UNIVERSITY OF CAPE COAST

SPATIAL ANALYSIS OF SOYBEAN YIELD RESPONSE TO FERTILIZER APPLICATION IN GHANA

BY

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DECLARATION

Candidate's Declaration

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

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

Name: Ebenezer Ntow

Supervisor's Declaration

I 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.

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

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ABSTRACT

Soybean is one of the crops grown in Ghana that generate income and serve as a source of protein, animal feed, and food security. However, yields are low, averaging 1.3 Mt/h compared to a potential yield of 3.0 Mt/h, despite an 8 kg/h increase in fertilizer application. The study aimed to analyse how soybean yields in Ghana respond to fertilizer application through spatial methods. We employed a yield modeling approach utilizing data from agricultural trials. To evaluate the variability in observed yields, we used the Multiple Linear Regression-Akaike Information Criterion (MLR-AIC). Additionally, we applied a Random Forest spatial prediction framework to analyze and map the predicted yields. The final and best MLR model achieved one (R=51%), indicating that the model explains about 51% of the variation in the dependent variable. A detailed regression analysis revealed that calcium (Ca), sodium (Na) and minimum temperature (Tmin) were the variables that had a significant negative (<1000 kg/ha) impact on yield. pH, carbon and potassium were the variables with the greatest positive impact on yield (>1000 kg/ha). The predicted soybean yield based on the trained random forest model ranged from 1.0 to 2.2 t/ha. The forecast remained at 1 to 1.8 t/ha in the northern parts and 2.0 to 2.2 t/ha for the southwest. Policy makers in Ghana need to consider high-potassium fertilizers and maintain sound agronomic practices to increase soybean yields.

KEY WORDS

Climate

Fertilizer Application

Random Forest

Soil

Soybean

Terrain

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DEDICATION

To my parents, Mr. and Mrs. Ntow

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CHAPTER ONE

INTRODUCTION

Considering the significance of soybeans as a vital protein source for both humans and livestock, researching how soybean yields in Ghana respond to fertilizer application is crucial. This study explores the regional variations in soybean yield response to fertilizers across different areas of Ghana. It also offers important insights into the optimal use of fertilizers in each region. Geospatial analysis tools, such as Geographic Information Systems (GIS) and remote sensing, are utilized to create maps illustrating the geographic distribution of soybean production in relation to fertilizer application.

1.1 Background to the Study

The growing world population, rising meat and dairy consumption, and increasing use of biofuels are the driving demand for food and food products (Ray, Ramanutty, Mueller, West & Foley, 2012). As a result, there has been a gradual decline in agricultural yields, and the current growth in food production is mainly due to the expansion of acreage. In 2020, an estimated 720 to 811 million people worldwide were affected by hunger, an increase of about 161 million people compared to 2019 (WHO, 2021). In addition, in the same year, an incredible 2.4 billion people, representing over 30 percent of the world's population, suffered from varying degrees of hunger, insecurity and limited regular access to adequate food (WHO, 2019). As emphasised by Arora and Mishra (2022), the aim of the Sustainable Development Goal 2 (SDG 2) is to eradicate hunger, ensure food security, improve nutrition and promote sustainable agriculture by 2030.

Globally, agriculture serves as the primary means of food production, providing the essential food needed to meet the needs of the world's growing population. It is essential for poverty alleviation in developing countries, where it is a major source of income (McKenzie & Williams, 2015). Agriculture impacts nutrition and public health, and access to a variety of nutrient-dense foods, including fruits, vegetables and grains, is critical to promoting health and preventing malnutrition. Its contributions and supports to rural development, livelihoods and social well-being through income generation, infrastructure and employment opportunities must be considered (Osabohien, Mathew, Gershon, Ogunbiyi and Nwosu, 2019). The 2019 Ghana Statistical Service report states that the agriculture sector employs over 45.38 percent of the workforce, making it the largest employer in the country (Nyamekye, Tian & Cheng, 2021). Ghana's economy benefited significantly from agriculture, which produced 20 percent of the country's total domestic production in 2019 and 19.25 percent in 2020. In 2020, Ghana's agricultural exports were US$3.63 billion, down US$240 million from 2019. Appropriate and sustainable agricultural practices are therefore crucial to ensure food security and fight hunger worldwide.

Sustainable agriculture is a holistic approach to food production that focuses on long-term environmental, social and economic viability (Velten & Newig, 2015). The goal is to meet the current needs of agricultural practices while preserving and enhancing natural resources for future generations (Gomiero, Pimentel & Paoletti, 2011) by integrating principles and practices that minimize negative impacts on the environment, giving priority to social justice and ensuring economic viability (Muoz-Torres, Fernndez-Izquierdo, Rivera-Lirio, Ferrero-Ferrero, Escrig-Olmedo, Gisbert-Navarro and Marullo, 2018).

As a highly nutrient-dense source of protein, soybeans (Glycine max) play a crucial role in the world's agricultural landscape and are used as forage for livestock and fish, as well as for domestic consumption and export markets (Siambele, 2021). It is widely grown in Sub-Saharan Africa (SSA) due to its food and economic importance, which powers several agro-industrial complexes. The agro-ecological zones of SSA offer significant opportunities for soybean cultivation as soybean acreage in the sub region has grown significantly, from 20,000 hectares in the early 1970s to 1,500,000 hectares in 2016 with a remarkable 177-fold increase, from 13,000 tonnes in the 1970s to 2,300, 000 tons in 2016 (Khojely, Ibrahim, Sapey & Han, 2018). Despite this expansion, average soybean production in SSA has remained constant over the past four decades at 1.1 tons per hectare, well below the global average of 2.4 tons per hectare (Akibode & Maredia, 2012). The region's low soybean yields could be caused by ineffective cultivars and a failure to make sustainable use of rhizobia inoculants and fertilizers.

Fertilizer management is one of the factors that contribute significantly to higher yields. Fertilizer use could significantly increase food production in SSA and reduce poverty, as highlighted at the Abuja Summit on Fertilizers (Winnie, Giweta, Gweyi-Onyango, Mochoge, Mutegi, Nziguheba, and Masso, 2022). The summit suggested that increasing fertilizer use from 8 to 50 kg of nutrients per hectare would improve food security, crop production and the well-being of rural residents in the sub region (Jayne & Rashid, 2013). However, attempts to increase fertilizer use in sub-Saharan Africa have focused on subsidies and loan schemes and its effectiveness use varies depending on the farm and ecological zones.

Soybean plants require various nutrients for their growth and development, including nitrogen (N), phosphorus (P) and potassium (K) (Weisany, Raei & Allahverdipoor, 2013). When applied, N P K fertilizers increase soybean productivity by replenishing the soil with essential nutrients (Mmbaga et al., 2014). These nutrients are essential for physiological processes such as photosynthesis, protein synthesis, and root development (Weisany et al.). However, the degree of availability of these nutrients in soil varies greatly by location due to different soil properties, climate conditions, and management practices (Nafi, Webber, Danso, Naab, Frei, & Gaiser, 2020). Ghanaian soils are often deficient in nutrients, particularly nitrogen and phosphorus, which limits soybean yields. Soils vary in nutrient content, organic matter content, pH and cation exchange capacity (CEC) (Gruba & Mulder, 2015). Soils with lower amounts of organic matter and nutrients may respond more readily to fertilizer application than soils with higher nutrient levels (Khojely et al., 2018).

Climate-related variables such as precipitation patterns, temperature, and sunlight affect nutrient availability and plant uptake, and impact regional variability in yield response to fertilizer application. Sites with more rainfall are more likely to experience nutrient leaching, leading to nutrient deficiencies and reduced yield response to fertilizer (Bationo, Fening & Kwaw, 2018). On the other hand, areas with less rainfall would experience water stress, which would reduce nutrient uptake and utilization. In addition, management practices, including tillage systems, crop rotation, and past fertilizer application histories contribute to spatial variability in yield response. Management practices also affect the mechanisms that control nutrient availability in the soil. Akibode and Maredia (2012) assert that a continuous cultivation of soybeans without proper nutrient management can lead to nutrient deficiencies in the soil and limit yield.

As in other countries, soybeans cultivation in Ghana significantly increases agricultural productivity and diversifies food sources with 30% cholesterol-free oil, 40% protein, and essential vitamins that are of great value to farmers and consumers (Byerlee, Falcon, & Naylor, 2017). The soybean industry in Ghana offers significant opportunities for value chain operators (Owusu-Adjei, Baah-Mintah & Salifu, 2017), yet yields are still low, averaging between 0.7 and 1.7 tons per hectare, mainly due to inadequate farming practices, technology and most importantly access to inputs such as fertilizers (Bumb, Johnson & Fuentes, 2011).

1.2 Statement of the Problem

Ghana's high nitrogen, phosphorus, and potassium depletion rates (N.P.K.) pose a serious agricultural issue, even though the country uses more fertilizer on average than the Sub-Saharan African recommendation of 15 kg/ha (Batiano et al., 2018). The paradoxical situation is evident in the soybean sector, where Ghana's average yield remains at a mere 1.3 tons per hectare, substantially below its potential yield of 3.0 tons per hectare (Mahama et al., 2020). This discrepancy raises crucial questions regarding the effectiveness of current fertilizer application practices and the relevance of long-standing fertilizer recommendations.

The Council for Scientific and Industrial Research's Soil Research Institute (SRI-CSIR) has initiated a revision of Ghana's decades-old fertilizer recommendation, proposing tailored formulations for two specific agro-ecological zones to address these concerns: the forest-savannah transition zone and the Guinea-savannah transition zone. An NPK fertilizer blend of N-P2O5-K2O: 20-60-30 + 0.8 Zn has been proposed across all agro-ecological zones in Ghana for soybeans. However, this standardized recommendation assumes uniform soil fertility, climatic and geographic conditions, overlooking the substantial spatial and climatic variations across the country.

Fertilizer recommendations and applications should be context-specific, considering local soil characteristics, climate nuances, crop nutrient requirements, and management practices. While previous studies (Chapoto & Tetteh, 2014; Tetteh *et al*., 2018; Atakora *et al*., 2014) have underscored the positive impact of fertilizer application on crop growth and productivity, these studies were limited in scope, focusing on specific agro-ecological zones. To address this knowledge gap comprehensively, a meticulous analysis is warranted. Such an analysis will yield region and site-specific fertilizer recommendations, poised to maximize soybean productivity, mitigate environmental concerns, and facilitate sustainable agricultural development in Ghana.

1.3 Research Objectives

The main objective of the study is to analyse the spatial response of soybean yield to fertilizer application in Ghana.

Specifically, the study seeks to;

1. Examine the effects of the physical and chemical properties of soil on soybean yield in Ghana
2. Examine the influence of climatic variables on soybean yield in Ghana
3. Assess the impacts of N. P. K on soybean yield in Ghana

4. Analyze the spatial variability of soybean yield based on soil physical-chemical, fertilizer, and climatic variables in Ghana on a map

1.4 Research Questions

1. How do the physical and chemical soil properties affect soybean yields in Ghana?
2. How do the climatic variables affect soybean yields in Ghana?
3. How does N P K influence soybean yields in Ghana?
4. What is the spatial differentiation of soybean yields in Ghana?

1.5 Significance of the Study

In recent years, Ghana's soybean demand, driven by industrial processing and other applications, has surged. However, local soybean production falls short of meeting this growing demand, leading to increased soybean imports. This study attempts to solve this issue by shedding light on how Ghanaian fertilizer usage might increase soybean yields. Employing spatial analysis techniques, the study identifies geographic patterns and variations in soybean production responses to fertilizers. These findings have the potential to transform agricultural practices, facilitating precision farming methods like variable fertilization.

This approach tailor's fertilizer application rates to specific field locations, optimizing soybean production, increasing profitability, cutting costs, and reducing environmental impacts. Additionally, the research supports the adoption of site-specific nutrient management (SSNM), which customizes fertilizer applications to match the unique nutrient needs of different soil types and field locations. Through precise fertilization, SSNM holds promise for significantly improving soybean cultivation efficiency and sustainability.

1.6 Delimitation of the Study

The study was conducted in all agro-ecological zones of Ghana where soybeans are grown and there is enough data for analysis. It was common throughout Ghana, not just in one specific region. The study analysis focused on the data collected from soybean fields in the country's agro-ecological regions in recent years. The study focused on soybean crops and how soil, weather and fertilizer treatments affected yield response. The study examined the geographic patterns of soybean production response to fertilizer application in Ghana using spatial regression and geospatial analysis approaches. The study made use of information from Ghana's International Fertilizer Development Centre (IFDC) and several other agricultural research institutions. The data's quality and availability restricted the extent of the analysis. Due to the study's data volume limitations, it's possible that some important factors influencing soybean yield were left out.

1.7 Limitations of the Study

The quantitative nature of the study may limit its ability to examine specific topics and contexts in depth. For example, help may be needed to fully understand the complex social, economic and cultural factors affecting soybean yields in Ghana. In addition, the quantity and quality of the data can limit the study, which can lead to important information being missing or having to be revised in the analysis. Random Forest can also have limitations as it is a model based on assumptions and simplifications of real-world relationships. Any assumptions about linearity or interactions may not hold and affect the accuracy of the results. Errors may occur in the analysis and modelling of the study, leading to incorrect results. Assume that the data used in the study is representative of only a portion of the soybean farming population in Ghana. In this case, the results need to be more applicable to the wider population. Therefore, the methodology and data sources of the study must be disclosed and the results carefully understood.

1.9 Organization of the Study

Six chapters, each with a distinct subject, make up this research. The issue statement, research objectives, research questions, and the study's importance are all summed up in the first chapter, which also provides background information and context for the research. The study's structure, parameters, and extent are also taken into account. The literature currently available on Ghanaian soybean production, including the variables influencing crop development, is reviewed in Chapter 2. The chapter also discusses important ideas on the use of GIS in agriculture and how soybean yields might be increased.

Chapter three describes the study area including location, agro-ecological zones, climate, and vegetation. Chapter four describes the research approach, including the subject area, research philosophies and designs, data sources, and statistical methods. The chapter also provides an overview of the data used in the study, describing their characteristics and sources and how they were collected and processed. Building on the goals and research questions formulated in the first chapter, chapter five presents the research results and provides comments on these results. It includes a data analysis and the findings from the statistical methods of the study. The final chapter of Chapter six summarizes the study, including key findings, conclusions and recommendations for future research or policy. It also includes suggestions on how the study results can be used to improve soybean yields in Ghana and support sustainable farming practices in the country.

CHAPTER TWO

SOYBEAN YIELD RESPONSE TO FERTILIZER: A LITERATURE REVIEW

2.0 Introduction

This chapter provides a comprehensive analysis of agricultural production in Ghana, with a particular focus on soybean cultivation across the country's diverse agroecological zones. It explores the driving factors influencing soybean yield, including environmental, agronomic, and socio-economic variables, and assesses the role of fertilizer application in enhancing productivity. The discussion extends to the application of geographic information systems (GIS) for mapping soybean yield variability, taking into account critical factors such as soil physicochemical properties, climatic conditions, and patterns of fertilizer use. Furthermore, the chapter examines competing conceptual models in crop yield modelling, highlighting their relevance and applicability to soybean production in Ghana. The chapter also delves into the multifaceted challenges constraining soybean production in Ghana.

These challenges include limited access to advanced agricultural technologies and financial resources, inadequate pest and disease management strategies, and the low adoption rate of improved farming practices among smallholder farmers. In response, the chapter explores the potential for enhanced government support and strategic partnerships with private sector stakeholders to bolster soybean production. Additionally, the socio-economic significance of soybean cultivation is underscored, particularly its potential as a critical source of income and a means of ensuring food security for smallholder farmers. The chapter also considers the prospects for Ghana to tap into export markets, leveraging soybean production to contribute to the nation's economic growth. Collectively, these discussions provide valuable insights into the current state and future potential of soybean production in Ghana, while identifying pathways for addressing existing constraints and optimizing productivity.

2.1 Agriculture Production in Ghana

Global agricultural food production is anticipated to rise by 70% by 2050 to accommodate the growing global population while maintaining sustainable resource use for future generations (Keating, Herrero, Carberry, Gardner & Cole, 2014; Awunyo-Vitor and Sackey, 2018; Van Alfin, 2014). This global trend underscores the crucial role of agriculture in addressing food security challenges and ensuring environmental sustainability. In Ghana, agriculture is a cornerstone of the economy, supported by diverse climatic zones that facilitate the cultivation of various crops. Key staples such as yams, grains, cocoa, oil palms, and kola nuts form the backbone of agricultural production, contributing significantly to both domestic consumption and export revenues (Ntow, 2008).

According to the 2011 report by the Statistical Research and Information Directorate (SRID) and the Ministry of Food and Agriculture (MoFA), approximately 57% (136,000 km^2) of Ghana's total land area (238,539 km^2) is classified as agricultural land. Of this, 24.4% (58,000 km^2) is actively cultivated, with only 11,000 hectares designated for irrigation (Mahama et al., 2020). Farm size distribution in Ghana reveals a predominance of smallholder agriculture. Approximately 60% of farms are less than 1.2 hectares, 25% range between 1.2

and 2.0 hectares, and only 15% exceed 2.0 hectares. Smallholder farmers account for 95% of cultivated land, which is typically under 10 hectares in size (SRID, 2011).

These farmers grow diverse crops, including rice, maize, pineapple, coconut, oil palm, cassava, yam, plantain, tomato, and pepper, which serve both subsistence and income-generating purposes. Traditional farming methods dominate, with tools like pickaxes and cutlasses being the primary implements. Although ox-farming is sporadically practiced in northern Ghana, machine farming remains limited nationwide. Precipitation patterns and soil quality are critical determinants of agricultural productivity. Smallholder farms frequently employ intercropping techniques, while larger commercial farms primarily adopt monoculture systems (Sharma et al., 2016). Historically, agriculture has been a pivotal sector in Ghana's economy. In 2013, it contributed 40% of the GDP and employed more than half of the labor force. By 2019, agriculture accounted for 45.38% of total employment, underscoring its continued significance. However, the sector's performance has faced challenges, including a decline in export value by US$240 million in 2019 (Awunyo-Vitor & Sackey, 2018).

Agriculture's contribution to total production stood at 20% in 2020, marginally higher than 19.25% in 2019 (Korankye, Frempong & Isaac, 2019). Despite its economic and social importance, Ghana's agricultural sector faces significant challenges. These include inadequate investment in research and development, limited market access for smallholder farmers, and the adverse effects of climate change. Erratic weather patterns, droughts, and floods often disrupt production cycles and reduce yields. Additionally, a lack of modern technology adoption, coupled with inadequate infrastructure for storage and transportation, further constrains productivity and market efficiency. These challenges underline the complexities facing Ghana's agricultural sector as it strives to maintain its crucial role in national development amidst growing pressures from environmental and demographic changes.

