/ha recorded the highest value (0.96 %) on mature farm whilst nitrate applied at 30 N kg/ha recorded the lowest (0.82 %) in the Coastal Savannah Zone. With regards to young cocoa farm, nitrate applied at 20 N kg/ha recorded the highest value (1.4 %) whilst urea applied at 30 N kg/ha recorded the lowest (1.05 %). Elsewhere in the Forest Zone, Ammonium applied at 0 N kg/ha recorded the highest value (0.96 %) on mature farm whilst urea applied at 0 N kg/ha recorded the lowest (0.87 %). In terms of the young cocoa farm, Nitrate applied at 40 N kg/ha recorded the highest value (1.86 %) whilst ammonium applied at 0 N kg/ha recorded the lowest (0.97 %) (Fig. 18).

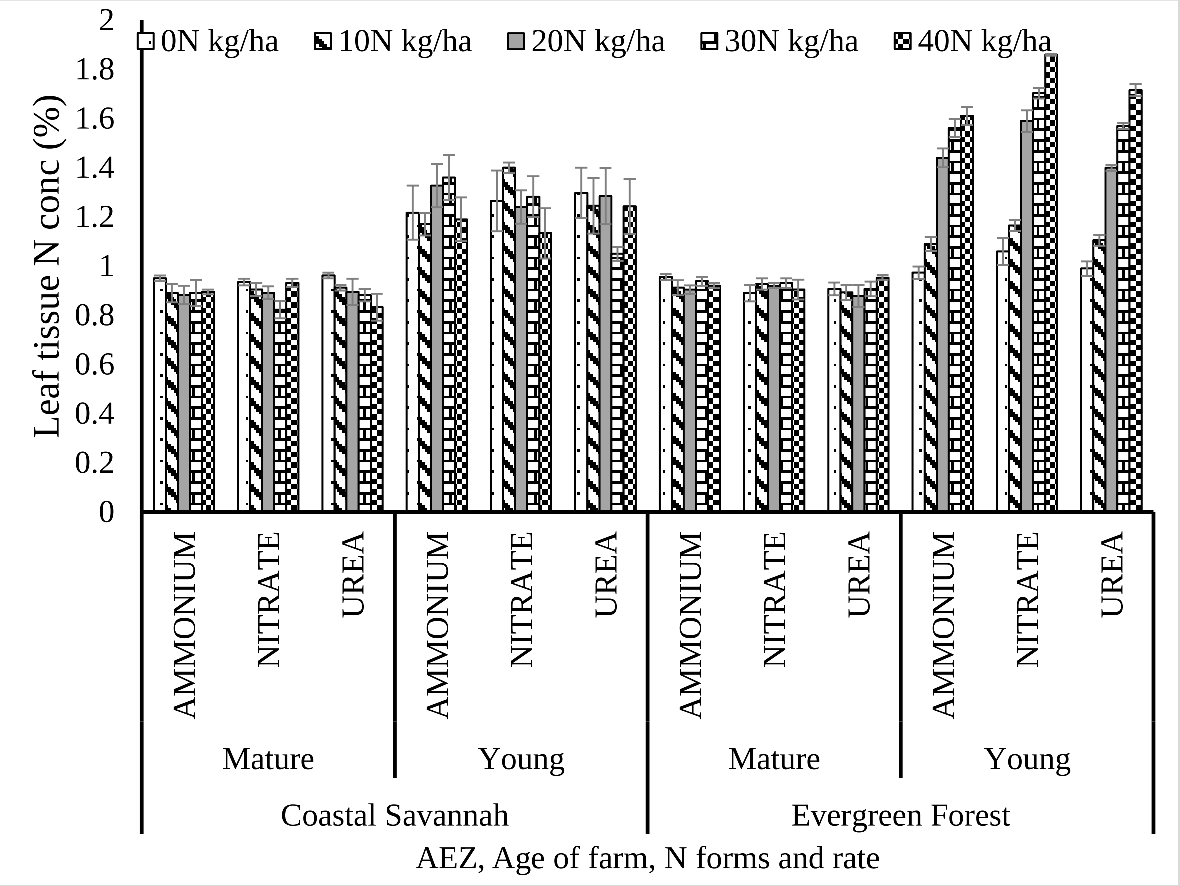

Figure 18: N in senescence leaf of mature and young cocoa trees subjected to different N-forms and N-rates grown in two Agro-Ecological Zones.

Figure 19 shows the interactive effect between the age of farms, forms of nitrogen and fertilizer application rates on litter leaf tissue N collected from the Coastal Savannah and Forest Agro-Ecological Zones. Invariably at all levels of applied N, Forest Zone had higher N concentration in litter than coastal zone; however, significant differences ($p < 0.05$) existed among the treatments (Fig. 19). Nitrogen-concentration in litter on mature farms in the two zones followed a similar trend as that of young cocoa farms, but a significant increase for litter tissue N was observed mostly for the nitrate treatment in young cocoa farms whilst in mature cocoa farms urea treated trees had higher litter tissue N. Ammonium applied at 40 N kg/ha recorded the highest value (1.08 %) on mature farm whilst nitrate applied at 10 N kg/ha recorded the lowest (0.82 %) in the Coastal Savannah Zone. With regards to the young cocoa farm, Nitrate applied at 40 N kg/ha recorded the highest value (1.63 %) whilst ammonium applied at 0 N kg/ha recorded the lowest (0.78 %). Elsewhere in the Forest Zone, ammonium applied at 40 N kg/ha recorded the highest value (1.62 %) on mature farm whilst nitrate applied at 10 N kg/ha recorded the lowest (0.91 %). In terms of the young cocoa farm, Nitrate applied at 40 N kg/ha recorded the highest value (1.81 %) whilst ammonium applied at 0 N kg/ha recorded the lowest (1.04 %) (Fig. 19).

