UNIVERSITY FOR DEVELOPMENT STUDIES, TAMALE

INCREASING YIELDS OF MAIZE (Zea mays L.) AND GROUNDNUT (Arachis hypogea): THE ROLE OF SOME SECONDARY, MICRONUTRIENTS AND CROPPING SYSTEMS

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THESIS SUBMITTED TO THE DEPARTMENT OF CROP SCIENCE, FACULTY OF AGRICULTURE, FOOD AND CONSUMER SCIENCES, UNIVERSITY FOR DEVELOPMENT STUDIES, IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF DOCTOR OF PHILOSOPHY (Ph.D.) DEGREE IN CROP SCIENCE

JULY, 2024

DECLARATION

STUDENT

I hereby declare that this is the result of my own original work and that no previous submission for a degree in this University or elsewhere has been made. All sources of information have been duly cited and acknowledged by reference to the authors.

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Supervisors' Declaration

We hereby declare that the preparation and presentation of this thesis was supervised in accordance with the guidelines on supervision of thesis laid down by the University for Development Studies.

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GENERAL ABSTRACT

Due to the fact that maize and groundnut yields in Northern Ghana and Ghana as a whole are significantly below potential levels, closing yield gap is viewed as a critical part of ensuring a sustainable and reliable food supply to fulfil the anticipated demand.

A comprehensive study was conducted to investigate various aspects of maize production in northern Ghana. The study comprised one socio-economic and agronomic survey and three field experiments. Two, maize nutrient omission on the magnitude and spatial-temporal patterns of maize yield responses to balanced and imbalanced nutrient applications. Three, contribution of secondary and micronutrients (S, Zn and B) fertilization in enhancing yield and yield quality of maize and four, effects on yields of maize groundnut cropping systems based on co-fertilization. These survey and experiments were conducted during 2020, 2021 and 2022 at 4R-NS project sites at Eastern corridor of northern Ghana, the research farms of the CSIR-SARI experimental sites at both Nyankpala and Damongo. In experiment one, the exploitable maize yield gap at farm-level reaches up to 7 t ha^{-1} and less than one percent of the farmer fields could achieve maize grain yield of 4 t ha-^{1}. The results have shown a mean yield of maize less than 1.5 tons ha^{-1} from all the four districts with a wide variation at a farmer level, ranged between 0.25 tons ha^{-1} and 4.0 tons ha^{-1} which proved the possibilities for yield improvement. In experiment 2, nutrient omission trials were conducted on 24 farms located in East Gonja, Kpandai, Nanumba North and Nanumba South selected to be representative of the main soil and management factors in maize based systems of Northern Ghana. Treatments comprised PK, NK, NP, NPK, and NPK plus SMN administrations in addition to a control (no fertilizer). The responses of maize yield to NPK plus SMN treatments showed clear spatial-temporal patterns. The first cropping season showed mean maize yields of 0.9, 1.2, 1.9, 3, 2.9, and 3.6 t ha^{-1}, whereas the second cropping season gave mean yields of 0.4, 0.8, 1.2, 31.9, 2.5, and 3.1 t ha^{-1} across the control, PK, NK, NP, NPK, and NPK + SMN treatments. The third season gave values of 0.5, 0.6, 0.8, 1.2, 1.6, and 1.9 t ha^{-1} in contrast.

In experiment 3, the field was laid in a split plot design with three replications. The main plot factor treatments were two NPK rates: 60, 40, 40 kg ha $^{-1}$ and 90, 60, 60 kg ha $^{-1}$ and the sub plot factor treatments were ten combinations of secondary and micronutrients (sulphur, and zinc and boron) and control (no MN). In Nyankpala, yields of 4.5 and 5.0 tons ha^{-1} were achieved with inclusion of S, Zn and B in both years while in Damongo, yields of 3.26 and 2.58 t ha^{-1} were achieved. For NPK-only treatment, average yields of 2.30 and 2.53 were achieved in Nyankpala for both years while 1.28 and 1.48 were achieved in Damongo.