2.2 Soybean Production in Ghana

Globally, approximately 65% of protein consumption is derived from plant-based sources, with grains and legumes playing a critical role, especially in underdeveloped countries and among vegetarians in developed nations (Sá, Moreno, & Carciofi, 2020). Soybeans are among the most widely cultivated and consumed legumes worldwide, valued not only for their nutritional benefits but also for their versatility, including their potential use in renewable energy production (Siambele, 2021). Soybean cultivation was introduced to Ghana in 1901, largely due to the crop's adaptability to diverse environmental conditions. Today, soybean farming spans multiple agro-ecological regions across the country (Mahama et al., 2020). Over the past two decades, the land area devoted to soybean cultivation in Ghana has expanded significantly, growing from 61,800 hectares in 2008 to 102,980 hectares by 2018.

This increase in cultivated land has corresponded with a rise in production, from 74,800 tons to 176,670 tons within the same period (MoFA, 2019). Despite this growth, soybean productivity in Ghana remains below the global average, with a national yield of approximately 1.3 tons per hectare (Tetteh et al., 2017). The sector is dominated by over 200,000 smallholder farmers, who manage farms averaging 1.4 hectares in size and produce an average yield of 0.5 tons per hectare annually. The yield gap is most pronounced in the agro-ecological savannah zones, where poor soil fertility, limited input utilization, and insufficient awareness of best agronomic practices contribute to suboptimal productivity (Awuni et al., 2023; Buah et al., 2017). The soybean industry in Ghana, however, is on an upward trajectory, fueled by increasing domestic and international demand. Key drivers include the expansion of the poultry and freshwater fisheries industries, increased exports to countries such as Turkey and China, and growing local demand driven by a rising middle class, urban migration, and population growth. As of 2021, soybean cultivation in Ghana covers an estimated area of 250,000 hectares, yielding an annual production capacity of approximately 700,000 tons, with the Guinea savannah and transitional forest zones being the primary production areas (MoFA, 2017).

Although the semi-deciduous forest zone has potential for soybean cultivation, its productivity is constrained by issues such as low soil pH and limited tuber formation. Studies have shown that addressing these constraints may require the application of rhizobium inoculants or phosphorus fertilizers to improve the adaptation of legumes to tropical environments (Adjei-Nsiah et al., 2022; Addae-Frimpomaah et al., 2022). Ghana's soybean export industry has also seen significant growth in recent years. In 2020, Ghana ranked 41st globally in soybean exports, generating US$6.45 million. By 2021, it had climbed to 31st position with exports worth US$24.2 million. In 2022, soybeans ranked as Ghana’s 27th most exported product. Turkey, India, the United States, Vietnam, and Italy were Ghana's top export markets for soybeans, with Turkey and India recording the largest growth in imports from Ghana between 2020 and 2021, valued at US$8.33 million and US$3.1 million, respectively. Soybean exports have thus become an integral component of Ghana's agricultural trade portfolio, reflecting both the crop's growing importance in the domestic economy and its potential to contribute to global food security.

2.3 Farmers' Challenges

Soybean farming in Ghana is associated with numerous benefits, such as reduced vulnerability to pests and diseases, improved storage capabilities, and better leaf biomass distribution compared to other grain legumes like peanuts and cowpeas (Dogbe, Etwire, Etwire, Baba & Siise, 2013). However, despite these advantages, Ghanaian soybean farmers face multifaceted challenges that significantly limit their ability to maximize productivity and profitability (Mbanya, 2011). The challenges are multifaceted and interconnected, ranging from limited access to inputs and markets to the adverse impacts of climate change and pests.

2.3.1 Access to Inputs and Technology

A significant obstacle for soybean farmers in Ghana is the limited availability and accessibility of high-quality inputs, such as certified seeds, fertilizers, and pesticides. Many farmers rely on recycled seeds from previous harvests, which typically have lower germination rates, reduced vigor, and less resistance to pests and diseases. Without access to certified improved seed varieties, farmers struggle to achieve optimal yields. Fertilizers and pesticides, though critical for enhancing crop productivity and controlling pests, are often prohibitively expensive. Furthermore, distribution networks for these inputs are underdeveloped in rural areas, forcing farmers to travel long distances to purchase them. For smallholder farmers with limited resources, these costs and logistical challenges are significant barriers. Irrigation infrastructure is another major limitation.

Ghana's soybean farmers primarily depend on rain-fed agriculture, which is highly susceptible to erratic rainfall and prolonged dry spells caused by climate change. Although irrigation systems can mitigate these risks, the initial investment and ongoing maintenance costs are unaffordable for most small-scale farmers. As a result, farmers face inconsistent yields and increased vulnerability to climate-induced crop failures.

2.3.2 Market Access and Price Volatility

The absence of organized markets and an efficient value chain significantly hampers soybean farmers' ability to sell their produce at competitive prices. Most farmers rely on middlemen who exploit the lack of market linkages to buy soybeans at low prices, often well below prevailing market rates. This reduces farmers' income and discourages investment in expanding production or improving practices (Abokyi et al., 2020). Additionally, the lack of formalized marketing infrastructure means that farmers have limited access to storage facilities. Without proper storage, farmers are often forced to sell their produce immediately after harvest when prices are at their lowest due to market saturation.

Poor storage facilities also lead to post-harvest losses, further reducing farmers' earnings. Farmers also suffer from limited access to real-time market information. Many are unaware of prevailing prices in local or international markets, leaving them at a disadvantage during price negotiations. Moreover, soybean prices are subject to fluctuations in global commodity markets, and farmers are unable to hedge against these risks due to the absence of insurance or futures markets tailored to their needs.

2.3.3 Climate Change and Environmental Degradation

Climate change poses a substantial threat to soybean production in Ghana. Unpredictable rainfall patterns, extended droughts, and extreme weather events such as floods disrupt planting schedules, reduce yields, and damage infrastructure. These conditions make it increasingly difficult for farmers to plan and optimize their production cycles. Soil degradation further compounds the challenges faced by soybean farmers. Continuous cultivation without replenishing soil nutrients, deforestation for agricultural expansion, and poor land management practices have resulted in declining soil fertility. Degraded soils produce lower yields and require higher input levels, increasing production costs for already resource-strapped farmers. Addressing soil health through sustainable practices such as crop rotation, organic amendments, and agroforestry systems is critical but requires education and resources that many farmers lack.

2.3.4 Small-Scale Farming

The predominance of smallholder farming limits economies of scale, which are essential for reducing production costs and enhancing profitability. Most soybean farms in Ghana are less than 1.5 hectares in size, making it difficult for farmers to afford bulk purchases of inputs or invest in advanced farming technologies such as mechanization. This reliance on traditional, labour-intensive farming methods restricts productivity and contributes to low yields. Access to credit is another significant issue. Financial institutions in Ghana often require collateral that smallholder farmers cannot provide, such as land titles or significant assets. Even when loans are available, high-interest rates deter farmers from seeking credit. This financial constraint limits their ability to purchase inputs, adopt new technologies, or expand their operations, keeping them trapped in cycles of low productivity and income (Ackah & Vuvor,2011).

2.3.5 Pest and Disease

Studies by Botha et al. (2020) highlights the impact of insect pests, including aphids, pod borers and whiteflies, on soybean production in the country. Soy aphids are a common pest that feeds on the sap of soybean plants, resulting in lower yields, browning foliage and stunted growth. Bean leaf beetles are another insect pest that damages soybeans by creating holes in the leaves and pods, negatively affecting the quality and yield of the plants. Armyworms pose another threat to soybeans as they can cause significant defoliation by feeding on the leaves, resulting in decreased photosynthesis and yield.

In addition to pests, soybean crops in Ghana are susceptible to various diseases. Examples of diseases that can affect soybeans are sudden death syndrome, Phytophthora root rot and brown stem rot. These diseases cause symptoms such as chlorosis and necrosis of leaf tissue, root rot, stunted growth, reduced seed production, wilting and premature death of plants. A coordinated efforts from the government, private sector, and development partners provide farmers with the resources, knowledge, and infrastructure needed to enhance productivity and sustainability which addresses these barriers, unlock soybean farming in its full potential as a vital contributor to the country’s agricultural economy.

2.4 Government Interventions

The government of Ghana has implemented measures aimed at enhancing soybean production and improving the livelihoods of farmers. These efforts focus on increasing productivity, promoting sustainability, and addressing key constraints within the sector to support agricultural development and economic growth.

2.4.1 Financial Support

The Ghanaian government has taken proactive steps to enhance access to financial resources for soybean farmers by collaborating with both local and international financial institutions. These partnerships aim to provide easier access to credit and loans that are essential for purchasing agricultural inputs such as seeds, fertilizers, and pesticides, as well as for acquiring modern farming equipment. The initiative is vital in boosting productivity, improving crop quality, and ensuring farmers' financial stability. A notable example of this support is the African Development Fund's approval of a US$27.9 million grant aimed at strengthening the agricultural value chains for key crops, including soybeans, in the Savannah region of Ghana. This grant specifically targets enhancing value chain processes by improving market access and promoting sustainable agricultural practices, with a strong focus on supporting the poultry industry, which heavily depends on soybean meal as a key component in animal feed.

The grant is expected to provide a long-term boost to local agricultural economies and create substantial employment opportunities across rural communities. Additionally, the Ghanaian government has implemented the Savannah Agriculture Value Chain Development Project, set to run from 2023 to 2027. This project is poised to directly benefit approximately 50,000 people and indirectly impact an estimated 150,000 individuals. Its objectives include facilitating the production of certified seeds by commercial farmers, thereby increasing the availability of high-quality seeds for smallholder soybean farmers. The project also includes the provision of essential agricultural equipment to smallholders, enabling them to adopt modern farming techniques and improve their productivity. Moreover, the initiative aims to enhance food security and nutrition, with specific emphasis on improving the diets of vulnerable households, especially those headed by women. This holistic approach is intended to boost the incomes of farmers while contributing to poverty alleviation in rural areas.

Such financial interventions by the government are critical for bridging the gap between smallholder farmers and the necessary resources that can drive the growth of the soybean industry in Ghana. They are also an important step towards creating a more inclusive agricultural economy, where farmers have the financial support to overcome the inherent risks and challenges of farming. These government-backed initiatives not only promise to improve the livelihoods of farmers but also seek to make Ghana a competitive player in the global soybean market.

2.4.2 Farmer Cooperatives and Associations

Farmer cooperatives and associations have played a pivotal role in the development of soybean production in Ghana, particularly in the northern regions. (Avea et al., 2016). These cooperatives, often established through public-private partnerships, have helped smallholder farmers overcome many of the challenges they face, including limited access to resources, knowledge, and markets. Collaborative efforts between non-governmental organizations (NGOs), development agencies, and government initiatives have fostered significant improvements in the soybean value chain, contributing to enhanced productivity and greater economic stability for farmers. Farmer Organizations (FBOs) have been instrumental in driving these improvements. By providing a platform for farmers to collectively address issues such as input costs, market access, and production challenges, FBOs have enhanced the technical efficiency of farmers.

These organizations have introduced various initiatives, including training programs focused on best agricultural practices, pest management, and soil fertility improvement, helping farmers increase their yield per hectare. The collaborative nature of these organizations also allows for shared knowledge and resources, making it easier for farmers to adopt new technologies and improve their farming practices. A key strategy employed by FBOs to streamline operations and improve profitability is group management training. This approach not only builds technical skills but also fosters stronger organizational structures that enable farmers to work together more effectively. Through the provision of financial management, marketing, and negotiating training, these cooperatives have decreased transaction costs and increased farmers' marketability. Farmers in cooperatives are better positioned to negotiate for higher prices and improve market access, reducing their reliance on middlemen and improving their profit margins.

In northern Ghana, the involvement of international organizations has further strengthened the soybean value chain. For example, organizations like the Cooperative for Assistance and Relief Everywhere (CARE) and the

International Fertilizer Development Center (IFDC) have partnered with local FBOs to advance both production and marketing strategies. CARE, with its focus on rural development, has provided critical support in areas such as capacity building, access to fertilizers, and the establishment of reliable market linkages. Similarly, IFDC has been instrumental in enhancing soil fertility and promoting sustainable agricultural practices, which are crucial for improving soybean yields.

These organizations, in collaboration with local FBOs, have helped increase the production of high-quality soybeans while also addressing environmental and economic sustainability. Cooperatives and farmer organizations have become important actors in Ghana's development of the soybean sector. These collaborations have given farmers access to better resources, technology, and market opportunities. FBOs' collective efforts, with support from both local and international partners, have pushed for a more profitable and sustainable soybean industry, enhancing rural economies and providing smallholder farmers with opportunities for success.

2.4.3 Input Subsidies

Input subsidies have been an important policy tool in Sub-Saharan Africa to support agricultural production, and Ghana is no exception. These subsidies aim to address the significant challenges farmers face in accessing essential agricultural inputs, which are often prohibitively expensive due to supply chain inefficiencies, market volatility, and limited access to credit. Subsidies help to reduce the financial burden on farmers, making inputs such as seeds, fertilizers, pesticides, and machinery more affordable and accessible, which in turn improves crop yields and supports sustainable farming practices

(Jayne et al., 2018). In Ghana, the government has historically implemented a range of input subsidy programs as part of its broader agricultural policy to enhance food security and stimulate economic growth. These programs are designed to alleviate resource constraints faced by smallholder farmers, enabling them to improve productivity and better manage the challenges of farming. One of the most prominent initiatives is the Planting for Food and Jobs (PFJ) program, launched in 2017.

This initiative provides subsidies for various agricultural inputs, including certified seeds, fertilizers, and pesticides, directly benefiting soybean farmers and other agricultural producers. By reducing the cost of essential inputs, the PFJ program has aimed to increase agricultural productivity and promote self-sufficiency, thus fostering sustainable growth within the agricultural sector (Pauw, 2022). In addition to national initiatives, various donors and development partners have also contributed to input subsidies and agricultural support programs in Ghana. These organizations have increased their financial aid, helping to ensure that more farmers have access to the resources they need. International support plays a crucial role in enhancing the effectiveness of input subsidies, particularly in rural areas where access to formal credit markets and input suppliers is limited.

Through financial contributions from development agencies, many farmers have been able to access subsidized inputs, thereby boosting their production capacity and improving the economic outcomes for farming households (Benin et al., 2013). Two other major initiatives, the Northern Rural Growth Program (NRGP) and Mennonites Economic Development Associates-Greater Rural Opportunities for Women (MEDA-GROW), have focused specifically on increasing agricultural production in northern Ghana, where soybean farming is a key livelihood activity. These programs work to improve the economic well-being of farm households, particularly women, by supporting farmers with both direct financial subsidies and indirect benefits, such as capacity building, access to markets, and improved agricultural techniques. The NRGP, for example, has helped farmers improve the use of quality inputs, enhance agricultural practices, and access new technologies, which has contributed to increased soybean yields and productivity.

Similarly, MEDA-GROW has focused on enhancing rural women's roles in soybean farming, providing them with access to financial resources, agricultural training, and better market opportunities (Pauw, 2022). Input subsidies in Ghana play a critical role in supporting the agricultural sector, particularly soybean farming, and these initiatives, alongside international support and collaborative partnerships, help to ensure that farmers can increase productivity, reduce the costs associated with farming, and improve the sustainability and profitability of their enterprises.

2.4.4 Training and Capacity Building

Training and capacity-building initiatives are critical in enhancing the capabilities of soybean farmers in Ghana. These programs provide farmers with the necessary knowledge and skills to adopt modern agricultural practices that can improve productivity, efficiency, and sustainability in soybean farming. Training initiatives are typically organized by the Ghanaian government, agricultural extension services, and various NGOs, with support from both local and international partners. These programs target a wide range of agricultural practices and technologies that are vital for increasing soybean yields and ensuring the sustainable use of resources (Avea et al., 2016). Key areas of training include seed selection, which ensures that farmers use high-quality seeds that are suited to the local climatic and soil conditions. This aspect of training is essential for reducing crop failure rates and improving overall yield quality. Additionally, farmers are trained on soil preparation techniques, which are fundamental for maintaining healthy soil and promoting strong plant growth.

Effective soil preparation helps to optimize the use of fertilizers and prevent soil degradation, a significant challenge for soybean cultivation in many parts of Ghana (Sugri, Abubakari, Owusu, & Bidzakin, 2021). Planting techniques are another critical focus, as these directly affect plant establishment, growth, and productivity. Training in nutrient management ensures that farmers understand the importance of balanced fertilization, which is key to avoiding soil nutrient depletion and optimizing soybean yield potential. Farmers are also educated on effective irrigation strategies that can mitigate the negative impacts of seasonal droughts, especially in rain-fed agricultural systems, and improve the consistency of production. Moreover, weed control is emphasized, as weeds can significantly reduce soybean yields by competing for nutrients, water, and light (Sugri et al., 2021).

Beyond the cultivation phase, training also extends to harvesting techniques. Farmers are taught the appropriate methods for harvesting soybeans at the optimal time, which helps in avoiding post-harvest losses and maintaining seed quality. The training programs also cover drying, cleaning, and storing soybeans, processes that are essential for minimizing grain losses, preserving seed quality, and ensuring market competitiveness. Proper post-harvest handling reduces fungal contamination, improves shelf life, and ensures that farmers can sell their soybeans at higher market prices (Bugri et al., 2016). In addition to technical skills, these training programs also aim to enhance farmers' understanding of the value and processing of soybeans. The training helps them to diversify their income streams and explore greater profitability. For example, farmers are encouraged to explore the potential of producing soy-based products like soy milk, tofu, and oil, which have growing demand both locally and internationally.

This knowledge equips farmers to add value to their produce, thereby enhancing their financial resilience. The success of these training and capacity-building programs is often dependent on the collaborative efforts of various stakeholders. The Ghanaian government, agricultural extension services, NGOs, and private sector actors work together to implement these initiatives, ensuring that farmers receive up-to-date information, practical skills, and support. Such partnerships facilitate the exchange of knowledge and resources, fostering a community-oriented approach to agricultural development.

Moreover, this collaboration encourages farmers to engage with one another, creating networks that strengthen the agricultural sector by promoting collective problem-solving, resource-sharing, and mutual support. These efforts help farmers overcome challenges, increase productivity, and improve their livelihoods (Avea et al., 2016). The transformation of soybean farming in Ghana is largely dependent on training and capacity-building programs, which give farmers the know-how to implement contemporary techniques and technologies, thereby increasing production, guaranteeing sustainability, and improving the financial stability of farming households.