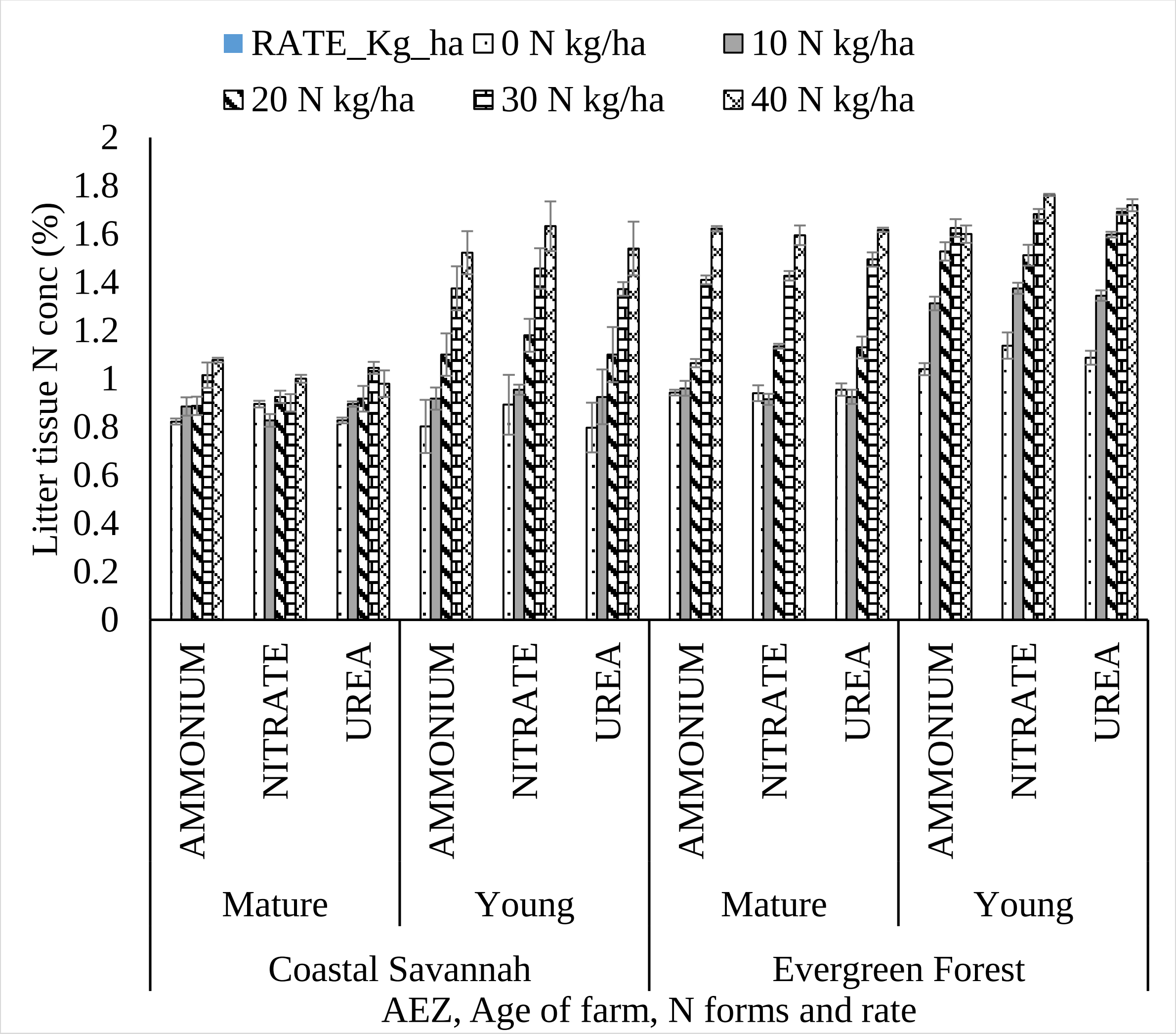

Figure 19: N in the litter of mature and young cocoa trees subjected to different N-forms and N-rates grown in two Agro-Ecological Zones.

CHAPTER FIVE

DISCUSSION

5.1 Soil-plant nutrition practices among cocoa farmers

The study revealed that the majority of the respondent farmers had similar characteristics and experience in cocoa production. Soil-plant nutrition practices among cocoa farmers were well known to farmers in both the Forest Zone and Coastal Savannah. This is in agreement with the UNDP (2012) report which states that cocoa production in Ghana has been implemented in two main regions: Moist Semi-Deciduous Forest (Eastern, Ashanti, Brong-Ahafo, Central Regions) and High Rainforest (Western Region and Western-North Region) Agro-Ecological Zones. Approximately, two-thirds (2/3) of the country’s cocoa is produced in the Forest Zone, and about 30 per cent in the Southern Savannah Zone (mainly Brong-Ahafo Region) and the Coastal zone takes the rest (GSS Survey, 2005/2006).

The high knowledge level of soil-plant nutrition practices among cocoa farmers could also be due to their experience in the production of cocoa. It was observed that majority of the farmers have been in the production of cocoa for over 10 years. Meanwhile, according to Ahenkorah (1987), the replenishment of soil nutrients by the application of fertilizer on cocoa farms in Ghana has been reported since 1987. Moreover, the proportion of the farmers who did not know nutrition practices (Table 2) could partially be attributed to the fact that they were new in the production of cocoa. The study revealed that about 10.8 % had been in the production of cocoa for less than 5 years (Table 1). This, therefore, agrees with Nagaraju *et al*. (2002) who reported that a number of years in farming can also serve as a means via which cocoa farmers get enlightened in addition to formal education being a source of information to farmers.

The majority of the respondent farmers adopted various methods in soil fertility management on their farms (Table 3) which suggest the existence of indigenous knowledge about the impact of fertilizer application on productivity and yield of cocoa. van Vliet *et al*. (2015) hinted that other fertilizer trials have also resulted in large yield increases due to fertilizer application. The use of fertilizer, be it organic or inorganic has been identified as a strategy for sustainable cocoa production by Ruf and Bini (2012). Appiah *et al*. (2000) discovered larger yields in fertilized farmer plots compared to unfertilized plots. Gockowski and Sonwa (2011), in their survey, discovered average cocoa yields in Ghana to be more than twofold those of Ivory Coast which they ascribed largely to more fertilizer use in Ghana.

The management practices deployed by the farmers were weed control, application of pesticides, pruning and fertilizer application. The survey revealed the use of granular NPK was on the decline whilst a greater percentage of farmers who indicated ‘others’ did so by foliar means which largely comes from Sidalco foliar fertilizer. Even though the majority of the farmers use fertilizers, some cocoa farmers considered the use of inorganic fertilizers cash-intensive and ineffective. Nyeverwai *et al*. (2014) has also reported that farmers’ adoption level depends on the claims and benefit of the innovation being introduced. Afrifa *et al*. (2000) observed that fertilizers have unique characteristics. Thus, some are granular while others are liquid, have high P and K but lacks nitrogen in the formulations (Cocofeed - N: P: K 0:30:20 and Asaase Wura - N: P: K 0:22:18), and others contain all the nutrients at varying concentrations of the nutrient elements.

5.2 Soil physical and chemical properties

For all the parameters measured, the soil under cocoa plantations in the selected farms and Agro-Ecological Zones were very low in essential nutrients. This support the claims by Hartemink and Donald (2005) that existing cocoa farms without fertilizer application are poor in soil nutrient content. From the initial soil analysis conducted, there was a high level of variation in soils on which cocoa trees were planted. This agrees with the report of Wood (1985) that soil diversity exists across cocoa-growing regions globally. However, soil pH for both the topsoil and subsoil sampled recorded higher values which were observed to be fairly suitable in most cases. Yet, soil from the Forest Zone was more acidic compared to the soil from the Coastal Savannah (Table 4). This could be due to the high amount of rainfall in the Forest Zone compared to the Coastal Savannah Zone.

Table 5 revealed appreciable improvement in chemical soil properties after the application of fertilizer treatments on the selected mature (12 years old) and young (9 years old) cocoa plantations across the two Agro-Ecological Zones. The pH recorded for both young and mature farms fell within the optimum range (pH 6.0 - 7.5) for cultivating cocoa (van Vliet *et al.*, 2015). For instance, where the initial pH was high, it dropped after fertilizer application. This is in agreement with findings of Ahenkorah *et al*. (1987) and Hartemink and Donald (2005) but in contrast with Ofori-Frimpong *et al.* (2007) who did not find lower pH values after fertilizer application. The increase or decrease in pH is a result of the residual acidity effect through the process of nitrification which releases H ions that result in a drop in pH (Hartemink and Donald, 2005). There were slight increases in the levels of the essential nutrients in soils under cocoa plantations after fertilizer application but had no significant impact on yield in the selected farms and Agro-Ecological Zones (Table 5). This could be attributed to the loss of nutrients via leaching most especially in the Forest Zone. This confirms findings of Snoeck *et al.* (2010) which state that nutrient leaching and acidity of soils is intense in areas with high precipitation.