In experiment four, five cropping systems (*viz.* sole continuous maize (SCM), sole continuous groundnut (SCG), maize-groundnut intercrop (MGI), groundnut/maize rotation (GMR) and maize/groundnut rotation (MGR)), each with or without fertilizer were established under RCBD at Nyankpala during the 2021 and 2022 cropping seasons. The results showed that intercrop and rotation treatments gave significant yields. The land equivalent ratios (LER) for the intercrops were 1.2 and 1.09 respectively, in the two seasons. To optimize soil health and crop productivity, farmers should adopt integrated soil fertility management practices, including: Application of NPK fertilizer supplemented with essential micronutrients like sulfur (S), zinc (Zn), and boron (B). Implementation of intercropping and rotation systems featuring maize and groundnut.These practices will enhance resource use efficiency, mitigate soil degradation, improve soil fertility, and ultimately boost overall productivity.

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DEDICATION

This thesis is dedicated to Almighty God, my late parents and all my teachers both present and past for making me what I am today.

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LIST OF ABBREVIATIONS

Abbreviation	**Full meaning**
AAS	Atomic absorption spectrometer
4R-NSP	4 Right Nutrient Stewardship Project
BA	Boric acid
BCR	Benefit Cost Ratio
CV	Coefficient of Variation
CSIR	Council for Scientific and Industrial Research
CART	Classification and regression tree
CSA	Climate-smart agriculture
EC	Emulsifiable concentrate
ECEC	Effective cation exchange capacity
EDTA	ethylenediaminetetraacetic acid
EEF	Enhanced efficiency fertilizer
EPA	Environmental Protection Agency
FAO	Food and Agriculture Organization
FAOSTAT	Food and Agriculture Organization Statistics
FAW	Fall armyworm
GHG	Greenhouse gas
GYGA	Global yield gag atlas
H.I	Harvest Index
IC	Inter cropping
IFPR	International Food Policy Research Institute
ISSER	Institute of Statistical Social and Economic Research
LAI	Leaf Area Index

LSD	Least Significant Difference
MOP	Moriate of potash
N2O	Nitrous oxide
NPK	Nitrogen, Phosphorous, Potassium
OC	Organic carbon
OPV	Open pollinated varieties
PAR	Photosynthetically active radiation
PCA	Principal component Analysis
PPM	Parts per million
SARI	Savanna Agricultural Research Institute
SDGs	Sustainable Development Goals
SMN	Secondary and micronutrients
SOC	Soil organic carbon
SOM	Soil organic matter
SPAD	Soil plant analysis development
SPSS	Statistical Package for the Social Sciences
SRID	Statistics Research and Information Directorate
SSA	Sub Saharan Africa
TE	Trace elements
VWC	Volumetric Water Content
WAP	Weeks after planting
Zn	Zinc

CHAPTER ONE

INTRODUCTION

1.1: Background

Agro-ecological diversity, erratic and unpredictable weather patterns, poor socio-economic conditions for farmers, and a number of technical constraints that have an impact on the production of maize and groundnuts are all characteristics of Ghana's agricultural sector, which is primarily small-scale and barely commercialized (Godfray et al., 2010). There are fewer options to expand the area utilized for cultivation as a result of growing population. Growing population has also increased the demand for maize and groundnuts as a staple food and cash crop. Due to the fact that crop yields in Northern Ghana and Ghana as a whole are significantly below potential levels, closing yield gap is viewed as a critical part of ensuring a sustainable and reliable food supply to fulfil the anticipated world food demand by 2050 (Van Ittersum et al., 2016). In Northern Ghana, it was found that on average, 20 percent of the potential maize yield of 7 tons per hectare and 38 percent of the potential groundnut yield of 2.5 tons per hectare are produced (GYGA, 2018). The total output of the maize and groundnut has significantly increased over the past few decades. However, the increase in total output has mostly been attributable to the area under cultivation (MOFA, 2010). Despite various government and industry stakeholder interventions, as well as the introduction of improved varieties to farmers, maize and groundnut yields have only slightly increased from 1.3 to 1.8 and 0.9 to 1.5 tons/hectare, respectively (ISSER, 2017)

According to an analysis of the elements that contribute to yield gap, fertilization (time, rate, source, and placement) frequently explains the yield difference for different crops (Beza et al., 2017). Some studies have demonstrated that increasing fertilizer rates alone could close the yield gap by 50 percent (Mueller et al., 2012). Although increased fertilizer use alone has been demonstrated to increase yields in Ghana, innate soil infertility can restrict the yield response (Chapoto et al., 2015; FAO, 2018; Agyare et al., 2014; Sileshi et al., 2010)