2.5 Impacts of soil physical properties on soybean yield

The physical characteristics of the soil are crucial in affecting soybean production. These characteristics include soil texture, structure, fertility, moisture content, and pH, all of which significantly influence plant health and nutrient availability (Fae et al., 2020). According to Kalev and Toor (2018), the amount of nutrients in the soil is influenced by several factors, including the amount of organic matter, parent material, naturally existing minerals, drainage, permeability, water-holding capacity, and the depth to bedrock, sand, or gravel. There are different soil types brought up by weathering with specific structural separations including clay, silt, sand, and loam, each with unique properties that affect plant growth and health. For example, clay soils are high in nutrients and moisture, but can be heavy and compact, making it difficult for roots to penetrate. Sandy soils, on the other hand, have good drainage but are poor in nutrients and moisture.

2.5.1 Soil Texture and Its Impact

Soil texture, defined by the relative proportions of sand, silt, and clay in the soil, is a critical factor influencing soybean yield (Fageria & Nascente, 2014). This property affects water retention, drainage, aeration, and nutrient availability, all of which are essential for soybean growth. Loamy soils, characterized by a balanced mix of sand, silt, and clay, provide the optimal environment for soybean development, as they offer adequate drainage while retaining sufficient moisture and nutrients. These properties facilitate robust root development and enhance nutrient absorption, creating ideal conditions for high yields. In contrast, clay-rich soils often pose challenges for soybean cultivation. Their fine particles result in poor drainage and reduced aeration, increasing the risk of waterlogging. Waterlogged conditions can inhibit root respiration, reducing nutrient uptake and ultimately lowering yields. Furthermore, the compact nature of clay soils can impede root growth, limiting the plant's ability to access water and nutrients stored deeper in the soil profile.

Effective soil management practices, such as tillage, addition of organic matter, or gypsum application, can help mitigate these issues by improving soil structure and permeability. Sandy soils, on the other hand, are characterized by coarse particles that provide excellent drainage and aeration. However, their low Cation Exchange Capacity (CEC) and reduced ability to retain moisture and nutrients often lead to suboptimal growing conditions for soybeans. Fageria and Nascente (2014) emphasize that soybeans grown on sandy soils typically require more frequent fertilization to replenish nutrients that are quickly leached away. This increased demand for fertilizers can raise production costs for farmers, especially in resource-limited settings. Soil texture also significantly influences root growth. Sandy soils allow for easier root penetration due to their loose structure, which can be advantageous for soybean plants in terms of accessing water and nutrients. However, the limited nutrient availability in sandy soils may offset this benefit. Conversely, clayey soils, though nutrient-rich, are often rigid and compact, potentially restricting root development and hindering nutrient uptake.

The surface texture of soils further impacts compaction, which can negatively affect soybean yields. Compacted soils reduce pore space, impairing water infiltration and root expansion. Bashir et al. (2022) found that sandy clay loams and sandy loam soils demonstrated a notable response to the application of fertilizers containing nitrogen (N), phosphorus (P), potassium (K), and manure. However, deficiencies in zinc (Zn) and NPK nutrients were observed to limit soybean performance and nutrient uptake in sandy clay and clay loam soils. The study concluded that using fertilizer formulations enriched with N, P, K, and Zn is essential for improving soybean production in these soil types. Managing soil texture with the right interventions is essential in Ghana, where different climatic and geological circumstances result in a variety of soil textures. Crop rotation, using customized fertilizer formulas, and adding organic matter are among strategies that can assist improve soil conditions and increase soybean growth and production potential.

2.5.2 Soil Structure and its Impacts

Soil structure, defined as the arrangement of soil particles into aggregates or clumps, plays a pivotal role in nutrient retention, water availability, and root growth (Vikram et al., 2022). The organization of these particles impacts several soil functions, including porosity, water infiltration, and aeration, all of which are crucial for plant health. A well-structured soil supports robust soybean growth by enabling efficient nutrient and water absorption, reducing water and wind erosion, and promoting soil biodiversity (Gerke et al., 2022). Soil structure also directly influences the movement of water and air through the soil. Properly aggregated soils provide adequate pore space for water infiltration and storage while allowing oxygen to reach the root zone. This balance is critical for healthy root systems and optimal soybean yields. Serafim et al. (2019) emphasize that well-structured soils promote uniform root growth and better access to water and nutrients, which are necessary for plant development. Conversely, poorly structured or compacted soils hinder root penetration, reduce aeration, and restrict nutrient uptake, leading to stunted growth and lower yields.

Compaction, a common issue arising from intensive farming practices, disrupts soil structure and limits its functionality. Correa et al. (2019) highlight that compacted soils reduce the movement of water and air, creating an inhospitable environment for root development. This can lead to reduced soybean yields as plants struggle to access the resources, they need for growth. Effective soil management practices, such as reducing heavy machinery use and employing proper crop rotation strategies, can mitigate compaction and restore soil structure. Improving soil structure is essential for maintaining high soybean productivity. Techniques such as the use of cover crops and adopting reduced or no-till farming systems have proven effective in enhancing soil aggregation and stability. Cover crops, for instance, help protect the soil surface, reduce erosion, and increase organic matter content, which strengthens soil structure over time. Similarly, no-till farming minimizes soil disturbance, preserving natural aggregates and maintaining a stable structure.

Ambus et al. (2018) underscore that a well-structured soil environment not only facilitates efficient nutrient cycling but also fosters a supportive ecosystem for beneficial soil microorganisms. These microorganisms contribute to nutrient availability and plant health, further boosting soybean productivity. For example, improved soil structure enhances microbial activity, leading to better decomposition of organic matter and increased nutrient recycling. Applications that improve soil structure are essential in areas such as Ghana, where agricultural output is hindered by soil compaction and degradation. Maintaining or restoring soil structure can be achieved by encouraging farmers to embrace conservation agriculture, use organic amendments, and participate in knowledge-sharing programs. The circumstances for growing soybeans may be greatly enhanced in this way, resulting in increased yields and environmentally friendly agricultural methods.

2.5.3 Soil Fertility

Soil fertility is a fundamental determinant of soybean production, as it reflects the soil's capacity to supply essential nutrients for plant growth (Alhassan, 2018). Soybeans require a range of macronutrients and micronutrients, including nitrogen (N), phosphorus (P), potassium (K), sulfur (S), iron (Fe), zinc (Zn), and manganese (Mn), to achieve optimal growth and yield (Radocvaj, 2020). The availability and balance of these nutrients significantly influence soybean health and productivity. Nitrogen is a particularly vital nutrient for soybeans, as it supports vegetative growth and seed development. While soybeans can fix atmospheric nitrogen through symbiotic relationships with rhizobia bacteria, deficiencies can still occur in nutrient-poor soils or when nodulation is inadequate. Such deficiencies result in stunted growth, pale leaves, and reduced yields. Phosphorus is another critical nutrient, essential for energy transfer and root development.

Deficient phosphorus levels can lead to weak root systems, delayed maturity, and lower yields. Potassium, essential for plant metabolism, stress tolerance, and overall development, is also crucial. A lack of potassium can manifest as smaller plants with discoloured leaves and reduced productivity. The soil’s pH is a critical factor influencing nutrient availability. Ideal pH levels for soybean cultivation range between 6.0 and 6.5, as soils within this range provide an optimal balance of nutrient availability (Stanton, 2012; Thapa et al., 2021). Soils that deviate significantly from this range can adversely affect nutrient absorption and plant growth. Acidic soils, for instance, may limit the availability of phosphorus, calcium, and magnesium, while simultaneously causing toxicity due to excessive aluminum and manganese levels, which can impair root development and nutrient uptake. On the other hand, alkaline soils can reduce the solubility of key micronutrients like iron, manganese, and zinc, leading to deficiencies that hinder plant health and development.

The application of fertilizers or soil amendments is critical to addressing fertility challenges. However, uneven or inappropriate fertilizer application can exacerbate nutrient imbalances, affecting soybean growth and yield. To mitigate this, farmers are encouraged to conduct soil testing to determine nutrient deficiencies and pH imbalances. Soil testing provides valuable insights, enabling targeted and efficient application of fertilizers and conditioners. For example, lime application can neutralize acidic soils, enhancing nutrient availability, while sulfur-containing fertilizers can address deficiencies in sulfur and other related nutrients. Integrated soil fertility management practices can also help sustain soil fertility over time.

Techniques such as crop rotation, the use of organic amendments like compost or manure, and the incorporation of legumes as cover crops can replenish soil nutrients and improve soil structure. These practices not only enhance nutrient availability but also promote soil biodiversity and microbial activity, which are vital for nutrient cycling and long-term soil health. In soybean production systems, maintaining optimal soil fertility is essential for achieving sustainable and high yields.

2.5.4 Soil Moisture

Soybean growth and productivity are highly dependent on consistent soil moisture levels throughout the growing season. A deficit in soil moisture causes water stress, which adversely affects vital plant processes such as photosynthesis, nutrient uptake, and overall growth, ultimately leading to reduced yields (Awuni et al., 2020). On the other hand, excessive moisture can create waterlogged conditions, reducing oxygen availability in the soil. This leads to root hypoxia, which impairs root function, nutrient absorption, and overall plant development (Kaur et al., 2020). The water requirements of soybeans vary across their growth stages. During the vegetative phase, soybeans need moderate amounts of water to support leaf and root development. However, water demand increases significantly during the reproductive phase, particularly during flowering and pod filling. Moisture deficits during these critical periods can result in reduced pod formation, smaller seeds, and lower yields.

Conversely, prolonged waterlogging during these stages can inhibit seed development and encourage root diseases, further compromising crop productivity. Proper soil moisture management is essential for optimizing soybean yields. Irrigation systems, such as drip or sprinkler irrigation, can help regulate water supply in regions where rainfall is insufficient or irregular. Additionally, mulching with organic materials, such as straw or crop residues, can help retain soil moisture by reducing evaporation and moderating soil temperature. In rain-fed agricultural systems, careful timing of planting to coincide with the rainy season can ensure that soybeans receive adequate moisture during critical growth stages. Soil structure also plays a role in soil moisture dynamics. Well-structured soils with good porosity facilitate water infiltration and drainage, helping to maintain a balance between moisture availability and aeration. In contrast, compacted soils may hinder water movement, leading to surface runoff or poor water distribution within the root zone. Adopting water conservation practices, such as contour farming and terracing, can help retain moisture in sloping areas, while the use of drought-resistant soybean varieties can mitigate the effects of moisture stress. Farmers may lessen the dangers of water surpluses or shortages by putting these measures into practice and keeping an eye on soil moisture levels. This will improve soybean development and guarantee sustainable harvests.

2.5.5 Soil pH

Soil pH, a measure of the soil's acidity or alkalinity, plays a pivotal role in determining nutrient availability and plant health, directly influencing soybean growth and productivity. Optimal soil pH levels for soybean cultivation range between 6.0 and 6.5, as this range ensures the maximum availability of essential nutrients and promotes healthy root development (Stanton, 2012). Deviations from this pH range can lead to nutrient deficiencies or toxicities, adversely affecting plant growth and yield potential. In soils with low pH, which are common in many agricultural regions, including parts of Ghana, the availability of key nutrients such as phosphorus, calcium, and magnesium decreases significantly. This limitation impairs root development, nutrient uptake, and plant vigor.

Moreover, low pH levels lead to the solubilization of aluminum and manganese, resulting in their toxicity to plants, which further suppresses soybean growth and reduces yields (Buri et al., 2005; Tetteh et al., 2016).

Conversely, high pH soils can create challenges related to micronutrient availability. Nutrients like iron, manganese, and zinc, which are critical for metabolic processes and chlorophyll production in soybeans, become less available in alkaline soils. Deficiencies in these micronutrients manifest as chlorosis, reduced photosynthetic efficiency, and overall stunted growth, which collectively diminish crop yield. Soil additives are frequently used to alleviate the issues related to suboptimal soil pH. One efficient method for balancing acidic soils and bringing pH values within the appropriate range is the use of lime (calcium carbonate or dolomite).

Additionally, lime provides calcium and magnesium, both of which are good for crop health. In alkaline soils, elemental sulfur or sulfur-based fertilizers can be used to reduce pH by increasing soil acidity through the microbial production of sulfuric acid. Soil testing is essential for accurately assessing pH levels and determining appropriate corrective measures. Regular monitoring and timely interventions not only enhance nutrient availability but also ensure that soybeans grow in a favourable soil environment, leading to improved productivity and sustainability. The potential of soybean crops may be maximized and nutrient-related pressures can be reduced by farmers by maintaining ideal pH levels.

2.6 Influence of Climatic Variables on Soybean Yields

Climate change poses a significant threat to agriculture across Africa, including Ghana (Turkhede et al., 2018). The continent's heightened sensitivity to climate variability and limited adaptive capacity make its agricultural systems particularly vulnerable (Diarra, 2009). Rising temperatures, reduced precipitation, prolonged droughts, and erratic rainfall patterns define the changing climate in Africa (Dai, 2011). These shifts have profound implications for soybean production, as key climatic variables such as temperature, rainfall, and humidity directly influence crop growth, development, and yields. Projections by UNEP indicate that precipitation patterns will become increasingly unpredictable and erratic, with average temperatures expected to rise by 1.5 to 5.2°C by the year 2090. Sea levels are predicted to rise by 34.5 cm within the same timeframe (Asante et al., 2014). Such changes disrupt established agricultural cycles, making it more challenging for farmers to rely on traditional planting and harvesting calendars. For instance, irregular rainfall patterns lead to inadequate water supply during critical growth stages, while excessive rainfall increases the risk of waterlogging and diseases that adversely affect soybean yields.

Temperature increases further compound the problem. Soybeans are highly sensitive to temperature fluctuations, particularly during their reproductive phase, where higher temperatures can cause flower and pod abortion, ultimately reducing seed formation and yield. Hatfield et al. (2011) note that rising temperatures not only affect crop growth but also exacerbate soil degradation and pest pressures, creating additional hurdles for agricultural productivity. Low soil productivity, coupled with the rapid pace of climatic changes, challenges farmers in their efforts to manage crops, livestock, and fisheries effectively. Farmers must adapt their practices to mitigate the adverse effects of climate change. Strategies such as adopting drought-resistant soybean varieties, improving water management through irrigation systems, and employing agroforestry techniques are becoming essential in building resilience.

2.6.1 Temperature Stress on Soybean Yield

Temperature stress poses a significant challenge to soybean production, particularly during critical growth stages. High temperatures during the vegetative phase impede plant growth and result in reduced yields. Heat stress triggers photorespiration, a process that lowers the efficiency of photosynthesis by increasing oxygen uptake and reducing carbon fixation (Jumrani & Bhatia, 2018). This physiological disruption affects biomass accumulation and slows overall plant development. Furthermore, heat stress exacerbates water loss through increased transpiration rates, leading to drought stress that restricts root development and weakens the plant's ability to absorb essential nutrients. Soybean plants react to excessive heat by closing their stomata to conserve moisture, but this response limits CO_2 intake and further hinders photosynthesis. This combination of reduced carbon fixation and increased water loss significantly compromises plant health and productivity.

Jumrani and Bhatia's research highlights that planting soybean seeds at 38°C and 42°C resulted in yield reductions of 62% and 64%, respectively. Additionally, their findings showed that water stress at all tested temperatures (30, 34, 38, and 42°C) significantly curtailed plant growth. In Ghana, regional climatic variations add complexity to soybean cultivation. Northern regions, where soybeans are predominantly grown, experience hotter and drier conditions compared to the south (McCarthy et al., 2022). The growing season in these areas typically sees temperatures ranging from 25°C to 35°C, which are generally favorable for soybean cultivation. However, when temperatures exceed 35°C, heat stress becomes a major concern, reducing yield potential (Gourdji et al., 2013). Temperature plays a pivotal role in soybean development, with the crop thriving within an optimal range of 20°C to 25°C during its reproductive phase (Hoffman et al., 2020). Deviations from this range, particularly extreme temperatures, can have detrimental effects. High temperatures during flowering and pod development stages can cause flower and pod abortion, directly reducing seed formation. On the other hand, temperatures below 10°C can slow germination, increase susceptibility to seedling diseases, and delay crop establishment (Adam Gasper, 2019).

Extreme temperatures also impact the availability of soil nutrients and root activity, further limiting plant growth. Heat stress reduces the size of soybean seeds, affecting both the quantity and quality of the harvest. Farmers can adopt strategies such as planting heat-tolerant soybean cultivars and adjusting planting schedules to avoid peak heat periods to mitigate these effects. Employing practices to maintain optimal temperature conditions during ripening, ranging from 20°C to 25°C can help maximize yields and ensure successful soybean production.

2.6.2 Soybean Reproductive Stage under Heat Stress

The reproductive stage of soybean growth is highly sensitive to heat stress, with significant implications for seed yield and quality. Physicochemical parameters such as protein content, oil composition, fatty acids, and carbohydrate levels are influenced by temperature fluctuations during this critical phase (Alsajri et al., 2020). The reproductive period encompasses key processes like flower pollination, pod development, and seed formation. Temperature variations outside the optimal range during this stage disrupt physiological and biochemical processes, leading to substantial yield losses. Elevated temperatures exert several detrimental effects on reproductive success.

Excessive heat can cause premature flower shedding, where flowers drop before successful pollination, thereby limiting pod growth. This loss in reproductive efficiency directly reduces the number of pods and seeds formed. Additionally, high temperatures adversely affect pollen viability, leading to incomplete or failed pollination. Consequently, seed numbers decline, and the few seeds that do develop are often smaller and lighter.

Seed size and weight are particularly affected due to heat stress interfering with the deposition of starch and other carbohydrates in developing seeds. This biochemical disruption results in seeds with lower density and reduced nutritional value. Heat stress also reduces pod production on individual plants by impairing the formation of reproductive structures, further limiting overall yield potential. The negative impacts of heat stress extend to the quality of the harvest. Protein and oil content, critical determinants of soybean market value, may also diminish under high-temperature conditions. Addressing heat stress during the reproductive stage requires targeted strategies. These include using heat-tolerant soybean cultivars, implementing shading techniques, and timing planting to avoid periods of excessive heat. Such measures can mitigate the adverse effects of temperature extremes and enhance soybean productivity during this critical growth phase.