5.3 Cocoa Yield

5.3.1 Weight of Pods per Plot

The study demonstrated that higher cocoa pods yield was observed in young (9 years old) cocoa trees than for mature cocoa (12 years old) in both Agro-Ecological Zones. This implies that young cocoa trees are highly productive. However, pods yield recorded on farms in the Coastal Savannah were greater than pods yield recorded in the Forest Zone. This could be attributed to the lower level of potassium found in soils in the forest zone as compared to the soils in the Coastal Savannah (Table 4). The availability of an adequate amount of K in cocoa soil promotes pods formation in cocoa. Snoeck *et al.* (2010) identified the Forest Zone as part of areas in Ghana where K needs are greater than the current recommendation.

This study revealed that yield response to nitrogen forms was significant in both Agro-Ecological Zones. The weight of pods per plot was significantly higher on plots or trees treated with nitrate and followed by urea treated trees on farms in both the Coastal Savannah and the Forest Zones. This could be attributed to the disparity in the percent N formulated. Leghari *et al.* (2016) reported that inorganic fertilizers are basically in the form of urea (46% N), ammonium (21% N), and nitrates (26% N). However, ammonium treated plots recorded the lowest weight of pods per plot recorded in both Agro-Ecological Zones. This implies that cocoa trees poorly absorbed and utilized nitrogen in the form of ammonium compared to nitrate and urea formulated nitrogen concerning pod weight. According to González-Raya *et al.* (2005), the core source of N for most crop species is NO_3^-.

This research established that the weight of pods response to N fertilizer rates of application was not significant in the Coastal Savannah whilst the weight of pods per plot recorded in the Forest Zone was highly significantly different in terms of varying N fertilizer application rates. This implies that the rate at which fertilizers are applied on a cocoa farm depends on the location of the farm. Thus, rate of fertilizer application is influenced by several factors and so cannot be generalised in cocoa production. Snoeck *et al.* (2010) identified the forest zone as part of areas in Ghana where K needs are greater than the current recommendation. The rate of 10 kg N/ha / FP was identified to be the key driving effect in that regard for the forest zone as far as pod yields are concerned. This rate recorded the highest mean cocoa pod yield compared to that which was recorded for trees fertilized at rates of 40 N kg/ha. This could be attributed to the fact that farmers in these areas use foliar fertilizer to supplement granular fertilizer and these foliar fertilizers might contained high amount of potassium which promote pod formation. Accordingly, Afrifa *et al.* (2000) reported that inorganic fertilizers possess unique characteristics.

This implies that young cocoa trees absorbed nitrogen in the form of nitrates whilst mature cocoa trees absorbed nitrogen in the form of urea. However, the highest pod weight recorded in the Forest Zone was lesser than that of the Coastal Savannah (Fig. 6b). This could be attributed to the high amount of rainfall experienced in the Forest Zone during the experimental period. This rainfall might have caused the nutrients from the fertilizer applied to be lost via leaching. This is in harmony with Snoeck *et al.* (2010) that the leaching of soil nutrients is very high in areas with higher precipitation rates per annum.

The pod yield recorded at different N fertilizer rates applied on young and mature cocoa farms gives an indication that a low level of N fertilizer is needed to maintain good pod weight in young cocoa trees but fully mature cocoa trees required a high level of N fertilizer. This agrees with Nur Sholecha (2016) that the requirement for N fertilizer increases significantly for fully mature cocoa trees. In contrast, Ling (1984) reported that as a result of poor growth rate and nutrient recycling from litter in mature cocoa, a lesser fertilizer response was seen. However, due to higher fertilizer cost and insignificant yield increases, a greater rate of N fertilizer may not be needed.

Though pods weight increased at an increasing rate in all three N formulated fertilizers, plots on which nitrate was applied recorded the highest value followed closely by urea. This confirms Nur Sholecha (2016) who reported that the least low level of N fertilizer (Urea at 200 gr/tree) is required to sustain a high yield of cocoa. According to González-Raya *et al.* (2005), the core source of N for most crop species is NO_3^-. This result from the study, however, contradicts findings of Coraspe-Leon *et al.* (2009) which hinted that all N absorbed by plant roots is either in the form of ammonium (NH_4^+) or/and nitrate (NO_3^-).

The variation in weight of pods per plot (kg/m^2) revealed in the Coastal Savannah ammonium treated trees on mature cocoa farm performed much better in terms of weight of pods per plot whilst nitrate treated trees on mature cocoa farm performed poorly in terms of pod yield. However, in young cocoa trees treated with nitrate with increasing N application rates, weight of pods per plot was significantly greater relative to ammonium treated young cocoa trees. This suggests that young cocoa trees have high affinity for nitrate formulated N than mature cocoa trees. This indeed agrees with results of Coraspe-Leon *et al.* (2009) which reported that N uptake in a plant is largely in the form of ammonium and nitrate. On the other hand, in the forest zone urea treated trees on mature cocoa farm performed much better in terms of weight of pods per plot whilst nitrate treated trees on mature cocoa farm performed poorly in terms of pod yield. However, in young cocoa trees treated with nitrate at increasing N application rates, weight of pods per plot was significantly greater relative to ammonium treated young cocoa trees. This trend could be attributed to the fact that the %N in urea and nitrate fertilizers is greater than that of ammonium fertilizer. Leghari *et al.* (2016) reported that inorganic fertilizers are basically in the form of urea (46% N), ammonium (21% N), and nitrates (26% N).

5.3.2 Dry Bean Yield of Cocoa (kg/m^2)

The result showed that young cocoa trees were very much productive compared to mature cocoa trees concerning the dry bean yield of cocoa. This implies that the age of trees influences the yield of the dry cocoa bean. Thus, the younger the cocoa trees, the higher the productivity rate; the older the trees, the lower the productivity rate. van Vliet *et al.* (2015) reported that aged cocoa trees are unproductive but could be productive with the application of fertilizer (van Vliet *et al.*, 2015).

Statistically, the form of nitrogen applied on cocoa farms did not significantly influence the dry bean weight per plot (kg/m^2) recorded for farms in the Coastal Savannah. In contrast, dry bean weight per plot recorded on farms in the Forest Zone was significantly different in terms of nitrogen forms applied. This implies that cocoa trees in the Forest Zone are more efficient in utilizing nitrate N fertilizer to produce yield compared to those in the Coastal Savannah Zone. However, this could be attributed to the high amount of rainfall in the Forest Zone which makes nutrients from applied fertilizer readily available to cocoa plants at the required soil moisture contents. Ghana Statistical Service survey (2005/2006) reported a higher cocoa dry bean yield in the Forest Zone than the Coastal Savannah. It is also not surprising that nitrate formulated N was largely absorbed by cocoa trees in both zones because nitrate is mostly preferred by the plant as compared to urea and ammonium. Nitrate is the main source of N for most crop species (González-Raya *et al.*, 2005).

In general, cocoa dry bean yield increased with an increasing level of N rates in both Zones. Yet, cocoa farms fertilized according to farmers practice (FP or 10 N kg/ha) in the Forest Zone recorded the highest mean cocoa dry bean yield relative to that recorded for trees fertilized at 40 N kg/ha. This implies that increasing N-rates under certain conditions is not being responded to by cocoa trees. This agrees with several cocoa fertilizer trial studies which concluded that nitrogen inputs make little or no difference to yields, whereas phosphorus and potassium inputs led to improvement (van Vliet *et al.*, 2015). Nur Sholecha (2016) reported that an even lower rate (Urea at 200 gr/tree) is needed to maintain an adequate yield of cocoa.