Biological and economic constraints are other factors besides fertilization that also affect the yield difference. Other studies have demonstrated that the factors driving the yield disparity might differ significantly between particular farms (Kihara et al., 2015; Mueller et al., 2012; Silva et al., 2018). Furthermore, technical efficiency of maize and groundnut producers also points to a wide range of variables that explain variations in farmer yields, such as seed input, fertilization, labour, cultural practices, farmer experience, age, education, and access to credit. While various methods, such as models and surveys, have been widely used in different countries to identify the causes of yield gaps (Rattalino Edreira et al., 2017; Silva et al., 2017, 2018), field experiments have not been explored as a complementary approach to analyze these gaps. It is anticipated that combining these methodologies with other levels of analysis, such as field and farm level data, will offer pertinent insight into the variables causing yield discrepancies. Because there is still potential for improvement, steps could be taken to raise yields among small-scale farmers in the nation by identifying and targeting the right influencers. One of the key strategies for boosting food production is sustainable agricultural intensification (Van Ittersum et al., 2016), particularly in densely populated areas where the ability to develop agricultural land is constrained. In addition, as shown in Northern Ghana, agricultural land is becoming more and more difficult to find as a result of population growth, modernization of agriculture coupled with high land demand due to the increased of area put under cultivation and rivalry with other forms of economic activities. To enhance agricultural output in Northern Ghana, new agricultural management techniques must be implemented. These techniques include the dibble and bury method of fertilization, enhanced irrigation, and improved cropping patterns such as crop rotation. In order to boost agricultural productivity over the previous few years, the fertilizer application rate has increased. However, due to crops continuously removing nutrients from the soils without reintroducing them to the soils, the current fertilizer types and suggested rates have become obsolete. Fertilizers also have a negative impact on both the atmosphere and the terrestrial environment, which is a major worry. The use of nitrogenous fertilizers (N-Fertilizer), in particular, has a significant impact on soil health, underground water quality and soil N_2O emissions. The overuse of nitrogenous fertilizers has led to soil acidification, water pollution, soil salinization, and the emission of greenhouse gases (Ju et al., 2009). Previous researches have demonstrated that fertilizer increases the amount of N_2O that agricultural soils emit (Roche et al., 2016, Liu et al., 2011).. Strategies that can slow down climate change or encourage adaptation to its effects are urgently needed to ensure sustainable development.

Quantifying the diversity in soil fertility status and related responses to nitrogen treatments is crucial for creating a more robust, long-lasting, and efficient method to fertilizer recommendation that targets particular field circumstances or growing environments. The most efficient and straightforward method to explore these variances in reaction is through heterogeneous farmers' fields, which can be found both on-station and across many locations.

A crucial factor in the poor and deteriorating yields of maize and groundnuts, according to the 4R-NSP base line and agronomic survey results, was a lack of sufficient nutrients. Therefore, it was advised to promote the 4R principles for a few crops, like groundnut and maize which are frequently grown by women, rather than concentrating on just one product, in order to increase gender inclusivity. In this regard maize is found to be a staple food crop which is cultivated by every household and groundnut also found to be cultivated by women.

This study which seeks to employ some secondary and micronutrients to improve grain yield of maize and groundnut is a build-up on the findings of, baseline and agronomic survey conducted in farmers' fields from the 4R-NSP and on-farm and on-station nutrient omission trials (NOTs) during 2020 farming season.

1.2: Problem Statement

In Northern Ghana, maize and groundnut yields are significantly below potential levels, resulting in a substantial yield gap. Despite various interventions, yields have only slightly increased, and the current fertilizer types and recommended rates have become obsolete. The overuse of nitrogenous fertilizers has led to environmental concerns, and there is a need for sustainable agricultural intensification strategies. Adopting intercropping and rotational systems with maize and groundnut may also offer a solution to improve soil fertility and boost groundnut productivity, thereby enhancing food security and livelihoods of smallholder farmers, particularly women.This study aims to investigate the effects of employing secondary and micronutrients on grain yield of maize and groundnut, building on the findings of previous baseline and agronomic surveys, and on-farm and on-station nutrient omission trials.