2.6.3 Rainfall Stress on soybean yield

Rainfall is a critical climatic factor affecting soybean growth, with both deficits and excesses having profound implications on yields. A study by Lamptey, Ahiabor, Yeboah, and Osei (2014) revealed that a sequence of drought during the vegetative phase followed by rainfall during the reproductive phase can boost crop production. This pattern allows plants to adapt to early water stress while benefiting from moisture during pod development. However, uneven or excessive rainfall can adversely affect soybean yields, particularly in regions like Ghana, where rain-fed agriculture is the primary cultivation method. Soybean growth and soil moisture levels are strongly influenced by regional and seasonal variations in rainfall patterns, as noted by Awuni et al. (2023). During the vegetative stage, adequate rainfall promotes robust plant growth, while during the reproductive phase, it supports critical processes such as pod development and seed formation. Insufficient rainfall during these stages can result in drought stress, leading to stunted growth and lower yields.

Conversely, erratic rainfall patterns, characterized by heavy downpours or prolonged periods of wet weather, can cause waterlogging. This condition hampers root respiration, restricts oxygen availability, and ultimately stresses the plant, reducing productivity. In southern Ghana, where heavy rainfall is more common, waterlogging presents significant challenges. Zougor et al. (2016) emphasized that excessive moisture in these regions often leads to restricted root growth and nutrient uptake, contributing to lower yields. Such conditions also create a conducive environment for diseases and pests, further compounding yield losses.

Strategies such as improved drainage systems in areas prone to waterlogging and supplementary irrigation in drought-prone regions when employed can help mitigate rainfall stress. Additionally, adopting soybean varieties with greater tolerance to water stress and developing resilient cropping systems are essential for stabilizing yields amidst erratic rainfall patterns.

2.6.4 Humidity Stress on Soybean Yield

Humidity is a significant environmental factor influencing soybean growth and productivity. While moderate humidity levels promote soybean growth by reducing water stress and supporting efficient water uptake (Montoya et al., 2017), excessive humidity can adversely affect various physiological processes, ultimately reducing yields. High humidity creates an environment conducive to the development of diseases, particularly fungal infections, which can damage plant tissues and reduce seed quality. Fungal diseases like rust and mold thrive in humid conditions, compromising the plant's health and productivity (Atanda, 2011). Furthermore, excessive moisture in the air can lead to pod breakage, which hinders pod development and reduces the number of seeds per plant. High humidity also impacts pollination, as it can lower the activity of pollinators and reduce seed set. This, in turn, decreases the potential yield of the crop.

Additionally, delayed harvests in highly humid conditions are common, as wet fields make harvesting difficult, and the prolonged exposure of soybeans to high moisture levels can lead to spoilage and a decrease in quality (Atanda, 2011). High humidity also fosters the growth of insect pests that thrive in moist environments. These pests can further damage the crop, feeding on the leaves, stems, and pods, which further reduces yields and quality.

As pests proliferate in such conditions, they stress the plants and hinder nutrient uptake, making it more challenging for the soybeans to reach their full potential (Montoya et al., 2017). Farmers must carefully select soybean varieties that are more resistant to fungal infections and pests to mitigate the negative impacts of humidity stress. In addition, optimizing planting dates to avoid peak humidity periods, employing proper crop rotation, and using fungicides or other plant protection strategies can help manage the effects of excessive humidity. By addressing these environmental challenges, farmers can improve the resilience of soybean crops and enhance yield stability under fluctuating climate conditions

2.7 Terrain

Topography has been demonstrated to be connected with several soil characteristics, including soil water content (Sadiq et al 2023). It significantly affects the spatial distribution of soil particles (erosion/deposition), organic matter, nutrients, and hydrologic conditions throughout the landscape (Matcham et al.,2020). Terrain can significantly affect the growth of a crop, affecting soil moisture, soil fertility, drainage and temperature, all of which are critical to crop health and production. Terrain can alter soil moisture content due to its effect on soil water distribution. In areas with steep terrain, there may be a higher risk of soil erosion and less stable soil moisture distribution. In contrast, crops grown on flat terrain tend to maintain more consistent soil moisture levels. It can change the distribution of nutrients in the soil and affect soil fertility. Crops grown on steep terrain may experience greater nutrient loss due to soil erosion, while those planted on flat ground can have more stable nutrient levels (Singh et al 2024).

Terrain also has an impact on temperature patterns, which are critical to plant development and growth. Plants located in low-lying areas may encounter higher temperatures, potentially leading to heat stress (Matcham et al.,2020). Conversely, plants at higher altitudes may be exposed to colder temperatures and enjoy a longer growing season. In certain regions like the northern savannah region, where temperatures range between 25°C and 40°C and annual rainfall falls between 800 mm and 1200 mm, the climate and soil conditions are well-suited for soybean cultivation (Franke *et al*., 2018). Soybeans are particularly drought-resistant, making them an excellent choice for local cultivation in these conditions. Specialized drainage systems may be necessary to address the sensitivity of plants to waterlogging, and these systems may need to be adapted to the specific environmental conditions dictated by the terrain. For instance, crops grown on sloping terrain may benefit from increased drainage, while flat terrain may be more prone to waterlogging issues (Singh et al 2024).

2.8 Response of Soybean to Fertilizer Applications

Fertilizer application is essential for improving soybean yields by supplying the necessary nutrients that support plant growth, development, and overall productivity. Proper fertilizer use is contingent on several factors, including the type and amount of nutrients required, the soil's nutrient profile, local climatic conditions, and the specific requirements of the soybean crop (Singh & Ryan, 2015). As fertilizer is applied, soybeans generally exhibit a curvilinear response pattern: yields increase with fertilizer application up to a certain point, after which additional fertilizer yields diminishing returns. It is crucial to identify and apply the optimal amount of fertilizer to avoid over-application, which can lead to environmental degradation and inefficiency in nutrient use.

The impact of fertilizer on soybean growth is particularly pronounced in warmer climates, where increased temperatures and enhanced microbial activity can lead to more effective nutrient uptake. In contrast, cooler climates may result in slower nutrient cycling, and thus, the response to fertilizers might be less dramatic (Singh & Ryan, 2015). Fertilizers primarily provide the macronutrients nitrogen (N), phosphorus (P), and potassium (K), all of which are essential for soybean growth. Nitrogen promotes robust vegetative growth and helps in the formation of proteins, phosphorus is crucial for root development and energy transfer, and potassium enhances disease resistance and improves the resilience of the plant (Tahiru et al., 2015). Research by Tahiru et al. (2015) has demonstrated the positive impact of balanced fertilizer application on soybean yields. Their study showed that combining nitrogen, phosphorus, and potassium resulted in significantly higher soybean yields, emphasizing the importance of nutrient management in optimizing crop production.

This nutrient synergy supports the development of a healthy root system, improves flowering and pod formation, and ultimately increases seed production. Effective fertilizer use not only improves the quantity of soybean yields but also contributes to the quality of the beans by ensuring that the plants have adequate resources throughout their growth cycle. In regions with warm climates, where conditions are favorable for nutrient uptake, fertilizer application becomes particularly vital to address nutrient deficiencies and improve overall productivity. The timing and form of fertilizer application are also critical to maximizing its benefits, as proper management can enhance nutrient efficiency, reduce losses to the environment, and ensure sustained soybean production. Thus, farmers must tailor fertilizer practices to their specific conditions, considering factors such as soil type, previous crop history, and current climatic patterns, to optimize soybean yield outcomes.

2.8.1 Response of Soybean to Nitrogen

Soybeans are nitrogen-fixing legumes, meaning they have the ability to harness atmospheric nitrogen through a symbiotic relationship with rhizobial bacteria in their root nodules. However, despite this ability, soybeans also require nitrogen from the soil to reach their full growth potential and optimize grain production (Fageria & Moreira, 2011). The specific nitrogen requirements of soybeans are influenced by various factors, such as soil type, climate, and the specific variety of soybean being cultivated. In general, soybeans need approximately 40-80 pounds of nitrogen per acre to achieve a good yield. While soybeans can fix a significant amount of nitrogen through their root nodules, they may still require supplemental nitrogen from fertilizers or inoculants to ensure they receive an adequate supply, especially in soils with limited nitrogen availability (Dong et al., 2012).

The first phase of growth, from seedling establishment to nodule formation, is particularly sensitive to nitrogen availability. During this period, the young soybean plants rely heavily on nitrogen from the soil to support early growth. In the second phase, nitrogen demand increases as the plants enter the reproductive stage, particularly during pod development and seed filling. At this stage, soybeans require large quantities of nitrogen to sustain the formation of pods and to optimize seed development. Effective nitrogen management is crucial for maximizing soybean productivity. One effective practice is split application, where a portion of nitrogen fertilizer is applied at planting, with the remainder applied later in the growing season. This ensures a steady nitrogen supply during critical periods of growth, preventing nitrogen deficiency when the plant needs it most (Mao et al., 2013).

Given the sensitivity of soybeans to nitrogen levels, over- or under-fertilization can lead to suboptimal growth and yield.The nitrogen content in soils can vary significantly across regions, and this is particularly important in countries like Ghana, where agro-ecological zones differ greatly in terms of soil fertility. In the northern regions of Ghana, for instance, soil nitrogen levels are often low due to factors such as soil erosion and limited organic matter (Bationo et al., 2018). In contrast, the middle belt and coastal regions of the country tend to have higher nitrogen levels, thanks to richer organic matter and less susceptibility to erosion (Nziguheba et al., 2016).

These regional variations necessitate tailored fertilizer strategies. For example, nitrogen application techniques such as banding, side dressing, fertigation, or injection should be adapted to local soil conditions to optimize nitrogen uptake and minimize losses. Thus, understanding and managing nitrogen dynamics are fundamental to achieving optimal soybean yields, especially in regions with varying soil fertility. By applying nitrogen fertilizers correctly, farmers can ensure that soybeans receive the necessary nutrients to thrive, leading to better growth, higher productivity, and improved yields.

2.8.2 Response of Soybean to Phosphorus

Phosphorus is a crucial nutrient for soybeans, significantly influencing various aspects of their growth and development. It plays an essential role in root formation, flower and seed production, and energy storage within the plant (Malhotra et al., 2018). Soybeans generally exhibit a positive response to phosphorus fertilization, particularly when grown in phosphorus-deficient soils. The addition of phosphorus to such soils enhances root growth, accelerates flowering, and increases seed yields. Moreover, phosphorus is vital for leguminous crops like soybeans, as it is a key element in nitrogen fixation—the process by which soybeans convert atmospheric nitrogen into a usable form (Prez-Fernandez et al., 2019). Without sufficient phosphorus, this crucial nitrogen-fixing process becomes inefficient, limiting soybean growth and productivity.

Maintaining adequate phosphorus levels in the soil is necessary to sustain optimal soybean yields. The optimal range for soil phosphorus is typically between 20 and 40 ppm (Staton, 2014). Soybeans are known for their substantial phosphorus uptake, and without replenishing phosphorus levels through fertilization, soil depletion can hinder their development. A common fertilization recommendation for soybean crops yielding 60 bushels per acre is 48 pounds of actual P2O5, which can be applied in the form of 90 pounds of monoammonium phosphate (MAP) or approximately 100 pounds of diammonium phosphate (DAP) per acre. These fertilizer rates ensure that soybeans receive sufficient phosphorus to support their growth stages, from root development to seed production.

In Ghana, phosphorus deficiency remains a significant challenge, particularly in regions such as the north, where soils tend to be poorer in phosphorus content (Masso et al., 2016; Buri et al., 2010). This deficiency can severely limit soybean productivity, making it imperative to adopt soil testing protocols to accurately assess phosphorus levels and tailor fertilizer applications accordingly. Implementing appropriate fertilization strategies is essential for addressing these deficiencies and ensuring that soybeans have access to the phosphorus they need to maximize growth and yields. By maintaining adequate phosphorus supply through proper fertilization, farmers can optimize soybean production and improve crop resilience.

2.8.3 Response of Soybean to Potassium

Potassium is the most abundant mineral in plants and plays a critical role in soybean development. It is the most important nutrient in soils, influencing a variety of physiological processes, including disease resistance, stem strength, and drought tolerance (Towett et al., 2015; Elbaalawy et al., 2016). Soybeans, in particular, require significant amounts of potassium during their growth, especially during the reproductive phase. Potassium contributes to the plant's overall health by supporting the development of strong stems and enhancing resistance to environmental stressors, including drought (Mostofa et al., 2022). A notable proportion of potassium is allocated to the seed, which highlights its importance for seed development. Without sufficient potassium, soybean plants may exhibit green stems, retained leaves, and underdeveloped seeds or seedless fruits (Nelson et al., 2012).

The potassium requirements of soybeans are particularly high during the reproductive phase, especially during pod filling. Proper potassium levels at this stage are essential for healthy flower and pod development, directly influencing seed yield and overall crop productivity (Mostofa et al., 2022). Field studies indicate that the application of 30 kg of K2O per hectare as a base treatment, followed by an additional 30-40 kg of K2O approximately 35 days after planting, can significantly reduce potassium loss from the soil and improve yield outcomes. Buah et al. (2017) found that adequate potassium application boosts seed weight and pod development, contributing to stronger and more stable plants. Additionally, potassium plays a crucial role in nutrient transport and water uptake, enhancing the plant's resilience to environmental stresses (Lamptey et al., 2014).

However, while potassium application can improve soybean health and pest resistance, it is vital to apply the nutrient in balanced amounts. Excessive potassium application can disrupt the balance of other nutrients in the soil, leading to nutrient imbalances that negatively affect plant growth (Malvi, 2018). The optimal soil potassium level for soybean growth is typically around 100 ppm, with a maintenance level of 130 ppm for soils with low cation exchange capacity (Staton, 2017). High potassium levels can decrease the availability of other essential nutrients, further impairing plant growth and productivity. In Ghana, soil potassium deficiency is common, especially in areas with erosion or low organic matter content. appropriate fertilization techniques must be employed, such as banding, side dressing, broadcasting, and fertigation as these methods ensure that potassium is delivered effectively to the plants, improving their resilience and productivity. In regions with potassium-deficient soils, tailored fertilization strategies are crucial to maintaining proper nutrient balance and optimizing soybean yields. Potassium is essential for enhancing soybean growth, health, and yield. The application of its fertilizers must be managed carefully, considering the local soil conditions, to maintain the right nutrient balance and promote sustainable crop production in Ghana.

2.9 GIS Application in Agriculture

Geographic Information Systems (GIS) have become an indispensable tool in modern agriculture, enabling farmers and researchers to develop more effective and efficient agricultural practices. GIS provides a spatial approach to managing and analyzing farmland, enhancing agricultural productivity, especially in areas grappling with food scarcity. By leveraging GIS technology, agricultural practices can be tailored to specific needs, increasing output and optimizing resource use. In the context of food security, this technological strategy has proven instrumental in improving food production on a large scale (Raman, 2017). Precision agriculture has experienced rapid advancements, thanks in part to GIS and remote sensing technologies. These innovations enable more efficient farming, reducing costs and increasing profitability by providing detailed insights into agricultural landscapes (Gebeyehu, 2019). GIS technology aids in decision-making processes, particularly in managing fertilizers, herbicides, and water resources.

It supports stress mapping and efficient irrigation systems, ensuring that agricultural inputs are applied only where and when needed (Abdelrahman et al., 2016; Montgomery et al., 2016). With GIS, the application of fertilizers, water, and other growth mediums becomes more precise. This precision reduces resource waste, lowers costs, and maximizes yields. Geospatial data, especially hyperspectral and multispectral imaging, is invaluable in monitoring soil moisture and plant health. Furthermore, precision farming employs Variable Rate Technology (VRT) to apply seeds, fertilizers, and herbicides at variable rates based on spatial variability, resulting in more efficient use of inputs (Bill, Nash, & Grenzdorffer, 2011). This not only reduces costs but also minimizes the environmental impact of overuse of chemicals, particularly in nitrogen application, by providing more accurate data-driven recommendations.

2.9.1 Machine Learning Modelling

Machine learning, a subset of artificial intelligence, has emerged as a powerful tool in agricultural decision-making. By creating algorithms that can learn from data and make predictions, machine learning enables computers to detect patterns and optimize agricultural practices without explicit programming. Several methods, including random forests, decision trees, linear regression, and XGBoost, are utilized to build predictive models. These models are trained on large datasets to recognize intricate relationships between input variables and crop performance, helping farmers make data-driven decisions. In agricultural applications, machine learning is particularly useful in Digital Soil Mapping (DSM). DSM allows for more precise soil classification and management, as it captures the geographical heterogeneity of soil properties more effectively than traditional soil mapping methods (Wadoux, Minasny, & McBratney, 2020). By integrating machine learning algorithms, such as logistic regression, classification trees, and random forests, DSM enables a more accurate prediction of soil characteristics, which is crucial for optimal soil management.

Machine learning models, including multivariate regression and artificial neural networks, are also valuable in predicting agricultural production outcomes. These models can analyze complex datasets that capture the interactions between environmental factors, genes, and crop yield, providing deeper insights into factors influencing agricultural productivity (Agarwal & Tarar, 2021). The choice of algorithm depends on the type of data available, and selecting the appropriate model is key to accurately predicting agricultural outputs and improving crop management strategies. By incorporating machine learning into agricultural practices, farmers can enhance productivity, optimize resource use, and increase sustainability in crop production.

2.10 The Conceptual Framework for the Study

This study adopts the digital soil mapping framework developed by the Natural Resources Conservation Service (NRCS) of the United States Department of Agriculture (USDA). The framework is based on a raster-based map, where the map is composed of two-dimensional cells, or pixels, arranged in a grid format. Each pixel corresponds to a unique geographic location and contains associated soil data. Digital soil mapping provides an advanced approach to understanding the spatial distribution of various soil properties, including texture, pH, fertility, and other relevant characteristics, and offers an effective method for analyzing and predicting soil conditions across large areas. The framework employed in this study integrates several critical components to explore the complex relationships between soil properties, fertilizer applications, climatic variables, and crop yield. Specifically, the study examines how spatial variability in soil characteristics influences agricultural productivity. Geospatial techniques, including Geographic Information Systems (GIS) and remote sensing, play a pivotal role in capturing this variability and mapping it in relation to other influencing factors, such as climatic conditions and fertilizer application.

Furthermore, the framework incorporates yield mapping, which involves the use of technology to assess crop yields across varying landscapes. This allows for an in-depth analysis of how different soil properties, coupled with climatic factors and fertilizer use, contribute to yield outcomes. Additionally, the framework accounts for the uncertainty inherent in soil predictions, providing a more nuanced understanding of the limitations and confidence associated with these data-driven approaches. The study's conceptual framework provides a thorough model for analyzing the dynamic relationships among crop output, climate, agricultural inputs, and soil conditions. This method promotes increased agricultural sustainability and production by helping to optimize farming operations and ensuring that tactics are customized to the unique environmental and soil conditions.