Dry bean yield followed a similar trend in the two Agro-Ecological Zones, with the highest found in a young cocoa farm in the Coastal Savannah (Fig. 13). This implies that young cocoa trees absorb nitrogen in the form of nitrates whilst mature cocoa trees absorbed nitrogen in the form of urea. However, the highest dry bean weight recorded in the Forest Zone was greater than that of the Coastal Savannah. This could be attributed to the high amount of rainfall experienced in the Forest Zone during the experimental period which made nutrients readily available to plant roots (UNDP, 2012).

Generally, it can be deduced from the result that cocoa dry bean yield increased at an increasing level of N rates on fertilized plots (Fig. 14). This implies that nitrogen have little or no impact on cocoa dry bean yield. This is in accordance with Uribe (2000) which hinted that increasing N rates significantly increased dry bean yield at high K levels. However, the values obtained are greater than Fonkeng (2014) which reported the average weight of normal beans seeds per pod as 118.2 g (0.118 kg).

Though bean yield increased with an increasing rate in all three N formulated fertilizers, plots on which nitrate was applied recorded the highest value followed closely by urea. This confirms Nur Sholecha (2016) that at least a low level of N fertilizer (Urea at 200 gr/tree) is required to sustain a high yield of cocoa. According to González-Raya *et al.* (2005), the core source of N for most crop species is NO_3^-. This result from the study, however, contradicts Coraspe-Leon *et al.* (2009) which hinted that all N absorbed by plant roots is either in the form of ammonium (NH_4^+) or/and nitrate (NO_3^-).

The differences in cocoa dry bean yield (kg/m^2) concerning the interaction effect among the age of farm, the form of nitrogen and rate of nitrogen in both the Coastal Savannah and Forest Agro-Ecological Zones is illustrated in figure 16. This suggests that young cocoa trees have high affinity for nitrate formulated N than mature cocoa trees. This indeed agrees with Coraspe-Leon *et al.* (2009) which reported that N uptake in plant is largely in the form of ammonium and nitrate. On the other hand, in the Forest Zone, urea treated trees on mature cocoa farm performed much better in terms of weight of dry bean per plot whilst nitrate treated trees on mature cocoa farm performed poorly in terms of dry bean yield. However, in young cocoa trees treated with nitrate at increasing N application rates, weight of dry bean per plot was significantly greater relative to ammonium treated young cocoa trees. This trend could be attributed to the fact that %N in urea and nitrate fertilizers is greater than that of ammonium fertilizer. Leghari *et al.* (2016) reported that inorganic fertilizers are basically in the form of urea (46% N), ammonium (21% N), and nitrates (26% N).

5.4 Plant Tissue Nutrient Analysis

In the Coastal Savannah, the nitrogen use efficiency of cocoa trees (NUEc) in the mature (12 years old) cocoa trees was greater than that of young (9 years old) cocoa trees (Table 6a). A similar trend was also seen in NUEc values recorded for cocoa farms in the Forest Zone (Table 6b), but these values were lesser than those recorded in the Coastal Savannah. This implies that mature cocoa trees were more efficient in utilizing nitrogen than young cocoa trees. The percentage of nitrogen resorption was significantly higher in mature cocoa trees than in young cocoa trees. However, the form of nitrogen was insignificant relative to the rate of N resorption and NUEc even though urea treated trees recorded the highest NUEc in the Coastal Savannah. Yet, % N resorption and NUEc increased with an increasing rate of N application. In addition, the age of cocoa trees did not significantly influence the form of N in terms of % N resorption and NUEc. The values recorded in this study are lower than those (80.7%, 91.1% and 97.3%) reported by Triadiati *et al.* (2007). Vitousek (1982) reported that NUEc simply aid describes the distribution of species across landscapes with variability in soil. The variability in %N resorption depicts diversity in environment and tree species (Aerts and Chapin, 2000).

One of the main ways by which nutrients move from plants to the soil is the falling of litter to the ground. Litterfall at 4 MAS revealed a significantly greater litter fall value in mature cocoa farms than in young cocoa farms in both the Coastal Savannah and Forest Zone. However, litterfall was higher in the Forest Zone as compared to the Savannah Zone. This could be attributed to the high rate of rainfall in the forest zone. The rate at which wind and rain occur influence the amount of litter produced over time (ICP Forests, 2004; Santiago and Mulkey, 2005). Also, the values are slightly similar to those reported by some researchers (Isaac *et al.*, 2005; Owusu-Sekyere *et al.*, 2006)

The nitrogen use efficiency at the ecosystem scale (NUE_{ES}) estimated from this study showed that cocoa trees in the Coastal Savannah had lower NUE_{ES} than those in the Forest Zone. Again, cocoa trees with lower foliar N content had higher $NUE_{ES.}$ This implies that nitrogen from the ecosystem when translocated to the leaves could increase the foliar N. This confirms the findings by Tateno and Kawaguchi (2002) who reported that lower nitrogen use efficiency at the ecosystem scale is a result of a higher level of leaf nitrogen content in the plant.

The findings revealed N concentration increased in green and senescing leaf tissues with increasing N fertilizer application rates. In this study the highest N concentration in well-developed green leaf tissues of mature cocoa trees in Coastal Savannah was recorded at urea applied 40 N kg/ha whilst treatment 0 N kg/ha recorded the lowest, but the young cocoa trees treated with nitrate at 40 N kg/ha recorded the highest and lowest at 0 N kg/ha. Elsewhere in the Forest Zone, Urea applied at 40 N kg/ha recorded the highest on mature farm whilst ammonium applied at 0 N kg/ha recorded the lowest. In terms of the young cocoa farm, Nitrate applied at 40 N kg/ha recorded the highest value whilst urea applied at 0 N kg/ha recorded the lowest (Figure 17). This implies that in order to increase the foliar N in cocoa trees there is the need to increase the application rates of N fertilizer for the plants to obtain adequate amount of N despite losses via leaching, runoff or volatilisation. According to Young (1997), losses occur via leaching, erosion, and product removal.

Urea applied at 0 N kg/ha recorded the highest on mature farm whilst nitrate applied at 30 N kg/ha recorded the lowest in the coastal savannah zone. With regards to young cocoa farm, nitrate applied at 20 N kg/ha recorded the highest value whilst urea applied at 30 N kg/ha recorded the lowest. This implies that high percentage of nutrient in the senescing leaf tissue is transferred to the soil when litter falls and decomposed. This concord with Hobbie (1992) who hinted that trees/shrubs through diverse means apportions extra N underneath the ground. Besides, the N concentration in the senescing tissues of cocoa was also higher than that recorded in other *Stipa* species cultivated in the semiarid ecosystems (Distel *et al.*, 2003; Moretto and Distel, 2003).

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The study revealed similar soil-plant nutrition practices among cocoa farmers in both the Coastal Savannah and the Forest Agro-Ecological Zones. Notably, the use of liquid foliar fertilizers was increasing compared to granular fertilizers. Again, it was observed that most of the inorganic granular fertilizers used by cocoa farmers did not contain nitrogen, hence the use of the liquid fertilizers to supply nitrogen and other nutrients to the cocoa plant.

Nitrogen supplied as nitrates was highly absorbed by young cocoa whereas mature cocoa trees absorbed most nitrogen supplied in the form of urea. Largely, cocoa yield increased with an increase rates in N but in some instances, the FP fertilizer application rates recorded higher dry bean yield in the Forest Zone. Notwithstanding, nitrogen applied at 20 to 30 kg N/ha recorded higher pod and dry bean yield of cocoa but an application rate beyond 30 kg N/ha could have negative effect.