2.10.1 Soil Properties

Soil properties, including texture, organic matter, pH, and nutrient availability, play a critical role in determining the response of soybean yields to fertilizer applications. The composition and structure of the soil influence its fertility, which in turn affects root growth, nutrient uptake, and overall plant health. Sand, clayey, or loamy soils, for instance, have an influence on drainage and water retention, which in turn affects the soybean plants' access to moisture and nutrients. Due to their ideal drainage and nutrient-holding ability, loamy soils are typically used for soybean growth.

Organic matter is another vital soil property that enhances soil structure, improves moisture retention, and provides a reservoir of nutrients that can be gradually released to plants. The level of organic matter also plays a significant role in the soil's biological activity, promoting a healthy rhizosphere for soybean roots. Soil pH is equally crucial, as it directly influences nutrient availability.

Soybeans typically thrive in slightly acidic soils with a pH range of 6.0 to 6.5. If the pH is outside this range, certain nutrients may become either more or less available, impeding plant growth. For example, in acidic soils, essential nutrients like phosphorus may become bound to soil particles and unavailable for uptake, while in alkaline soils, micronutrients such as iron and zinc can become deficient. Nutrient availability is another key factor that influences soybean yield response to fertilizers. Essential macronutrients—nitrogen, phosphorus, and potassium—must be present in adequate amounts for optimal plant growth. The soil's nutrient content determines the type and amount of fertilizer needed to enhance growth and ensure efficient nutrient uptake. In regions where soils are nutrient-deficient, fertilizer application is critical for improving soil fertility and ensuring the plants receive the nutrients necessary for healthy growth and high yields. Therefore, understanding and managing these soil properties is essential for optimizing fertilizer application strategies and maximizing soybean productivity.

2.10.2 Fertilizer Application

The type, amount, timing, and method of fertilizer application are crucial elements that influence soybean yield. Proper fertilizer application ensures that soybeans receive the essential nutrients required for optimal growth, productivity, and overall plant health, while minimizing potential environmental impacts such as nutrient leaching or soil degradation. The type of fertilizer applied is an important consideration, as soybeans require primary nutrients such as nitrogen (N), phosphorus (P), and potassium (K), which must be provided in the appropriate ratios to support various growth stages. In addition to these primary nutrients, micronutrients like calcium, magnesium, sulfur, and trace elements are also necessary for healthy plant development. The choice of fertilizers—whether organic, synthetic, or a combination—depends on the specific nutrient deficiencies of the soil and the needs of the soybean crop. For example, nitrogen-based fertilizers are often necessary when the soil's nitrogen content is insufficient, especially in soils with low organic matter or when the crop's nitrogen-fixing capacity is compromised.

The amount of fertilizer applied must be carefully calibrated to match the nutrient requirements of soybeans at different stages of growth. Applying too much fertilizer can lead to nutrient imbalances, while insufficient fertilization can limit growth and reduce yields. Fertilizer recommendations are typically based on soil testing results, which help determine the exact deficiencies and nutrient needs specific to each field. Applying the correct amount of fertilizer is vital to avoid wastage, reduce environmental pollution, and prevent unnecessary increases in production costs. Timing plays a critical role in the effectiveness of fertilizer application. For soybeans, fertilizers should be applied at key growth stages: at planting, during the vegetative phase, and at pod development. Fertilizing at planting helps establish strong root systems, while later applications support pod formation and seed filling. Split applications, in which fertilizers are applied at multiple stages throughout the growing season, help ensure that nutrients are available when the plants need them most, promoting sustained growth and maximizing yields.

The method of fertilizer application also impacts nutrient uptake efficiency and environmental outcomes. Methods such as broadcasting, banding, side-dressing, fertigation (through irrigation), and injection all offer different benefits and challenges. Banding and side-dressing, for instance, place fertilizers closer to the plant roots, improving nutrient availability and reducing the risk of runoff or leaching. In contrast, broadcast applications are easier to implement but may lead to greater nutrient losses due to volatilization or surface runoff, particularly in areas with heavy rainfall. In addition to these factors, the use of precision agriculture technologies like Variable Rate Technology (VRT) and conducting regular soil nutrient testing can further enhance the efficiency of fertilizer use. These technologies allow for a more tailored approach to fertilization, adjusting nutrient application based on the specific needs of the soil and crop, thus reducing environmental harm while ensuring optimal soybean yield and quality.

2.10.3 Geospatial Techniques

Geospatial techniques, including Geographic Information Systems (GIS), remote sensing, and spatial statistics, are essential tools for analyzing the response of soybean yields to various factors such as soil properties, fertilizer applications, and climatic variables. These technologies enable the efficient collection, processing, and interpretation of spatial data, providing farmers and researchers with detailed insights into the geographical and environmental factors influencing crop production. GIS technology allows for the integration of various types of spatial data, such as soil characteristics, weather patterns, and topography, to create detailed maps that highlight spatial variability across agricultural landscapes. This information is invaluable for understanding how different areas within a field may respond to fertilizer applications, irrigation, or other management practices. GIS also facilitates the visualization of yield variations, enabling farmers to make informed decisions regarding crop management.

Remote sensing, which involves the use of satellite imagery, drones, and other aerial technologies, provides real-time data on plant health, soil moisture, and other critical environmental factors. Remote sensing allows the monitoring of crop development and stress levels through the capture of multispectral and hyperspectral pictures, which facilitates the early diagnosis of problems including water stress, insect infestations, and nutritional deficits. This technology, combined with GIS, offers a powerful tool for precision farming, where inputs can be applied in a targeted manner to optimize soybean yields and minimize environmental impact. Spatial statistics further enhance the analysis of geospatial data by providing methods for identifying patterns and relationships between spatial variables. These techniques help quantify spatial variability in soil properties, yield data, and climatic factors, enabling more precise predictions of soybean yield responses. By integrating spatial statistics with machine learning algorithms, such as random forests, it becomes possible to capture complex interactions between variables and predict yield outcomes with greater accuracy.

Machine learning algorithms, particularly random forests, are increasingly used in geospatial applications for their ability to handle large, multidimensional datasets and uncover intricate relationships between input variables. These models can process complex datasets, identify important predictors of soybean yield, and make predictions based on spatially distributed data. By learning from historical yield data and environmental factors, machine learning models can generate insights into how different soil, weather, and fertilizer conditions interact, providing actionable recommendations for improving yield management. Incorporating these geospatial techniques into agricultural practices enables more precise, data-driven decision-making, leading to better resource allocation, higher yields, and reduced environmental impacts. Through the combination of GIS, remote sensing, spatial statistics, and machine learning, farmers are better equipped to manage the complexities of modern agriculture and enhance soybean production sustainably.

2.10.4 Spatial Variability

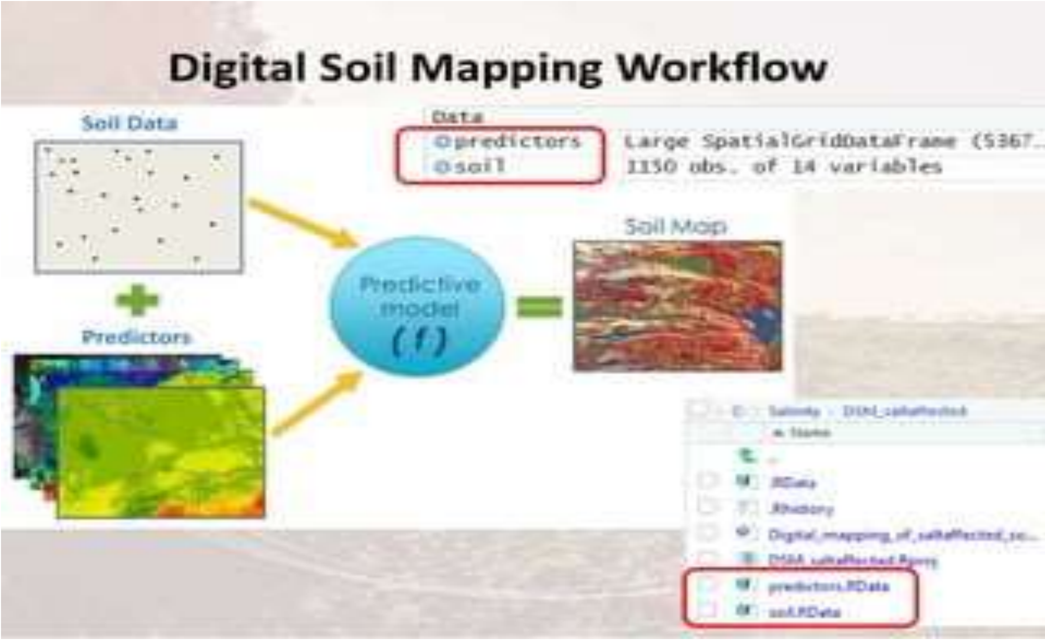
Spatial variability refers to the differences in physical, biological, or chemical properties across a given area, and it plays a significant role in determining soybean yield response within a field. These variations are influenced by a range of factors, including soil properties, topography, climate, and other environmental conditions. Understanding and accounting for spatial variability is essential for optimizing agricultural practices, as it enables farmers to tailor their management strategies to the specific needs of different areas within a field. Soil properties, such as texture, nutrient content, pH, and organic matter, exhibit substantial spatial variability within agricultural fields. These differences in soil characteristics can lead to varying plant growth conditions, influencing factors such as root development, water retention, and nutrient availability. For instance, areas with sandy soils may have lower water-holding capacity compared to clayey soils, affecting water availability to soybean plants and ultimately impacting yield.

Conversely, areas with high organic matter content typically support better soil fertility and nutrient availability, leading to more robust plant growth. Topography also contributes to spatial variability, as the elevation, slope, and aspect of a field can influence water drainage, sunlight exposure, and soil erosion. For example, areas at the bottom of a slope may accumulate water, potentially leading to waterlogging, while higher areas may experience quicker drainage and drier conditions. These topographical differences can create distinct microenvironments within the same field, requiring different management practices for optimal crop production. Climatic factors, such as temperature, rainfall, and humidity, also exhibit spatial variability within regions, which further affects soybean growth. Weather conditions can vary across a field due to local topographic features or proximity to water bodies, creating microclimates that influence plant health and productivity. For example, a field located near a large water body may experience more stable temperatures and higher humidity, while areas further from water sources may face more extreme temperature fluctuations, impacting crop development. Incorporating spatial variability into agricultural practices involves using tools such as GIS and remote sensing to map and monitor these differences across the landscape.

2.10.5 Yield Mapping

Yield mapping is a crucial tool in modern precision agriculture that involves measuring and mapping variations in crop yield within a field. Using technologies such as Global Positioning System (GPS) and Geographic Information Systems (GIS), yield data is collected in real-time during harvesting. This information is then used to create detailed maps that illustrate the spatial distribution of yield across a field. Yield mapping enables farmers to identify areas of high and low productivity, which can be linked to various factors such as soil properties, nutrient levels, and environmental conditions. The primary objective of yield mapping is to optimize farming practices by making data-driven decisions. In addition, yield mapping facilitates the efficient application of resources, as inputs can be applied precisely where and when they are needed, rather than uniformly across the entire field. Moreover, yield mapping allows farmers to track the effectiveness of their management practices over time.

This historical data helps refine decision-making, promoting continuous improvement in crop production. In the context of this study, yield mapping plays a vital role in understanding how fertilizer application impacts soybean yield in Ghana. It provides valuable insights into spatial variability in productivity, enabling farmers and researchers to assess the relationship between fertilizer use, soil properties, and crop response. The information derived from yield maps supports the development of more efficient and sustainable agricultural practices, ultimately contributing to enhanced soybean productivity. This conceptual framework, which incorporates yield mapping as a key component, offers a comprehensive approach to studying the spatial dynamics of soybean yield. It combines the use of geospatial techniques, soil properties, and fertilizer management to provide a deeper understanding of how different factors influence soybean production in Ghana, thereby enabling the formulation of targeted, site-specific recommendations for optimizing yields.



Source: NRCS, USDA

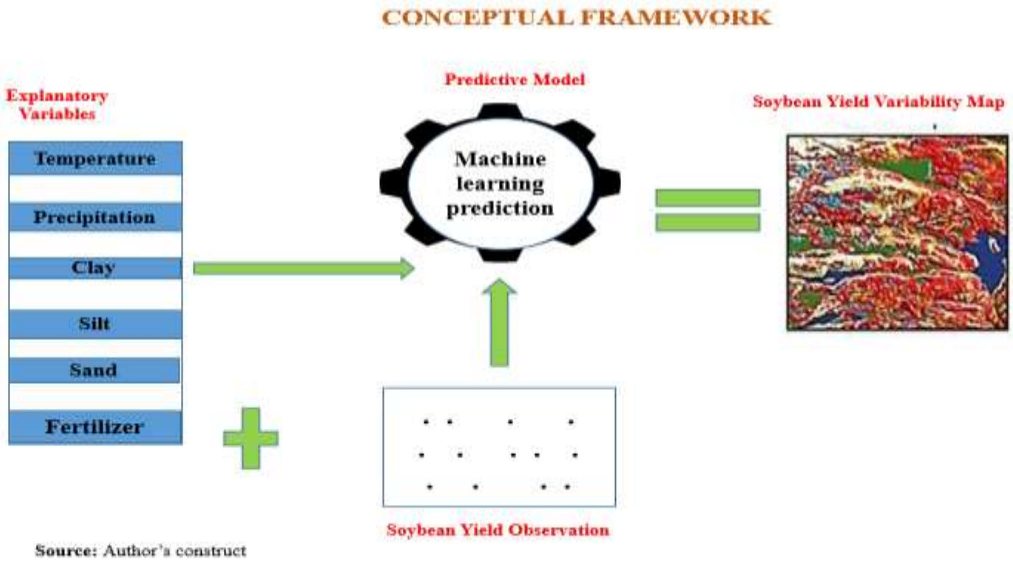


Figure 1: Conceptual framework on spatial analysis of soybean yield response to fertilizer application in Ghana.

CHAPTER THREE

STUDY AREA

3.0 Introduction

This chapter describes extensively the area for which the study was carried out which includes; location, agro-ecological zones, vegetation, climate, soil and economy of Ghana.

3.1 Location

Ghana is located in West Africa and borders Ivory Coast to the west, Burkina Faso to the north, Togo to the east and the Gulf of Guinea to the south (Opong-Anane, 2006). The capital is Accra. The country covers an area of approximately 238,539 square kilometers (92,098 sq mi) with a coastline running 560 kilometers (350 mi) south on the Gulf of Guinea in the Atlantic Ocean between latitudes 4°N and 11°N and longitudes 4°W and 2°E (MoFA, 2015; Nkrumah et al., 2014). The diverse geography includes coastal plains, tropical rainforests, savannas and hills. The topography is low and slightly hilly with a gradient of less than one percent. The southern part of Ghana is characterized by a narrow coastal plain that stretches inland for a short distance before reaching the central forest belt**.**

The coastal plain is dotted with lagoons and sandy beaches and is home to the country's main ports and cities. The savannah region lies north of the forest belt, which covers about two-thirds of the country. Flat grasslands, scattered trees, and the occasional rocky outcrop characterize this region. The savanna region is home to the country's main agricultural activities, including cocoa, cassava, yams and other crops. The northern region lies north of the savannah region and is characterized by rocky terrain and arid scrubland. This region is sparsely populated and home to many small mining and pastoral communities. Ghana's highest point is Mount Afadja on the border with Togo, reaching a height of 885 meters (2,904 feet) above sea level.

3.2 Agro-Ecological Zones

Ghana, located in the tropical belt, experiences a tropical climate characterized by distinct wet and dry seasons. The distribution of rainfall, temperature, and elevation across the country defines its agro-ecological zones, which significantly influence agricultural practices and the types of crops cultivated. These zones include the Guinea Savannah, Sudan Savannah, Coastal Savannah, Forest, and Transitional Zones, each with unique climatic, soil, and vegetation characteristics (Ghana Statistical Service, 2012; 2013b).

3.2.1 *Coastal Savannah Zone*

Located along the coast, this zone is characterized by a humid tropical climate, making it a hot and humid environment. The Atlantic Ocean has a significant impact on the region's climate as it helps regulate temperature and maintains high levels of humidity. There are two distinct rainy seasons in the region: the greatest between March and July and the shorter from September to November. The area receives significant rainfall during these periods, making it suitable for plant cultivation. The rains are often heavy and long-lasting, sometimes causing flooding.

The temperature in this zone is typically between 24°C and 30°C and provides a warm and favourable environment for plant growth. Crops grown in this zone include corn, cassava, plantain, coconut and oil palm. The soils in this area are predominantly sandy with low nutrient content, which pose a challenge for agriculture. Farmers in this region often need to use fertilizers and other soil improvers to improve the soil's nutrient content.

3.2.2 *Forest Zone*

About one-third of the country's land area is in the High Forest zone in the south, while the other two-thirds is in the Savannah Zone in the north. High-value redwoods and other commercially significant species can be found in the closed forest zone. This zone has a tropical rainforest climate that covers most of the central and southern parts of Ghana. The temperature is relatively constant and is between 22 °C and 28 °C. The region has high annual rainfall with an annual average of about 1750 mm.

The soil is nutrient-rich and cocoa, oil palms, rubber, timber and yams are among the crops grown in this zone. In addition, the central and southern parts of Ghana have a diverse and thriving ecosystem with numerous plant and animal species. The rainforest provides habitat for many endangered species, including primates such as chimpanzees and the rare forest elephant. This zone is also home to many indigenous communities who depend on the forest for their livelihoods, including traditional medicine, hunting and gathering.

3.2.3 *Guinea Savannah Zone*

The Guinea Savannah Zone of Ghana lies in the middle belt of the country, serving as a transition between the rainforest zone to the south and the semi-arid zone to the north. It is characterized by a tropical savannah climate with distinct wet and dry seasons. The rainy season typically spans from May to October, while the dry season lasts from November to April. Annual rainfall ranges from 1,000 mm to 1,400 mm, and temperatures fluctuate between 26 °C and 34 °C. The landscape features rather short trees with shrub and scrub undergrowth, particularly in less disturbed areas of the habitat. The northern edge of this zone marks the transition where the dry semideciduous forest (fire zone subtype) merges into the forest zone. Despite being less fertile than soils in the rainforest zone, the soils in the Guinea Savannah can be enhanced through sustainable farming practices to support agriculture effectively. The Guinea Savannah Zone supports the cultivation of various crops, including rice, cowpeas, peanuts, yams, cassava, and maize. Livestock farming is another significant economic activity, with cattle, sheep, and goats being the most common animals. This dual emphasis on crop cultivation and animal husbandry makes the Guinea Savannah Zone a vital region for Ghana's agricultural economy.

3.2.4 *Transitional Zone*

The transition zone of Ghana is located in the central part of the country and stretches from south to north. The region covers about 30% of the total land area of Ghana. It is characterized by a transitional climate and vegetation between the wooded south and the savannah north. The transition zone is characterized by a semi-arid to sub-humid climate with two distinct rainy seasons: the high season from April to July and the low season from September to November. The annual rainfall is between 750 and 1200 mm.

The temperature is generally high, ranging from 25ºC to 35ºC. The transition zone's vegetation is mostly made up of savannah grasslands with scattered trees and shrubs. However, some areas have been degraded by human activities such as agriculture, logging, and charcoal production. Climate, soil, and vegetation influence the agroecological zones in Ghana, and each zone has unique crops and farming practices. Understanding these zones is critical to effective agricultural planning, management, and development in Ghana.

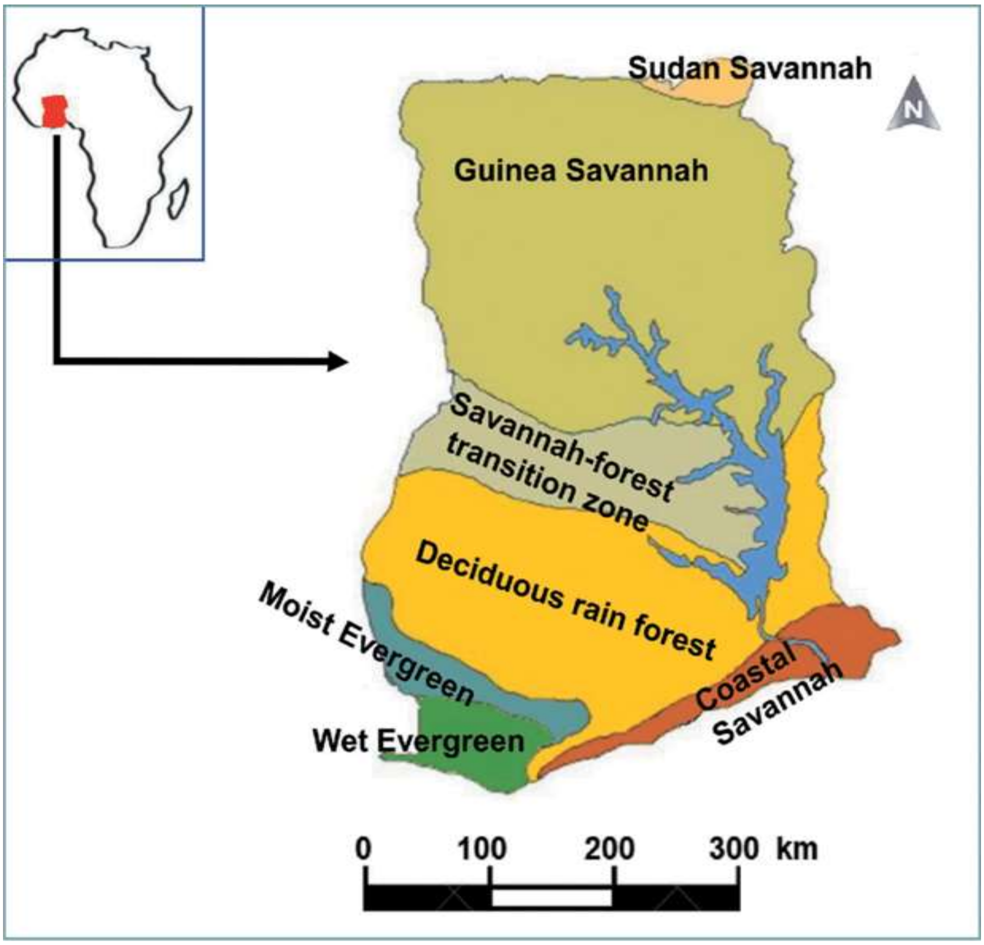


Figure 2: Agro-ecological zones of Ghana
Source: *Global Yield Atlas*

3.3 Climate

Ghana has a tropical climate which is divided into three main zones, namely the coastal zone, forest zone and the savannah zone (Yamba, Aryee, J Quansah, Davies, Wemegah, Osei, & Amekudzi, 2023). Most of the country belongs to the tropical savanna climate and humid region of Sub-Sahara Africa. The country's climate is influenced by several factors, including its proximity to the equator, the West African Monsoon, and the interactions between different air masses (Quagraine, 2014). The climate is also affected by the

Harmattan, a dry, dusty wind that blows from the Sahara Desert during the dry season which causes hazy conditions and reduces visibility.

The southern coastal areas receive more rainfall than the northern regions, which experience a more pronounced dry season (Yamba *et al*., 2023). Annual rainfall decreases with increasing altitude to the north, where a savannah climate prevails.

It is warm and comparatively dry along the south-east coast, hot and humid in the south-west and hot and dry in the north. The average annual temperature is between 25°C and 27°C and is relatively constant throughout the year, annual rainfall is up to 2,000 mm in the south-western part of the country, but decreases towards the north-east, dropping to 1,000 mm in the northern border area (Quagraine, 2014). The coastal zone experiences a tropical maritime climate which has two main seasons; the rainy season and the dry season. The rainy season is characterized by frequent and heavy rainfall, especially between April and July and in September and October and is influenced by the West African Monsoon, which brings moist air from the Atlantic Ocean. The dry season runs from December to March and is marked by lower humidity and significantly less rainfall.

About 35% of Ghana's land area is covered by the forest zone, which is found in the southwest of the nation. High yearly rainfall is one of its defining characteristics. (1,500-2,000 mm), high humidity, and warm temperatures (25-30°C). The forest zone is home to the country's most diverse vegetation, including rainforests, evergreen forests, and deciduous forests. It is also home to a wide variety of wildlife, including elephants, lions, monkeys, and birds. The savannah zone covers about 60% of Ghana's land area and is located in the north and east of the country. It is characterized by a dry season (November-March) and a wet season (April-October). The annual rainfall in the savannah zone ranges from 700-1,500 mm. The temperatures are also warm, with average maximum temperatures of 30-35°C. The savannah zone is home to a variety of vegetation, including grasslands, shrubs, and trees. It is also home to a variety of wildlife, including antelopes, zebras and birds.

Figure 3: Climatic zones of Ghana
Source: *Department of Agriculture, KNUST: https://doi.org/10.1002/met. 2049*

3.4 Soils

Ghana's soils exhibit unique characteristics resulting from local temperature, plants and other species acting on various geological components that have been modified by local relief or topography over time (Huat, Toll, & Prasad, 2012; Walter, 2012). The soils of Ghana play a crucial role in the success of agricultural practices in the country. The heavily weathered parent material of Ghana's soils, combined with common processes such as weathering, leaching and the formation of hard pans of laterite, creates a challenging environment for agriculture (Krishna, 2013). As a result, most soils in Ghana are inherently barren or have become barren through human activities.

Acrisols, rich in clay, dominate the southern half of Ghana but have low fertility and toxic levels of aluminum (Wood, 2013). In addition, ferralsols dominate the rainforest zone and are characterized by high levels of kaolinitic clay, metal oxides, and low cation exchange capacity. These soils pose a major challenge for farmers, as extensive use of fertilizers and other inputs is required to support crop growth. These soils also require careful management to support sustainable agriculture. Luvisols dominate the northern half of Ghana. Luvisols are characterized by mixed mineralogy, high nutrient content, and good drainage.

In the savannah and transition zones, there is a deficiency of nitrogen and organic matter. Leaching is more prominent in the rainy south, whereas laterite production is more prominent in the arid north. On-site, most soils are often formed from low-fertility source rock that is prone to long-term erosion. In the woodland zone, lateritic soils predominate. Ochrosoles (red, brown, and tan, reasonably well-drained soils) that get moderate rainfall are separated into less acidic and more fertile categories. Oxisols (red, brown, and tan, reasonably well-drained soils) are separated by the extreme southwest into less fertile and more acidic oxisols (1,650 mm). Ochrosols are found in great quantities in the northern savanna and coastal regions. The soil in the woodland zone is perfect for farming.

3.4.1 *Coastal Sands*

Ghana and other tropical nations have coastal sands, which are soil profiles found along their coastlines. These sandy-textured, low-fertility, high-salinity soils are found along Ghana's coast and drain effectively. The coastal savanna zone has a variety of soil types, such as tropical black soil, tropical grey soil mounds, acid vleisols, and sodium vleisols. The majority of these soils, save for tropical black soil, sometimes called Akuse clay, are not very important for agriculture. The coastal savannah lowlands are mostly covered by the Akuse Clays. They are appropriate for automated farming and irrigation, despite being heavy and unyielding. Nonetheless, they may be utilized to cultivate certain grass species, salt marshes, and mangroves—crops that can withstand salt.

3.4.2 *Forest Ochrosols*

The high organic matter content of these soils provides essential nutrients for plant growth, and the dense root networks help hold the soil in place and prevent erosion. They are well drained and are excellent for farming. Both the northern savannah and coastal areas have extensive ochrosol coverage. They are the ideal arable soil, similar to the forest zone. Forest ochrosoles support a rich and diverse ecosystem including a wide variety of plant species and diverse animals such as monkeys, birds and insects in Ghana. Despite their importance, the forest ochrosoles in Ghana are in danger due to human activities such as agriculture and logging. Deforestation destroys vital trees, which lead to soil erosion and degradation.

3.4.3 *Ferralsols*

Ferralsols are soil types found in tropical regions including Ghana. They are characterized by a high content of iron and entimeter oxides, which give them their red and yellow colour. They are typically found in areas with high rainfall and a warm climate and are often associated with tropical forest ecosystems. In Ghana, ferralsols are found in the country's forested regions and are mainly used in agriculture, particularly for growing crops such as cassava, plantains, and coconut trees. These soils are typically deep and fertile, but can also be very acidic, limiting the ability to grow crops on them. Farmers often use traditional soil management practices such as slash and burn, as well as modern techniques such as fertilizer application and liming to improve soil fertility.

3.4.4 *Nitosols*

Nitosols are soil profiles composed primarily of nitrogen horizons. These horizons are generally found in regions that receive a lot of rain and contain a lot of organic material, which can lead to the accumulation of nitrates in the soil. These soil types are characterized by deep, black topsoil that is rich in organic matter, leading to their overall high fertility. They are good for farming and are commonly used to grow crops such as cocoa, oil palm, and rubber.

3.4.5 *Acrisols*

Acrisols, typically clayey soils with low activity, coarse texture and limited water-holding capacity, are most widely used and dominant in Ghana's Guinea savannah zone, which serves as a centre for soybean cultivation. Acrisols are soil profiles typically found in areas with high rainfall and moderate to high temperature swings. They are characterized by an argic horizon, a layer of clayey soil formed by the accumulation of clay minerals in the soil profile. In Ghana, acrisols are found in various regions, including both forested and nonforested areas. They are typically associated with areas of high rainfall and temperature and are found in many agricultural regions of the country. These soils are generally considered fertile and good for agriculture and are often used for growing crops such as cocoa, oil palm and rubber. They are poorly drained and have low fertility but can be improved with proper management.

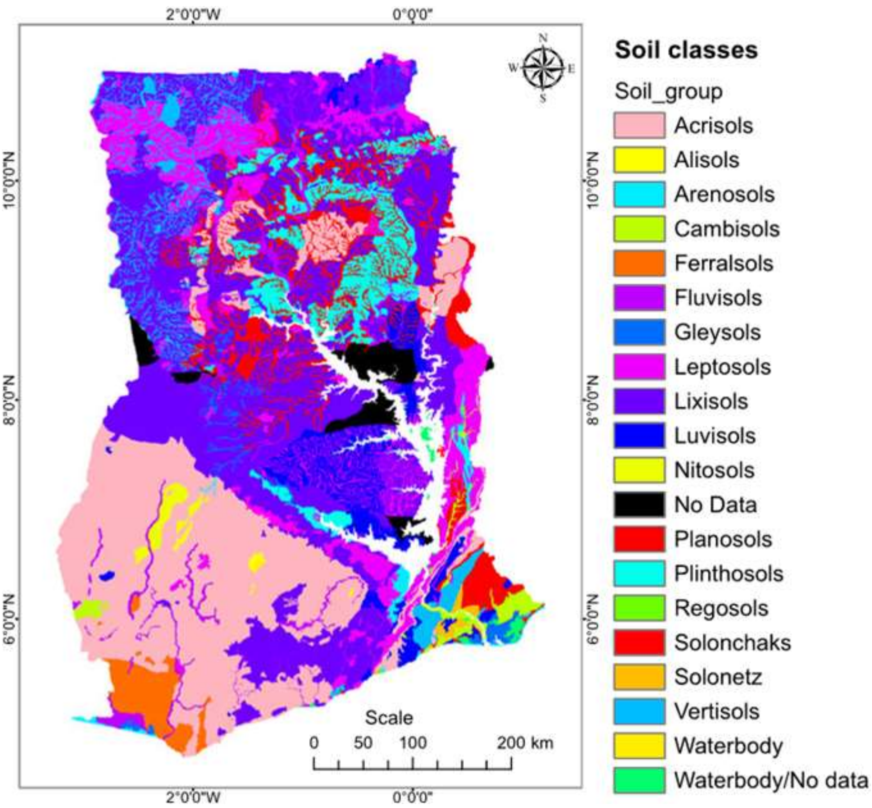


Figure 4: Soil map of Ghana

Source: *Geological Survey Department of Ghana: http://www.ghanamining. Org*

3.5 Vegetation

Average annual rainfall is directly related to most of Ghana's natural plant cover. The main vegetation types are closed forests, northern savannas, coastal strips and mangrove formations (Domson & Vlosky, 2007). The high forest zone in the south, which accounts for one-third of the land area, and the savannah zone in the north, which accounts for the other two-thirds, roughly divide the nation. High-value sequoias and other species of economic interest are found in the closed forest zone (Gyamfi *et al*., 2021). The land surface of Ghana is covered with two main types of vegetation. Forest and savannah were defined at a pan-African conference in Yangambi and more recently by UNESCO, along with the many forms that can classify those (Kumi-Boateng *et al*., 2012).

The forest lacks a continuous layer of green ground cover and is dominated by trees at least 5 m tall with interlocking crowns. Savannah trees have divided crowns or may be treeless, but there is usually a dense understory of seasonal grasses. The country's vegetation is a crucial natural resource for the country's economy and biodiversity. The country's location in West Africa, where it experiences both tropical and subtropical climate conditions, has led to the development of different types of vegetation. Forest, savanna and coastal vegetation are the three main types of vegetation cover in Ghana. Tropical rainforests covered with forest flora dominate in the southern regions of Ghana. Various species of trees are found in the rainforests, including mahogany, ebony and teak. Many creatures, including monkeys, birds and reptiles, also make their home in these forests.

Forest vegetation is progressively disappearing due to deforestation for agriculture and other human activities. The northern regions of Ghana are covered with savannah vegetation characterized by grasslands and scattered trees. Baobab trees, acacias and grasses dominate the savannah vegetation suited to the semi-arid environment. Elephants, antelopes and hyenas are some species that live in the savannah vegetation. Mangroves and coconut palms are distinctive features of the coastal vegetation that dominates Ghana's coastline.

The production of coconut products from coconut palms is a significant source of income for the coastal population. At the same time, the mangroves are an important habitat for fish and other marine animals.

3.6 Soil Fertility

Soil fertility is a crucial factor for agricultural productivity and sustainable development in every country, including Ghana. The country has a variety of agro-ecological zones, each presenting unique challenges and opportunities for soil fertility management. The tropical climate with pronounced wet and dry seasons influences the nutrient dynamics of the soil; climate, parent material, topography, biota, and agricultural practices affect soil fertility. Heavy rainfall causes nutrient leaching, while high temperatures accelerate decomposition rates and affect organic matter levels.

The parent material, that is, the geological material from which soils develop, influences the initial nutrient content of the soil. Ghana's soils vary greatly in these properties due to geographical location and geological differences; forested areas in the south have more acidic soils, while savannah regions in the north have soils with higher pH values. Ghana often faces nutrient deficiencies, with phosphorus deficiencies being a common challenge, limiting plant growth and yield potential. Unsustainable agricultural practices, deforestation and poor land management contribute to soil erosion, leading to loss of topsoil and nutrients and threatening soil fertility in Ghana (Fosu *et al*., 2020). Soil degradation, which includes nutrient deficiencies, compaction and salinity, further erodes soil's ability to support crop growth and agricultural productivity.

The incorporation of organic matter through practices such as cover cropping, incorporation of crop residues and composting has shown positive effects on soil health and fertility in Ghana, particularly in agroforestry systems and organic farming practices. While fertilizer use can address nutrient deficiencies and improve soil fertility, improper or overuse can lead to environmental and economic consequences (Nkansah *et al*., 2017). Balancing nutrient use with crop needs is crucial for sustainable soil fertility management, as overuse can lead to water pollution and increased production costs.

3.7 Population

According to Statistics Times, Ghana's population was expected to reach 31.73 million in 2021, a 2.12% increase from 31.07 million in 2020. The country's population has been growing steadily at a rate of 2.2% annually over the past few decades. Measured in terms of population and population growth, Ghana ranks 47th internationally. With an average age of 21 years, Ghana's population is relatively young. About 40% of the population is under 15 years old, while 55% of people are between 15 and 64 years old. The remaining 5% are aged 65 and over. Ghana, which ranks 33rd, had 0.9 million births in 2021, or 2,456 per day. The average number of births per 1000 people was 28.23, while the death rate was 0.22 million or 616 per day, ranking 44th (UNWPP, 2019). On average, 7.08 people died per 1000 people. According to the World Health Organization (WHO), the maternal mortality rate in Ghana was 319 per 100,000 live births in 2017. This is a significant improvement compared to the 2007 statistic of 451 deaths per 100,000 live births. 18.2 million People (57.99%) of Ghana's population live in urban areas, ranking Ghana 132nd in terms of urbanization, with Kumasi, Accra and Tamale are the main urban areas (Ghana Statistical Service, 2021).