Young cocoa trees were more efficient in nitrogen use than mature cocoa trees. However, the per cent N resorption for mature cocoa trees was greater than per cent N resorption recorded for young cocoa trees in both Agro-Ecological Zones.

The estimated nitrogen recycled through litter fall production indicates that with increasing N application rates litterfall production, and litter tissue N content increased, respectively. Hence, nitrogen recycled from cocoa litter is not negligible.

6.2 Recommendations

Based on the results from the study, the following recommendations are suggested:

1. Closer farmer-extension officer collaboration is needed to allow for effective communication regarding cocoa fertilization and other best practices that ensure the overall productivity of the cocoa industry.
2. Increasing use of inorganic fertilizers by cocoa farmers in liquid form has the potential to result in an unintended consequence on the cocoa rhizosphere effect that needs to be investigated.
3. The scope of similar future fertilizer trials on cocoa farms should be widened to include all cocoa growing regions as well as an increase in the length of the study to allow for more robust data that could help in instituting fertilizer scheme for the high yielding cocoa production system in Ghana.
4. Although the yield effect was short term, there is the potential benefit to cocoa plants regardless of the age and location when N in the form of nitrate is added to fertilizers for young plants whilst urea could be incorporated into more mature cocoa plant nutrition in both Agro-Ecological Zones of Ghana.
5. The most promising nitrogen (N) rates for an effective cocoa yield in terms of the pod and dry bean yield ranges from 20 kg N/ha to 30 kg N/ha.

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APPENDICES

APPENDIX A: QUESTIONNAIRE

Section A: Demographics of cocoa farmers

1. Gender: i. Male { } ii. Female { }
2. Age: ……………
3. Education: i. Formal { } ii. Informal { } iii. Non-formal { }
4. If formal to Q3, Which level
   i. Basic { }
   ii. Secondary { }
   iii. Tertiary { }
   iv. Others ……………….
5. Experience in cocoa production ……………………….
6. Average income per year from cocoa production …………….

Section B. Soil fertility management/ plant nutrition strategies by cocoa farmers

7. Do you use organic fertilizer? i. No { } ii. Yes { }

If **No**, continue from Q12,

8. If **Yes**, what type of organic fertilizer do you use? …………………………
9. What is your source of your organic fertilizer? ……………………………….
10. What is quantity do you apply per area? ……………………………….
11. Who recommended the application rate for you? …………………………..
12. Do you use inorganic fertilizer? i. No { } ii. Yes { }
13. If **Yes** to Q12, which form of inorganic fertilizer?
    i. Granular { }
    ii. Foliar { }
    iii. Both { }
14. Which blend do you apply?
    i. NPK 15:15:15
    ii. NPK 23:10:5
    iii. Others, specify…………………
15. What is your application rate per plant/area? ……………………………

16. Where did you source this recommendation? ……………………………
17. Do you apply both inorganic and organic fertilizers? i. No { } ii. Yes {}
18. If **Yes**, In which proportions? i. 50:50 { } ii. 70:30 { } iii. Others { }
19. Does farm age or growth stage informed these ratios? i. No { } ii. Yes { }
20. How often do you apply fertilizer and why? …………………………
21. Mention the specific type of fertilizer used? …………………………
22. When was the last time you applied fertilizer on your farm and why? ………
23. What is your motivation for both fertilizer applications? ……………………
24. Kindly share your view on impact of nutrient nitrogen on cocoa ……………

Section C: Willingness of farmers to allow on-farm experimental trials

25. Will you allow an on-farm experimental trials on your farm? i. No {} ii. Yes {}
26. If **No**, why? ……………………………………………………………
27. If **Yes**, what land size are you ready to offer? ………………………………
28. For how many years?
    i. Less than one year { }
    ii. One year { }
    iii. One and half years { }
    iv. Two years { }
    v. More than two years { }
29. Should there be any monetary compensation for you? i. No { } ii. Yes { }
30. If **Yes**, how much are you ready to accept?
    i. Less than GHc 1000.00 per year { }
    ii. Between GHc 1000.00 to GHc 1500.00 per year { }
    iii. Between GHc 1500.00 to GHc 2000.00 per year { }
    iv. Between GHc 2000.00 to GHc 2500.00 per year { }
    v. Above GHc 2500.00 per year{ }

Appendix B: Analysis of Variance Tables
Soil physico-chemical properties

Variate: **%Total_Nitrogen**

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
BLOCK	1	0.0000504	0.0000504	0.05	0.822
REGION	1	0.1368038	0.1368038	138.48	<.001
FARM	1	0.0005704	0.0005704	0.58	0.449
FORM	2	0.0010225	0.0005112	0.52	0.597
RATE_Kg_ha	4	0.0092225	0.0023056	2.33	0.060
BLOCK.REGION	1	0.0000204	0.0000204	0.02	0.886
BLOCK.FARM	1	0.0152004	0.0152004	15.39	<.001
REGION.FARM	1	0.0042504	0.0042504	4.30	0.040
Residual	120	0.1185500	0.0009879		
Total	239	0.4036662			

Variate: **Available_P**

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
BLOCK	1	5.10	5.10	0.27	0.602
REGION	1	0.70	0.70	0.04	0.846
FARM	1	0.20	0.20	0.01	0.917
FORM	2	23.63	11.82	0.63	0.533
RATE_Kg_ha	4	60.29	15.07	0.81	0.523
BLOCK.REGION	1	21.00	21.00	1.12	0.291
BLOCK.FARM	1	165.00	165.00	8.84	0.004
REGION.FARM	1	0.20	0.20	0.01	0.917
Residual	120	2240.50	18.67		
Total	239	4892.40			

Variate: **Potassium**

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
BLOCK	1	162.	162.	0.03	0.860
REGION	1	24301.	24301.	4.69	0.032
FARM	1	23.	23.	0.00	0.946
FORM	2	4677.	2338.	0.45	0.638
RATE_Kg_ha	4	34324.	8581.	1.66	0.164
BLOCK.REGION	1	7315.	7315.	1.41	0.237
BLOCK.FARM	1	2781.	2781.	0.54	0.465
REGION.FARM	1	23.	23.	0.00	0.946
Residual	120	621166.	5176.		
Total	239	1119498.			

Variate: **CEC**

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
BLOCK	1	29.05	29.05	2.10	0.150
REGION	1	29.05	29.05	2.10	0.150
FARM	1	13.68	13.68	0.99	0.322
FORM	2	60.67	30.34	2.19	0.116
RATE_Kg_ha	4	33.31	8.33	0.60	0.662
BLOCK.REGION	1	0.38	0.38	0.03	0.869
BLOCK.FARM	1	9.09	9.09	0.66	0.419
REGION.FARM	1	13.68	13.68	0.99	0.322
Residual	120	1659.90	13.83		
Total	239	3205.37			

Variate: **pH**

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
BLOCK	1	0.0007	0.0007	0.00	0.970
REGION	1	0.6407	0.6407	1.35	0.247
FARM	1	13.1602	13.1602	27.83	<.001
FORM	2	0.3961	0.1980	0.42	0.659
RATE_Kg_ha	4	1.1082	0.2770	0.59	0.674
BLOCK.REGION	1	0.6407	0.6407	1.35	0.247
BLOCK.FARM	1	1.5682	1.5682	3.32	0.071
REGION.FARM	1	13.1602	13.1602	27.83	<.001
Residual	120	56.7500	0.4729		
Total	239	132.9373			

Appendix C: Impact of N-forms and N-rates on yield of young and mature cocoa trees in the coastal savannah zone

Variate: **Weight_of_pods_plot_kg**

Source of variation	d.f.	(m.v.)	s.s.	m.s.	v.r.	F pr.
BLOCK	1		588.7	588.7	4.52	0.038
FARM	1		4438.4	4438.4	34.08	<.001
FORM	2		1162.2	581.1	4.46	0.016
RATE_Kg_ha	4		572.9	143.2	1.10	0.366
BLOCK.FARM	1		21.0	21.0	0.16	0.690
BLOCK.FORM	2		2218.4	1109.2	8.52	<.001
FARM.FORM	2		2582.2	1291.1	9.91	<.001
BLOCK.RATE_Kg_ha	4		1131.8	283.0	2.17	0.084
FARM.RATE_Kg_ha	4		300.0	75.0	0.58	0.681
FORM.RATE_Kg_ha	8		397.5	49.7	0.38	0.926
BLOCK.FARM.FORM	2		20.7	10.4	0.08	0.924
BLOCK.FARM.RATE_Kg_ha	4		300.3	75.1	0.58	0.681
BLOCK.FORM.RATE_Kg_ha	8		2696.7	337.1	2.59	0.018
FARM.FORM.RATE_Kg_ha	8		1890.7	236.3	1.81	0.094
BLOCK.FARM.FORM.RATE_Kg_ha	8		613.7	76.7	0.59	0.783
Residual	55	(5)	7163.3	130.2		
Total	114	(5)	25789.3			

Variate: **Dry_bean_weight_Kg**

Source of variation	d.f.	(m.v.)	s.s.	m.s.	v.r.	F pr.
BLOCK	1		12.160	12.160	4.77	0.033
FARM	1		83.667	83.667	32.79	<.001
FORM	2		15.165	7.583	2.97	0.060
RATE_Kg_ha	4		10.784	2.696	1.06	0.387
BLOCK.FARM	1		18.565	18.565	7.28	0.009
BLOCK.FORM	2		29.423	14.711	5.77	0.005
FARM.FORM	2		72.865	36.433	14.28	<.001
BLOCK.RATE_Kg_ha	4		29.704	7.426	2.91	0.030
FARM.RATE_Kg_ha	4		3.152	0.788	0.31	0.871
FORM.RATE_Kg_ha	8		30.236	3.780	1.48	0.185
BLOCK.FARM.FORM	2		2.843	1.422	0.56	0.576
BLOCK.FARM.RATE_Kg_ha	4		7.332	1.833	0.72	0.583
BLOCK.FORM.RATE_Kg_ha	8		30.985	3.873	1.52	0.172
FARM.FORM.RATE_Kg_ha	8		40.428	5.053	1.98	0.066
BLOCK.FARM.FORM.RATE_Kg_ha	8		38.607	4.826	1.89	0.080
Residual	55	(5)	140.350	2.552		
Total	114	(5)	563.591			

Appendix D: Impact of N-forms and N-rates on yield of young and mature cocoa trees in the forest zone

Variate: **Weight_of_pods_plot_kg**

Source of variation	d.f.	(m.v.)	s.s.	m.s.	v.r.	F pr.
BLOCK	1		139.751	139.751	18.87	<.001
FARM	1		92.751	92.751	12.53	<.001
FORM	2		244.753	122.377	16.53	<.001
RATE_Kg_ha	4		286.384	71.596	9.67	<.001
BLOCK.FARM	1		233.803	233.803	31.58	<.001
BLOCK.FORM	2		818.829	409.415	55.29	<.001
FARM.FORM	2		1461.279	730.639	98.67	<.001
BLOCK.RATE_Kg_ha	4		711.342	177.836	24.02	<.001
FARM.RATE_Kg_ha	4		396.966	99.241	13.40	<.001
FORM.RATE_Kg_ha	8		530.081	66.260	8.95	<.001
BLOCK.FARM.FORM	2		11.004	5.502	0.74	0.480
BLOCK.FARM.RATE_Kg_ha	4		204.792	51.198	6.91	<.001
BLOCK.FORM.RATE_Kg_ha	8		397.670	49.709	6.71	<.001
FARM.FORM.RATE_Kg_ha	8		677.845	84.731	11.44	<.001
BLOCK.FARM.FORM.RATE_Kg_ha	8		1077.870	134.734	18.20	<.001
Residual	59	(1)	436.875	7.405		
Total	118	(1)	7712.437			

Variate: **Dry_bean_weight_Kg**

Source of variation	d.f.	(m.v.)	s.s.	m.s.	v.r.	F pr.
BLOCK	1		0.752	0.752	0.41	0.524
FARM	1		2.852	2.852	1.56	0.217
FORM	2		12.912	6.456	3.52	0.036
RATE_Kg_ha	4		28.904	7.226	3.94	0.007
BLOCK.FARM	1		1.102	1.102	0.60	0.441
BLOCK.FORM	2		17.179	8.590	4.69	0.013
FARM.FORM	2		24.204	12.102	6.60	0.003
BLOCK.RATE_Kg_ha	4		6.654	1.664	0.91	0.465
FARM.RATE_Kg_ha	4		12.887	3.222	1.76	0.149
FORM.RATE_Kg_ha	8		26.046	3.256	1.78	0.100
BLOCK.FARM.FORM	2		11.754	5.877	3.21	0.048
BLOCK.FARM.RATE_Kg_ha	4		15.054	3.763	2.05	0.098
BLOCK.FORM.RATE_Kg_ha	8		10.946	1.368	0.75	0.650
FARM.FORM.RATE_Kg_ha	8		32.212	4.027	2.20	0.040
BLOCK.FARM.FORM.RATE_Kg_ha	8		52.246	6.531	3.56	0.002
Residual	59	(1)	108.125	1.833		
Total	118	(1)	360.143			

Appendix E: Nitrogen recycling through litterfall production in the coastal savannah zone

Variate: NITROGEN

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
BLOCK stratum	1	0.250253	0.250253	43.19	
BLOCK.*Units* stratum					
FARM	1	1.795853	1.795853	309.93	<.001
FORM	2	0.018380	0.009190	1.59	0.210
RATE_Kg_ha	4	3.525888	0.881472	152.13	<.001
FARM.FORM	2	0.072427	0.036213	6.25	0.003
FARM.RATE_Kg_ha	4	1.332672	0.333168	57.50	<.001
FORM.RATE_Kg_ha	8	0.050162	0.006270	1.08	0.383
FARM.FORM.RATE_Kg_ha	8	0.043748	0.005469	0.94	0.485
Residual	89	0.515697	0.005794		
Total	119	7.605080			

Variate: Dry_weight_of_litterfall_g

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
BLOCK stratum	1	262.0	262.0	0.76	
BLOCK.*Units* stratum					
FARM	1	422.1	422.1	1.22	0.273
FORM	2	1145.7	572.8	1.65	0.198
RATE_Kg_ha	4	3449.5	862.4	2.49	0.049
FARM.FORM	2	956.6	478.3	1.38	0.257
FARM.RATE_Kg_ha	4	380.5	95.1	0.27	0.894
FORM.RATE_Kg_ha	8	4380.8	547.6	1.58	0.143
FARM.FORM.RATE_Kg_ha	8	1736.4	217.1	0.63	0.754
Residual	89	30877.5	346.9		
Total	119	43611.2			

Appendix F: Determining nitrogen use efficiency and nitrogen resorption of young and mature cocoa trees in the coastal savannah zone