Based on the ratio of women to men, Ghana ranks 174th out of 201 nations and territories. For every 100 women there are 102.81 men. Ghana has 15.65 million women and 16.09 million men. The male population is 50.69% while the female population is 49.31%. In Ghana there are 0.44 million more men than women. Ghana's education system has seen tremendous improvements in recent times. Around 79% of the population can read and write, and primary and secondary education is free and compulsory. Nevertheless, there are still significant differences in access to education, especially in rural areas. Outcomes and access to health care have improved significantly, but problems remain. The country has a high infant mortality rate and a low life expectancy of around 64 years.

3.8 Economy

Ghana has experienced significant economic growth over the past few decades and is one of Africa's fastest growing economies (Chavula, 2014). The GDP of Ghana was estimated at about US$68 billion in 2020 and the per capita income was about US$2,221 and the main engines of the economy was agriculture, manufacturing and services. Unlike other countries in the region, Ghana has a market-based economy with comparatively few regulatory barriers to trade and investment and is rich in natural resources (GSS, 2020). After 25 years of comparatively sound administration, a dynamic business climate, and a steady decline in poverty, Ghana's economy has suffered from lax fiscal policies, high budget and current account deficits and a flagging Cedi in recent years (Loloh, 2020).

CHAPTER FOUR

METHODOLOGY

4.0 Introduction

This chapter discusses the strategies and tactics used to achieve study goals. The research data source, ethical issues, research design, philosophy and field of study are explained.

4.1 Research Design

Correlation research design was used for the study. It involves measuring two or more variables and determining the degree of their relationship. This design is particularly useful when studying complex phenomena where experimental manipulation is not possible or ethical.

4.2 Research Philosophy

The study acknowledged the use of quantitative methods or approach which is a principle of the positivist philosophy. Positivist philosophy is a philosophical framework that emphasizes the importance of empirical evidence and scientific method in understanding and explaining phenomena.

4.3 Research Approach

The quantitative research approach was used for the study, which emphasizes the use of static, numerical data and careful, convergent reasoning. A quantitative research study aims to classify traits, quantify them, and create statistical models to account for observable events. This method enables researchers to find connections, links or patterns between variables and thus draw conclusions from the data.

4.4 Data Types and Sources

The data sources for the study were secondary, derived from reputable and reliable platforms to ensure accuracy and relevance to the research objectives. Secondary geocoded data on soybean field trials were obtained from the International Fertilizer Development Centre (IFDC), Ghana. These data provided critical insights into the spatial variability of soybean yield and fertilizer application patterns across various field sites. Additionally, data on the chemical and physical properties of the soil, with a spatial resolution of 250 meters, were downloaded from the ISRIC World Soil Information data platform. These data were essential for understanding the soil's role in influencing soybean yield and were processed to align with the geographical scope of the field trials. Climate variables, including precipitation and temperature, were sourced from the WorldClim website.

These variables were integrated to account for environmental factors that could influence yield variations. Data from all sources were cleaned, standardized, and analyzed using geospatial and statistical tools to ensure consistency and compatibility. The rigorous handling of secondary data included pre-processing steps such as geospatial alignment, interpolation where necessary, and validation against field trial metadata to ensure reliability. A total of 782 observations of soybean yields were analysed to determine the influence of various factors such as soil physical and chemical properties, weather and terrain on soybean yield in Ghana. The table below represents the variables for the study.

Table 1: Data Variables Used in the study

Variable	Description	Unit
Yield	Soybean observed Yield (dependent variable)	kg/ha
N. F	Soil Nitrogen fertilizer	kg/ha
P2O5.F	Soil Phosphorous fertilizer	kg/ha
K2O.F	Soil Potassium fertilizer	kg/ha
Zn. F	Soil Zinc fertilizer	kg/ha
Inoculant	Soil Inoculant application	kg/ha
pH	Soil Ph	-
C	Soil Carbon	%
N	Soil Nitrogen	%
P	Soil Phosphorous	mg/kg
Zn	Soil Zinc	mg/kg
Fe	Soil Iron	mg/kg
Ca	Soil Calcium	meq/100g
Mg	Soil Magnesium	meq/100g
K	Soil Potassium	meq/100g
Na	Soil Sodium	meq/100g
EA	Soil Exchangeable Acidity	meq/100g
BS	Soil Base Saturation	-
SO4S	Soil Sulphate fertilizer	mg/kg
Sand	Soil sand composition	%
Silt	Soil silt composition	%
Clay	Soil clay composition	%
Tmax	Weather maximum temperature	Deg. Celsius
Tmin	Weather minimum temperature	Deg. Celsius
Prec	Weather precipitation	M
Elev	Terrain elevation	M

Source: field data, 2023

The variables for the study included dependent and independent variables are listed in Table 1. The dependent variable in this situation was the yield of the soybeans. At the same time, the physical and chemical properties of the soil, weather (temperature and precipitation), and terrain (altitude) were the independent factors. Soil physical and chemical properties included pH, carbon, nitrogen, clay and silt content. Fertilizers included nitrogen, phosphorus, potassium and other minor nutrients. Climatic factors included maximum and minimum temperatures and precipitation.

4.5 Covariates

A variable that could have a predictive relationship with the outcome being studied is called a covariate in statistics (Gore & Reynolds, 2012). While the direct effects of fertilizers on soybean yields can be studied, a significant amount of unexplained variance could be attributed to a secondary variable indirectly affecting the yield response. When evaluating crop yields, several variables are considered in addition to fertilizer application, such as: B. local climatic conditions, terrain characteristics, the number of inputs made in addition to fertilizers, pests and diseases, and various management techniques used in the field.

4.6 Data Processing and Analysis

Data on soybean yields, fertilizer application, and other relevant factors from various farms across Ghana were cleaned by handling missing values, outliers, and inconsistencies to ensure the accuracy of the analysis. The researcher identified the dependent variable (soybean yield) and independent variables (fertilizer, soil, weather and terrain) that were likely to influence soybean yield based on domain knowledge and preliminary data exploration. Exploratory data analysis was conducted to visualize the distribution of variables, identify potential relationships, and detect any anomalies. A correlation coefficient between variables were calculated to understand the strength and direction of linear relationships.

The researcher checked the assumptions of multiple linear regression, including linearity, independence, homoscedasticity (constant variance), and normality of residuals. The MLR model was built using a stepwise variable selection procedure based on the Akaike Information Criterion (AIC) to find the best model with the lowest AIC value; and MLR equation formulated was of the form:

Soybean Yield = $\beta_0 + \beta1_{Soil} + \beta2_{Weather} + \beta3_{Terrain} + \varepsilon$, eq……. ()

where β_0 is the intercept, $\beta1$- $\beta3$ are the coefficients, and ε is the error term. Statistical and spatial analysis software such as Excel sheet, R packages and R Studio were used to fit the MLR model to the data.

Associations between data were evaluated using Pearson's correlation analysis and linear regression equations were estimated by least squares regression. Differences between observed and predicted yields were assessed using a paired Students' t-test. The model's goodness of fit was assessed using metrics such as coefficient of determination (R^2) and the adjusted coefficient of determination (Adj. R^2) to understand how well the model explains the variability in soybean yield. The researcher checked for multicollinearity among independent variables using methods like variance inflation factor (VIF). Careful examination of residuals concluded this process, confirming conformity to the model's assumptions, encompassing normal distribution, constant variance, and independence. (referred to Appendices A-C).

4.6.1 Random Forest Prediction

In this study, the RF machine learning algorithm was selected to model and predict soybean yields in unknown locations in Ghana. The choice of a nonparametric machine learning method was due to its ability to handle complex relationships, handle interactions among variables, and provide robust predictions even with noisy or high-dimensional data. The goal was to improve the explanatory power beyond the limits of the multiple linear regression model, which achieved a variability of 51 percent. Because fertilizer application values were not available at all of the unknown locations, predictors related to fertilizers were excluded from the mapping model, making it more cost-effective.

Instead, other relevant variables such as meteorological information, soil type, and topography were used to predict soybean yields at unidentified locations. The dataset was divided into two subsets: a training set for model training and a validation set for evaluating model performance. The researcher utilized a machine learning library (The random forest package in R) to train the random forest model on the training dataset and configured hyper-parameters such as the number of trees, maximum depth, and minimum samples per leaf to optimize model performance. The feature importance score generated by the random forest model was analysed to understand which variables have the most influence on soybean yield predictions. The RF model formula includes.

Yield = Soil (Chemical, Physical) + Weather (Tmin, Tmax) + Terrain (Elev) + error eq…………... (..)

CHAPTER FIVE

RESULTS AND DISCUSSION

5.0 Introduction

This chapter introduced the research findings and studied the factors affecting the soybean production in the study region. The chapter provides insights into increasing soybean productivity and sustainability in the region and contributes significantly to our understanding of how soybean yield responds to fertilizer application in Ghana.

5.1 Soybean Yield Analysis

The final and best multiple linear regression model achieved an R-squared of 51%, indicating that the model explains about 51% of the variation in the dependent variable. This high R-squared value suggests that the model fits the data well and can capture the relationships between the independent and dependent variables. The model includes many statistically significant variables related to soil physical and chemical properties, weather, and terrain. These variables were found to have a significant and meaningful impact on the dependent variable and were included in the final model.

However, at a 95% confidence level, it was found that only zinc fertilizer and soil iron were not statistically significant. This means that there is not a strong enough correlation between these factors and the dependent variable to be considered relevant. The absence of these variables in the final model results in a simpler and sparser model that focuses on the crucial predictors. It is important to note that the variables R-squared value and statistical significance are not the only factors to consider when evaluating a regression model. Among other things, the models on which the assumptions are based, the general interpretability and the usefulness of the results should be taken into account. The table below shows the results of the regression.

Table 2: Multiple regression model structure results

Variables	Estimate	Std. Error	t value	p value	Significance
(Intercept)	15994.11	4128.224	3.874	0.000116	***
N. F	11.0285	5.0981	2.163	0.030832	*
P205.F	9.7549	4.7115	2.07	0.038747	*
Zn. F	33.3833	18.39	1.815	0.069872	.
Inoculant	-1.7055	0.72	-2.369	0.018092	*
pH	1507.731	207.0894	7.281	8.32E-13	***
C	1092.238	187.8987	5.813	9.04E-09	***
P	-80.991	6.033	-13.425	< 2E-16	***
Zn	39.4127	11.9099	3.309	0.00098	***
Fe	2.9476	1.5806	1.865	0.062577	.
Ca	-1556.82	1036.863	-1.501	0.13365	
K	3240.531	382.909	8.463	< 2E-16	***
Na	-2158.72	663.3357	-3.254	0.001187	**
EA	656.1689	333.356	1.968	0.049389	*
BS	-32.7615	8.2369	-3.977	7.63E-05	***
SO4S	21.1485	10.5184	2.011	0.044719	*
Tmax	343.8035	149.9646	2.293	0.022146	*
Tmin	-1420.7	282.0397	-5.037	5.91E-07	***
Prec	-109.383	26.3862	-4.145	3.77E-05	***
Sand	-1.8717	0.5058	-3.7	0.000231	***
Clay	-4.4914	1.1764	-3.818	0.000146	***
Silt	3.4489	0.483	7.141	2.17E-12	***
Elev	3.8673	0.8332	4.641	4.08E-06	***

Dependent variable is Yield, F (37.27), p (<2.2e-16)
R-squared = 51%
Significance codes: 0 *** 0.001 ** 0.01 * 0.05. 0.1

Source: field data, 2023

Table 2 shows that soybean yield increases significantly (p<0.05) with potassium, pH, organic carbon, exchangeable acidity, maximum temperature, zinc, zinc fertilizer, nitrogen fertilizer, phosphorus pentoxide, elevation, silt, and iron. This shows that different factors influence the variability of the soybean yield response. pH, carbon and potassium are the factors with the greatest impact on yield (>1000 kg/ha). Accordingly, an increase of 1 unit in each variable would result in an average increase in soybean yield of 1507.731 kg/ha, 1092.238 kg/ha, and 3240.531 kg/ha, respectively. This indicates that the same amount can increase soybean yield by increasing pH, C, and K levels, aligning with previous research. For instance, Elbaalawy et al. (2016) and Towett et al. (2015) highlighted the critical role of potassium in soybean nutrition, emphasizing its influence on nutrient uptake and translocation.

Similarly, Khojely et al. (2018) underscored the importance of organic matter in enhancing soil fertility and buffering capacity, which can indirectly affect pH and nutrient availability, meaning they can withstand pH changes when acidic or alkaline substances are added and increasing organic carbon tends to increase yield. The significant positive correlation between pH and yield is consistent with the findings of Staton (2012) and Thapa et al. (2024), who reported that optimal pH levels between 6.0 and 7.0 maximize nutrient uptake and biological nitrogen fixation. Additionally, the positive association with silt content can be attributed to its role in improving soil water-holding capacity and drainage, providing a favourable environment for soybean crops as suggested by Lal (2020).

In contrast, sodium, calcium, minimum temperature, precipitation, phosphorus, base saturation, clay, sand, and inoculant exhibited significant negative correlations with yield significantly. Variables with a clearly significant negative impact (<1000 kg/ha) on yield include calcium (Ca), sodium (Na) and minimum temperature (Tmin). Therefore, increasing these variables by one unit would decrease soybean yield by -1556.82 kg/ha, -2158.72

kg/ha, and -1420.7 kg/ha, respectively. This means that an equivalent amount can decrease soybean yield by increasing Ca, Na and Tmin levels.

The low total phosphorus observed in Table 2 indicates that the nutrient is a limiting factor for optimal soybean production and that a response to phosphorus is to be expected. This confirms a study by Mirriam et al (2023) that phosphorus is often the nutrient that severely limits the productivity of soybeans. Hailu and Mehari (2021) and Rietra et al. (2017) have documented the detrimental effects of high sodium and calcium levels on soil salinity and nutrient imbalance, respectively. Regarding the minimum temperature, the following studies confirm the results in Table 2.

Adam Gasper (2019) states that around 21 °C is the ideal temperature for soybean germination and that at soil temperatures below 10 °C, the dangers of slow germination, infection with seedling diseases and poor stand formation increase. George, Horst and Neumann (2012) emphasized that chemical processes and root activity are slowed down in cool soil temperatures, making nutrients less accessible to the crop. Mark et al. (2020) also claims that cold and wet conditions before and after soybean planting damage developing seedlings, delay germination and emergence, and reduce stand formation, resulting in low yield. As reported by McCarthy et al. (2022) found that the northern regions of Ghana, with temperatures between 25 °C and 35 °C, offer ideal conditions for developing soybeans, and a temperature of 29°C is recommended for the growth of soybeans.

5.2 Machine Learning Mapping Analysis

Soybean output has been predicted using a Random Forest model within the machine learning mapping analysis framework. The model uses various factors, including soil properties, weather characteristics and topographic features affecting crop production as shown in table 3 below.

Table 3: Random Forest Model Variables

Variable	Description	Unit
Yield	Soybean observed Yield (dependent variable)	kg/ha
Sand	Soil sand composition	%
Clay	Soil clay composition	%
Silt	Soil silt composition	%
pH	Soil Ph	-
N	Soil Nitrogen	%
P	Soil Phosphorous	mg/kg
K	Soil Potassium	meq/100g
C	Soil Carbon	%
Zn	Soil Zinc	mg/kg
Ca	Soil Calcium	meq/100g
Fe	Soil Iron	mg/kg
OM	Soil Organic Matter	%
CEC	Soil Cation Exchange Capacity	meq/100g
Mg	Soil Magnesium	meq/100g
Na	Soil Sodium	meq/100g
Prec	Weather precipitation	M
Tmax	Weather maximum temperature	Deg. Celsius
Tmin	Weather minimum temperature	Deg. Celsius
Elev	Terrain elevation	M

Source: field, 2023

5.3 Machine Learning Mapping Results

The trained random forest model could explain 68% of the variability in soybean yield because it could capture nonlinear relationships in the data. Variability refers to the differences or fluctuations observed in actual soybean yields at different locations or over different periods and arises from a variety of factors including soil properties, weather conditions, and agricultural practices. This implied that the model accounted for 68% of the differences in soybean yields influenced by the input variables it was trained on. This trained model was used to predict soybean yields at unknown locations in Ghana.

The model received data from different locations in Ghana where soybean yields are unknown and used the historical patterns and relationships learned during training to make predictions about soybean yields in these unknown locations. The model also reports variable importance, indicating how each variable best contributes to the model, or to understand the importance of different input variables (traits) in predicting the target variable (outcome). In this specific context, the variable importance chart was created based on the analysis of a trained model predicting soybean yields in Ghana, as shown in the figure below.