Variate: Senesced leaf NITROGEN

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
BLOCK stratum	1	0.03072	0.03072	1.64	
BLOCK.*Units* stratum					
FARM	1	3.64008	3.64008	194.20	<.001
FORM	2	0.00937	0.00469	0.25	0.779
RATE_Kg_ha	4	0.07880	0.01970	1.05	0.386
FARM.FORM	2	0.00795	0.00398	0.21	0.809
FARM.RATE_Kg_ha	4	0.03855	0.00964	0.51	0.725
FORM.RATE_Kg_ha	8	0.16786	0.02098	1.12	0.358
FARM.FORM.RATE_Kg_ha	8	0.21987	0.02748	1.47	0.181
Residual	89	1.66823	0.01874		
Total	119	5.86144			

Variate: Well-developed leaf NITROGEN

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
BLOCK stratum	1	0.006601	0.006601	4.18	
BLOCK.*Units* stratum					
FARM	1	0.171008	0.171008	108.23	<.001
FORM	2	0.075795	0.037898	23.99	<.001
RATE_Kg_ha	4	5.167187	1.291797	817.57	<.001
FARM.FORM	2	0.142985	0.071493	45.25	<.001
FARM.RATE_Kg_ha	4	0.048447	0.012112	7.67	<.001
FORM.RATE_Kg_ha	8	0.050938	0.006367	4.03	<.001
FARM.FORM.RATE_Kg_ha	8	0.112048	0.014006	8.86	<.001
Residual	89	0.140624	0.001580		
Total	119	5.915633			

Appendix G: Determining nitrogen use efficiency and nitrogen resorption of young and mature cocoa trees in the forest zone

Variate: FL NITROGEN

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
BLOCK stratum	1	0.080601	0.080601	15.87	
BLOCK.*Units* stratum					
FARM	1	2.009841	2.009841	395.77	<.001
FORM	2	0.048122	0.024061	4.74	0.011
RATE_Kg_ha	4	6.941553	1.735388	341.72	<.001
FARM.FORM	2	0.025252	0.012626	2.49	0.089
FARM.RATE_Kg_ha	4	0.602280	0.150570	29.65	<.001
FORM.RATE_Kg_ha	8	0.024512	0.003064	0.60	0.773
FARM.FORM.RATE_Kg_ha	8	0.047865	0.005983	1.18	0.321
Residual	89	0.451974	0.005078		
Total	119	10.231999			

Variate: Dry_weight_of_litterfall_g

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
BLOCK stratum	1	2600.	2600.	2.35	
BLOCK.*Units* stratum					
FARM	1	37712.	37712.	34.06	<.001
FORM	2	141.	70.	0.06	0.938
RATE_Kg_ha	4	4343.	1086.	0.98	0.422
FARM.FORM	2	5387.	2694.	2.43	0.094
FARM.RATE_Kg_ha	4	1467.	367.	0.33	0.856
FORM.RATE_Kg_ha	8	10761.	1345.	1.21	0.300
FARM.FORM.RATE_Kg_ha	8	11064.	1383.	1.25	0.281
Residual	89	98548.	1107.		
Total	119	172023.			

Variate:FS NITROGEN

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
BLOCK stratum	1	0.010641	0.010641	3.46	
BLOCK.*Units* stratum					
FARM	1	6.707141	6.707141	2180.31	<.001
FORM	2	0.108832	0.054416	17.69	<.001
RATE_Kg_ha	4	2.402462	0.600615	195.24	<.001
FARM.FORM	2	0.124402	0.062201	20.22	<.001
FARM.RATE_Kg_ha	4	2.286572	0.571643	185.83	<.001
FORM.RATE_Kg_ha	8	0.046418	0.005802	1.89	0.072
FARM.FORM.RATE_Kg_ha	8	0.027948	0.003494	1.14	0.348
Residual	89	0.273784	0.003076		
Total	119	11.988199			

Variate: FD NITROGEN

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
BLOCK stratum	1	0.085333	0.085333	19.74	
BLOCK.*Units* stratum					
FARM	1	0.182520	0.182520	42.23	<.001
FORM	2	0.217462	0.108731	25.16	<.001
RATE_Kg_ha	4	6.140353	1.535088	355.17	<.001
FARM.FORM	2	0.211085	0.105542	24.42	<.001
FARM.RATE_Kg_ha	4	0.358413	0.089603	20.73	<.001
FORM.RATE_Kg_ha	8	0.107272	0.013409	3.10	0.004
FARM.FORM.RATE_Kg_ha	8	0.138532	0.017316	4.01	<.001
Residual	89	0.384667	0.004322		
Total	119	7.825637			

Variate: WDL NITROGEN

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
BLOCK	1	0.0697004	0.0697004	72.76	<.001
AGRO_ECOLOGICAL_ZONE	1	0.0142604	0.0142604	14.89	<.001
FARM	1	0.3534337	0.3534337	368.96	<.001
FORM	2	0.2678933	0.1339467	139.83	<.001
RATE_Kg_ha	4	11.2639525	2.8159881	2939.70	<.001
BLOCK.AGRO_ECOLOGICAL_ZONE	1	0.0222338	0.0222338	23.21	<.001

BLOCK.FARM	1	0.1020938	0.1020938	106.58	<.001
AGRO_ECOLOGICAL_ZONE.FARM	1	0.0000938	0.0000938	0.10	0.755
BLOCK.FORM	2	0.0008233	0.0004117	0.43	0.652
AGRO_ECOLOGICAL_ZONE.FORM	2	0.0253633	0.0126817	13.24	<.001
FARM.FORM	2	0.3429900	0.1714950	179.03	<.001
BLOCK.RATE_Kg_ha	4	0.0359308	0.0089827	9.38	<.001
AGRO_ECOLOGICAL_ZONE.RATE_Kg_ha	4	0.0435875	0.0108969	11.38	<.001
FARM.RATE_Kg_ha	4	0.0820142	0.0205035	21.40	<.001
FORM.RATE_Kg_ha	8	0.1319900	0.0164988	17.22	<.001
BLOCK.AGRO_ECOLOGICAL_ZONE.FARM	1	0.0377504	0.0377504	39.41	<.001
BLOCK.AGRO_ECOLOGICAL_ZONE.FORM	2	0.0055900	0.0027950	2.92	0.058
BLOCK.FARM.FORM	2	0.0051100	0.0025550	2.67	0.074
AGRO_ECOLOGICAL_ZONE.FARM.FORM	2	0.0110800	0.0055400	5.78	0.004
BLOCK.AGRO_ECOLOGICAL_ZONE.RATE_Kg_ha	4	0.0370558	0.0092640	9.67	<.001
BLOCK.FARM.RATE_Kg_ha	4	0.0200458	0.0050115	5.23	<.001
AGRO_ECOLOGICAL_ZONE.FARM.RATE_Kg_ha	4	0.3248458	0.0812115	84.78	<.001
BLOCK.FORM.RATE_Kg_ha	8	0.0203517	0.0025440	2.66	0.010
AGRO_ECOLOGICAL_ZONE.FORM.RATE_Kg_ha	8	0.0262200	0.0032775	3.42	0.001
FARM.FORM.RATE_Kg_ha	8	0.2159433	0.0269929	28.18	<.001
BLOCK.AGRO_ECOLOGICAL_ZONE.FARM.FORM	2	0.0208433	0.0104217	10.88	<.001
BLOCK.AGRO_ECOLOGICAL_ZONE.FARM.RATE_Kg_ha	4	0.0707142	0.0176785	18.46	<.001
BLOCK.AGRO_ECOLOGICAL_ZONE.FORM.RATE_Kg_ha	8	0.0208017	0.0026002	2.71	0.009
BLOCK.FARM.FORM.RATE_Kg_ha	8	0.0203317	0.0025415	2.65	0.010
AGRO_ECOLOGICAL_ZONE.FARM.FORM.RATE_Kg_ha	8	0.0346367	0.0043296	4.52	<.001
BLOCK.AGRO_ECOLOGICAL_ZONE.FARM.FORM.RATE_Kg_ha	8	0.0128983	0.0016123	1.68	0.109
Residual	120	0.1149500	0.0009579		
Total	239	13.7555296			