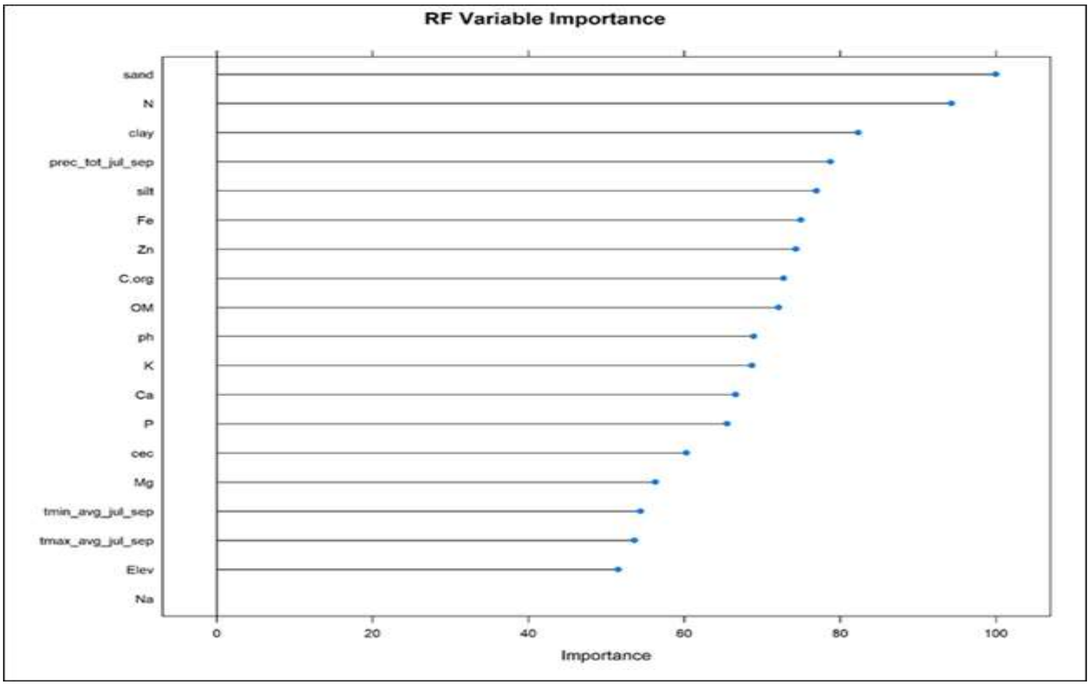
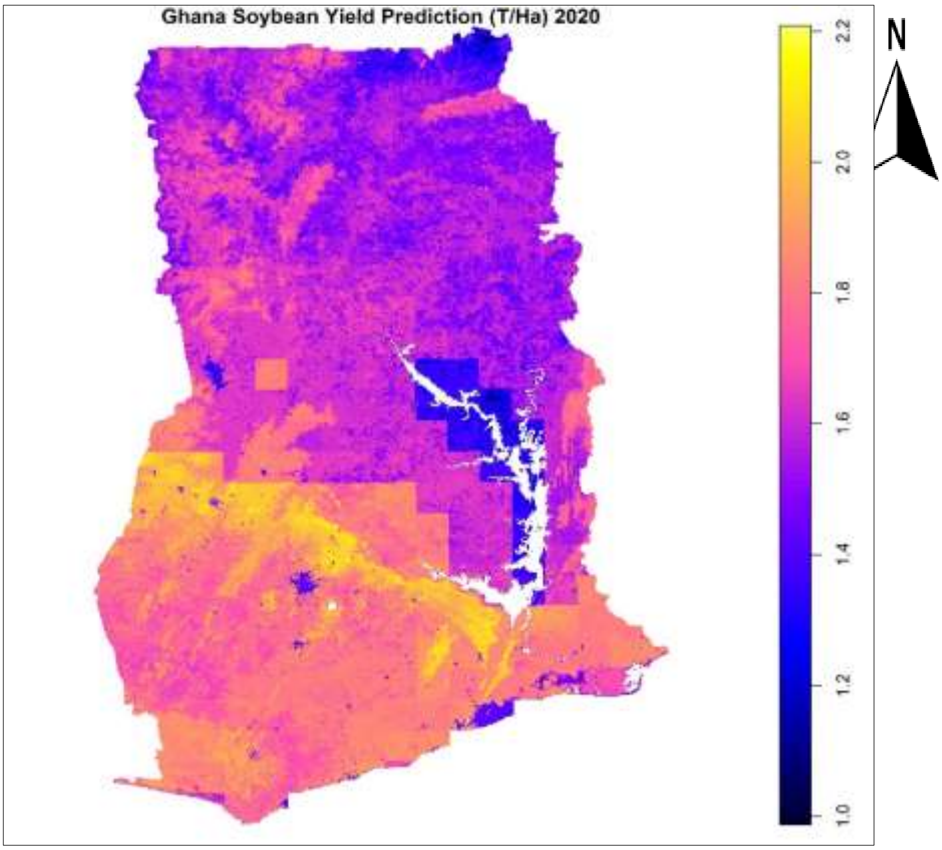


Figure 5: Random forest variable importance
Source: *Author's data analysis*

From the variable importance chart, it could be seen that sand is the most critical variable and sodium is the least important. The identification of sand as the most critical variable suggests that soil properties, specifically sand content, play a critical role in determining soybean yields. Conversely, sodium's minor importance means that its presence or concentration in soil could have minimal impact on soybean yields. However, this does not mean that sodium is irrelevant in all cases; in this particular model for predicting soybean yields, it has little impact. The map in Figure 4 was created using several advanced statistical methods. It shows a spatial response of predicted soybean yield distribution to Ghana's meteorological information, soil type and topography. It shows Ghana's predicted soybean yield based on the trained random forest model.

The map shows that the predicted yield was between 1.0 and 2.2 t/ha. According to MoFA (2020), the achievable soybean yield in Ghana is around 3.0 t/ha, but yields vary between 1.7 and 1.8 t/ha. The prediction shown in yellow in the south-west part of the map result from over-predictions due to less o observation data in the region. Therefore, the model attempted to resolve the predicted values from the explanatory variables only, resulting in the prediction of higher values. In the northern parts, where there is more observed data, shown in blue, purple and pink colours, the prediction remained at 1 to 1.8 t/ha, confirming the MoFA (2020) report. The map also showed that certain areas in the country have a higher predicted yield than others.

These areas, located mainly in the northern regions of Ghana, exhibit an ideal combination of weather, soil type and topography that favours soybean cultivation. A study by Adjei-Nsiah et al. (2022) confirms that the northern regions of Ghana with temperatures between 25 °C and 35 °C offer ideal conditions for the development of soybeans. In the southwest of the country, on the other hand, less favourable conditions prevail, which leads to lower yield predictions. While the semi-deciduous forest zone has the potential to support soybean cultivation, its productivity is limited by factors such as low soil pH and insufficient tuber formation (Adjei-Nsiah et al., 2022).



0 10 20 30 40 meters
|------|------|------|------|

Figure 6: Ghana Soybean Yield Prediction Map
Source: *Author's construct*

CHAPTER SIX

SUMMARY, CONCLUSION AND RECOMMENDATION

6.0 Introduction

The study shed light on several important insights into the variability of soybean yield. The research examined the influence of soil physical and chemical properties on soybean yield, determined the influence of climatic variables on soybean yield, and determined the effects of fertilizers on yield. The study utilized secondary geocoded data from soybean field trials at research facilities using multiple regression models and random forest models, and analysed the resulting data to draw meaningful conclusions. This chapter contains the conclusions of the study, an executive summary and suggestions based on the results.

6.1 Summary

In this study, a total of 782 observations of soybean yields were analysed to determine the influence of various factors such as soil physical and chemical properties, weather and terrain on soybean yield in Ghana. With yield as the dependent variable and the other characteristics as explanatory or independent variables, a stepwise multiple linear regression model was used to explain 51% of the yield variability. An important finding of the study was that there were many inconsistencies in the model map representations of the soybean yield gradient being higher in the northern AEZs than in the southern ones, highlighting the predictions in the northern AEZs, which are consistent with those from the Ministry of Food and Agriculture (MoFA) yields reported in 2020.

However, forecasts for the Southwest have been overstated, likely due to the absence of observational data for the region. The soybean yields in Ghana expected by the Ministry for 2020 are between 1.0 and 2.2 t/ha. Potassium had the greatest positive impact on production, while pH, carbon, zinc, and elevation were important factors that positively impacted yield. For example, increasing potassium by 1 meq/100g could result in a yield increase of 3.2 t/ha. Phosphorus, base saturation, minimum temperature, precipitation, sand and clay are critical factors that have been shown to negatively impact yield, with minimum temperature having the greatest impact. With every degree Celsius increase in the minimum temperature, the yield can drop by around 1.4 t/ha.

Sand, nitrogen, clay, precipitation, silt, iron and zinc are among the key factors discovered to explain the variability in soybean yields, according to results from a random forest-monitored machine learning model with an R-square of 68%. This study provided remarkable results by applying a spatial perspective on soybean yields in Ghana while using limited spatial observational data to explain the impact of soil and environmental factors on yield.

6.2 Conclusion

The study reveals the critical role of fertilizer application in enhancing soybean yields across various sites in Ghana. However, the relationship between fertilizer uses and soybean yield is complex and influenced by site-specific conditions. The analysis confirms that soil properties significantly impact soybean yield, aligning with the objective to examine the effects of physical and chemical properties of soil. Tailoring fertilizer use to the unique soil conditions at each site proved essential, ensuring optimal crop performance and reducing fertilizer waste, promoting sustainable agricultural practices.

Among climatic variables, minimum temperature emerged as the most influential factor affecting soybean yield. This finding supports the objective to examine the influence of climatic variables. The study found that even minor temperature fluctuations could lead to substantial yield reductions, with each degree variance resulting in a decrease of 1.4 tonnes per hectare. This highlights the vulnerability of soybean yields to temperature variations and underscores the importance of developing adaptive strategies to mitigate the effects of climate change.

The study identified potassium as the most critical nutrient influencing soybean yield among the N, P, K trio, which directly addresses the objective to assess the impacts of N. P. K. Potassium's significant impact offers valuable insights for farmers and agronomists, emphasizing the need to prioritize potassium in nutrient management strategies to achieve more efficient and yield-maximizing practices.

The spatial analysis demonstrated the variability of soybean yield based on soil physical-chemical properties, fertilizer application, and climatic variables, fulfilling the objective to analyze spatial variability. This underscores the necessity for spatially explicit recommendations and interventions to optimize soybean productivity across different regions in Ghana.

6.3 Recommendations

Based on the results of the study, the following recommendations are made:

1. Tailored Fertilizer Recommendations and Promotion of High Potassium Fertilizers

Ministry of Food and Agriculture (MoFA), Agricultural Extension Services, and Fertilizer companies should provide farmers with personalized fertilizer recommendations based on soil testing results and promote the use of high-potassium fertilizers to enhance soybean yields, ensuring targeted soil fertility management practices.

2. Embrace Precision Agriculture and Regular Soil Testing

The adoption of precision agriculture technologies such as GIS and remote sensing must be encouraged by institutions such as the Council for Scientific and Industrial Research (CSIR), MoFA, and Agricultural Universities to improve fertilizer management. This would help to conduct routine soil testing to monitor nutrient status and pH levels, helping farmers make informed decisions about fertilizer types and quantities.

3. Streamlined Fertilizer Distribution

MoFA and Agricultural Cooperatives should ensure efficient logistics for the temporal and spatial distribution of fertilizers to increase farm yields and income, considering the key covariates highlighted in the study.

4. Expand Data Collection and Further Research

Research Institutions and Universities should conduct research on the interactions between soil properties, climatic variables, socioeconomic and environmental factors, and management practices to develop strategies for boosting soybean production. They should expand and increase data collection efforts, particularly in the southwestern regions of Ghana, to enhance future predictions and understand factors influencing soybean yields.

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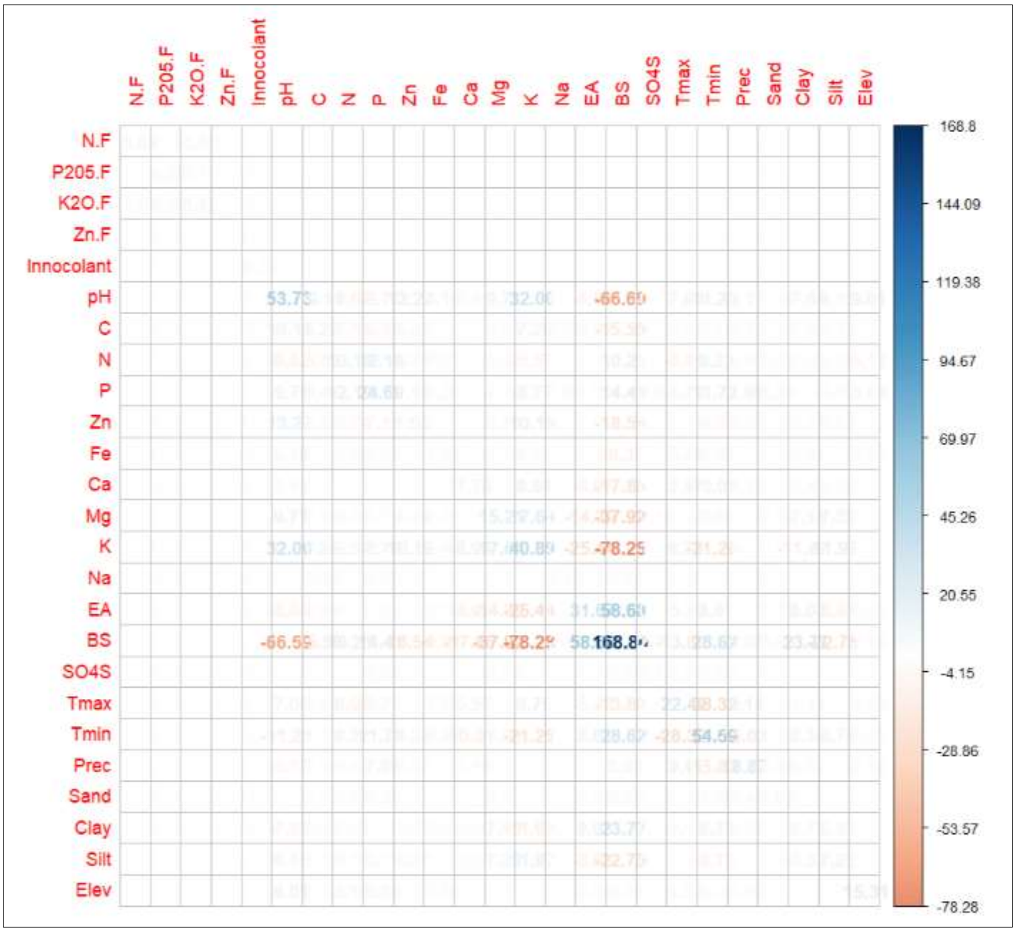
APPENDICES

Appendix A: Exploratory Data Analysis

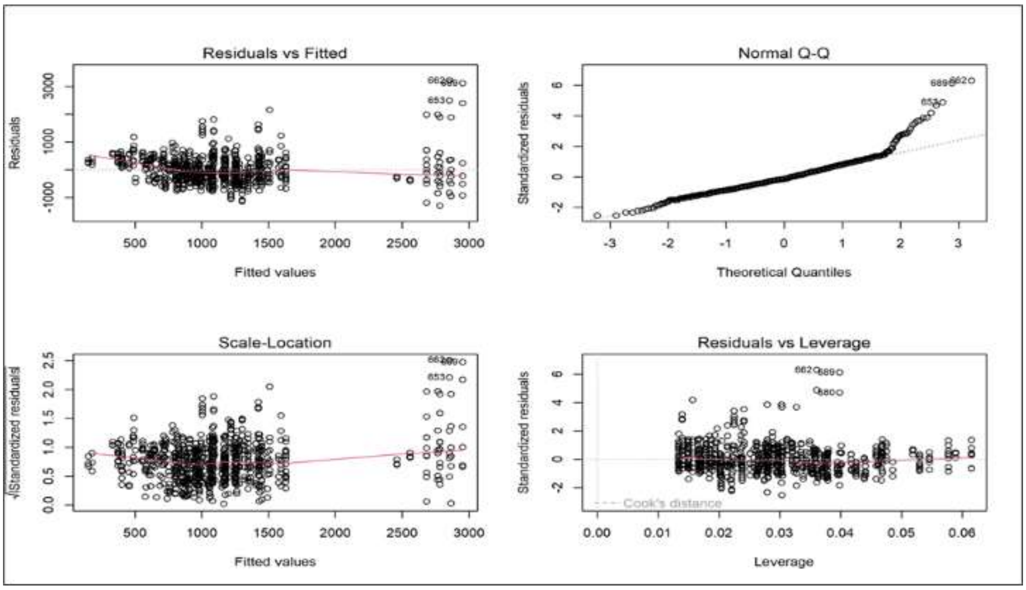
Regression models are used to understand the relationship between a dependent variable and one or more independent variables. In some cases, however, the independent variables can be highly correlated, a phenomenon known as multicollinearity. Therefore, the regression coefficient estimates may need to be more accurate and stable, and it may be difficult to understand how each variable affects the dependent variable. This can also result in inflated standard errors and reduced statistical power, making it more difficult to see the true impact of the independent variables.

A regression model is run on all variables involved and the degree of correlation between the variables is examined to check for multicollinearity. A variance inflation factor (VIF), which shows the degree of correlation between independent variables, can be used to test for multicollinearity. A VIF greater than 5 indicates that multicollinearity may be present. Examining the correlation matrix of the independent variables is another technique to determine if a system exhibits multicollinearity. It can indicate multicollinearity when the correlation coefficient between two independent variables is high (over 0.7). The problem can be addressed by removing one of the strongly correlated variables, combining it into one variable, or using techniques such as principal components analysis or ridge regression. In the above case, the researcher ran a regression model that included all variables and achieved an R-squared of 52%. R-square measures how well the model fits the data, with a higher value indicating a better fit. In this case, the R-squared value of 52% indicates that the model explains about 52% of the variation in the dependent variable. However, this does not necessarily mean that the model lacks multicollinearity. The correlation between the explanatory factors was assessed using a correlation matrix. The presence of multicollinearity was assessed using a plot of the leading diagonal of the inverse correlation matrix reflecting the variance inflation factor (VIF). As shown in the figure below, multicollinearity was significantly affected by VIF values greater than ten on the leading diagonal.



Appendix B: Homoscedasticity checks on a regression model

The idea of homoscedasticity, which refers to the assumption that the variance in errors is constant across all levels of the independent variable, is expected to be followed by several linear regression models. This state is reached when the regression errors vary slightly. A violation of this condition, called heteroscedasticity, means that the model is missing some important explanatory variables and this can lead to unreliable or unstable estimates of the regression coefficients. To assess homoscedasticity, the researcher examined the relationship between the fitted values and the residuals. Ideally, when the residuals fall around zero, the model exhibits homoscedasticity. In addition, a homoscedastic model also has standardized residuals that follow a normal distribution. Once all of this is true, the regression model satisfies the homoscedasticity assumption. Suppose the model does not satisfy the homoscedasticity assumption. In this case, methods such as transformation, adding a weight variable, or using another model such as heteroscedasticity-consistent standard errors should be used to correct. The figure below illustrates the homoscedasticity diagrams.



Appendix C: Model fitted vs Observed values

As a final check, the correlation between model-fitted and observed values was evaluated. It's called a residual plot and is used to test the assumptions behind linear regression. Results were obtained using a scatterplot with a regression line overlay to compare the fitted or predicted values to the observed yields. In general, a positive regression line indicates good agreement between the fitted and observed values. If the points form a pattern, such as a funnel shape or a U-shape, this can indicate a problem with the model, such as nonlinearity, outliers, or omitted variables. In such cases, the points in the scatterplot should be randomly distributed around the regression line with no systematic pattern. The residual plot can also be used to test for homoscedasticity, which refers to the assumption that the variance of the errors is constant across all levels of the independent variable. If the residuals are randomly and patternlessly distributed around zero, the model satisfies the homoscedasticity assumption. If the residuals form a pattern, such as a funnel shape, this could indicate that the model does not meet the homoscedasticity assumption and may need to be corrected. The residuals can be shown to show that the model fits the data well and that the linear regression assumptions have been met. This increases our confidence in the model's results and predictions. The figure below shows the plot.