Variate: SL NITROGEN

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
BLOCK	1	0.002600	0.002600	0.62	0.431
AGRO_ECOLOGICAL_ZONE	1	0.380010	0.380010	91.16	<.001
FARM	1	10.114720	10.114720	2426.32	<.001
FORM	2	0.078910	0.039455	9.46	<.001
RATE_Kg_ha	4	0.844053	0.211013	50.62	<.001
BLOCK.AGRO_ECOLOGICAL_ZONE	1	0.038760	0.038760	9.30	0.003
BLOCK.FARM	1	0.005134	0.005134	1.23	0.269
AGRO_ECOLOGICAL_ZONE.FARM	1	0.232504	0.232504	55.77	<.001
BLOCK.FORM	2	0.030143	0.015072	3.62	0.030
AGRO_ECOLOGICAL_ZONE.FORM	2	0.039293	0.019647	4.71	0.011
FARM.FORM	2	0.085363	0.042682	10.24	<.001
BLOCK.RATE_Kg_ha	4	0.260506	0.065126	15.62	<.001
AGRO_ECOLOGICAL_ZONE.RATE_Kg_ha	4	1.637212	0.409303	98.18	<.001
FARM.RATE_Kg_ha	4	1.174211	0.293553	70.42	<.001
FORM.RATE_Kg_ha	8	0.098128	0.012266	2.94	0.005
BLOCK.AGRO_ECOLOGICAL_ZONE.FARM	1	0.031054	0.031054	7.45	0.007
BLOCK.AGRO_ECOLOGICAL_ZONE.FORM	2	0.002403	0.001202	0.29	0.750
BLOCK.FARM.FORM	2	0.034230	0.017115	4.11	0.019
AGRO_ECOLOGICAL_ZONE.FARM.FORM	2	0.046990	0.023495	5.64	0.005
BLOCK.AGRO_ECOLOGICAL_ZONE.RATE_Kg_ha	4	0.088096	0.022024	5.28	<.001
BLOCK.FARM.RATE_Kg_ha	4	0.347314	0.086829	20.83	<.001
AGRO_ECOLOGICAL_ZONE.FARM.RATE_Kg_ha	4	1.150911	0.287728	69.02	<.001
BLOCK.FORM.RATE_Kg_ha	8	0.057994	0.007249	1.74	0.096
AGRO_ECOLOGICAL_ZONE.FORM.RATE_Kg_ha	8	0.116153	0.014519	3.48	0.001
FARM.FORM.RATE_Kg_ha	8	0.088474	0.011059	2.65	0.010
BLOCK.AGRO_ECOLOGICAL_ZONE.FARM.FORM	2	0.016360	0.008180	1.96	0.145
BLOCK.AGRO_ECOLOGICAL_ZONE.FARM.RATE_Kg_ha	4	0.080944	0.020236	4.85	0.001
BLOCK.AGRO_ECOLOGICAL_ZONE.FORM.RATE_Kg_ha	8	0.163709	0.020464	4.91	<.001
BLOCK.FARM.FORM.RATE_Kg_ha	8	0.144541	0.018068	4.33	<.001

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AGRO_ECOLOGICAL_ZONE.FARM.FORM.RATE_Kg_ha
                                8    0.159339    0.019917     4.78   <.001
BLOCK.AGRO_ECOLOGICAL_ZONE.FARM.FORM.RATE_Kg_ha
                                8    0.179336    0.022417     5.38   <.001
Residual                      120    0.500250    0.004169
Total                         239   18.229646
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Variate: NITROGEN

Source of variation           d.f.       s.s.        m.s.     v.r.   F pr.
BLOCK                           1    0.023404    0.023404    17.86   <.001
AGRO_ECOLOGICAL_ZONE            1    5.025720    5.025720  3835.21   <.001
FARM                            1    3.802684    3.802684  2901.89   <.001
FORM                            2    0.043116    0.021558    16.45   <.001
RATE_Kg_ha                      4   10.157306    2.539326  1937.80   <.001
BLOCK.AGRO_ECOLOGICAL_ZONE
                                1    0.307450    0.307450   234.62   <.001
BLOCK.FARM                      1    0.009004    0.009004     6.87   0.010
AGRO_ECOLOGICAL_ZONE.FARM
                                1    0.003010    0.003010     2.30   0.132
BLOCK.FORM                      2    0.032283    0.016141    12.32   <.001
AGRO_ECOLOGICAL_ZONE.FORM
                                2    0.023386    0.011693     8.92   <.001
FARM.FORM                       2    0.084532    0.042266    32.25   <.001
BLOCK.RATE_Kg_ha                4    0.226478    0.056619    43.21   <.001
AGRO_ECOLOGICAL_ZONE.RATE_Kg_ha
                                4    0.310136    0.077534    59.17   <.001
FARM.RATE_Kg_ha                 4    0.599589    0.149897   114.39   <.001
FORM.RATE_Kg_ha                 8    0.045697    0.005712     4.36   <.001
BLOCK.AGRO_ECOLOGICAL_ZONE.FARM
                                1    0.023010    0.023010    17.56   <.001
BLOCK.AGRO_ECOLOGICAL_ZONE.FORM
                                2    0.015376    0.007688     5.87   0.004
BLOCK.FARM.FORM                 2    0.061043    0.030521    23.29   <.001
AGRO_ECOLOGICAL_ZONE.FARM.FORM
                                2    0.013146    0.006573     5.02   0.008
BLOCK.AGRO_ECOLOGICAL_ZONE.RATE_Kg_ha
                                4    0.096481    0.024120    18.41   <.001
BLOCK.FARM.RATE_Kg_ha           4    0.114661    0.028665    21.87   <.001
AGRO_ECOLOGICAL_ZONE.FARM.RATE_Kg_ha
                                4    1.335362    0.333841   254.76   <.001
BLOCK.FORM.RATE_Kg_ha           8    0.063830    0.007979     6.09   <.001
AGRO_ECOLOGICAL_ZONE.FORM.RATE_Kg_ha
                                8    0.028977    0.003622     2.76   0.008
FARM.FORM.RATE_Kg_ha            8    0.065613    0.008202     6.26   <.001
BLOCK.AGRO_ECOLOGICAL_ZONE.FARM.FORM
```

	2	0.026766	0.013383	10.21	<.001
BLOCK.AGRO_ECOLOGICAL_ZONE.FARM.RATE_Kg_ha	4	0.062188	0.015547	11.86	<.001
BLOCK.AGRO_ECOLOGICAL_ZONE.FORM.RATE_Kg_ha	8	0.014037	0.001755	1.34	0.231
BLOCK.FARM.FORM.RATE_Kg_ha	8	0.022287	0.002786	2.13	0.038
AGRO_ECOLOGICAL_ZONE.FARM.FORM.RATE_Kg_ha	8	0.026000	0.003250	2.48	0.016
BLOCK.AGRO_ECOLOGICAL_ZONE.FARM.FORM.RATE_Kg_ha	8	0.042980	0.005372	4.10	<.001
Residual	120	0.157250	0.001310		
Total	239	22.862800			