1.3: Study Justification

By the year 2050, there will be about 9.22 billion people on the planet (Ray et al., 2013). In order to combat population pressure, climate change, and water imbalance, food production must be improved on the limited amount of arable land available. Maize and groundnut have been an important staple foods in Ghana for many decades. As the country's population rises, there is the need for an increased production of these key food crops. Crop yields in Northern Ghana and Ghana as a whole are substantially below attainable levels, so narrowing yield gap is crucial for ensuring a sustainable and reliable food supply. This is a concern since many places in Ghana, where productivity is highly variable and yields are poor, have stagnated in recent years.

Over past decades, maize sector has seen tremendous increase in output. The increased output, can be attributed to an increase in the area under cultivation. Despite multiple initiatives by the government and industry players, as well as better varieties offered to farmers, maize yields have only increased moderately from 1.3 to 1.8 tons per hectare, and therefore solution to the problem is needed.

1.4: General expected research results and relevance for stakeholders.

The research aims to generate results that:

1. Provides policy makers with insights into maize performance determinants and how they are linked to policy and donor interventions.
2. Assisting farmers and rural people by giving information and education on how maize output in the target region can be enhanced (using on-farm demos and active dissemination and extension actions to share practical knowledge).
3. Contributing to capacity development in agronomic research, policy making and other supply chain stakeholders.

1.5: Main objectives of the study

The overall objective of the study is to achieve enhanced sustainable maize and groundnut production through participatory soil fertility and cropping system diagnosis and the specific objectives are to:

1. Assess and identify key yield limiting factors of maize in the predominant maize groundnut smallholder cropping systems of Northern Ghana through a comprehensive agronomic survey;
2. Elucidate on the effects of Sulphur, Zinc and Boron;
3. Quantify yield response patterns of maize to the secondary and micro nutrients inclusion in fertilizer blends;
4. Improve site-specific fertilizer use recommendations for maize and groundnut;
5. Assess the effect of different cropping systems of maize - groundnut on the grain yield of maize.

1.6: Hypotheses of the study

Based on the research objectives and literature review, the following hypotheses are formulated:

1. It is hypothesized that intercropping maize and groundnut will improve soil fertility and increase groundnut yields compared to monocropping.

2. It is expected that rotational systems with maize and groundnut will enhance soil nutrient availability and boost groundnut productivity.

3. The application of secondary and micronutrients is expected to increase grain yields of maize and groundnut compared to the use of conventional fertilizers.

4. It is hypothesized that intercropping and rotational systems with maize and groundnut will reduce the need for nitrogenous fertilizers, thereby minimizing environmental concerns.

5. The combination of intercropping/rotational systems and secondary/micronutrient application is expected to have a synergistic effect on maize and groundnut yields, leading to improved food security and livelihoods for smallholder farmers.

1.7: Thesis chapters overview

There are eight chapters in this thesis. This chapter (one) provides an overview of the issues surrounding the production of maize and groundnuts in smallholder farming systems in northern Ghana, as well as an analysis of the potential contributions of cropping systems and fertilizer to increased crop productivity in these systems. Chapter two literature review is a comprehensive and systematic analysis of existing research and scholarly writings on a specific topic or research question. Chapter three is the methodology which is the systematic and scientific approach used to conduct research, including the methods, procedures, and techniques employed to collect, analyze, and interpret data.

Chapter four focuses on understanding the socio-economic setting and characteristics of farms and farming households involved in maize production in northern Ghana. Assess current crop and nutrient management practices and productivity.

Chapter five evaluates maize nutrient omission with the objective, to assessing the extend and spatio-temporal patterns of maize yield responses to balanced and imbalanced nutrient applications. The chapter also evaluate the effects of balanced and imbalanced nutrient applications on yield and yield quality and effects of balanced and imbalanced nutrient applications on soil nutrient balances.

Chapter six evaluates the contribution of secondary and micronutrients (S, Zn and B) fertilization in enhancing yield and yield quality of maize with the objectives to identify the main secondary or micronutrient limiting maize yields in northern Ghana and assess the potential for profitability of different combinations under heterogeneous smallholder farming conditions.

Chapter seven investigates maize and groundnut cropping systems to evaluate feasible options for enhancing crop productivity. This is to enable the evaluation of yield, economic, and resource use benefits associated with improved fertilizer management in maize and groundnut cropping systems with the potential objectives of quantifying yield benefits related to co-fertilization. Also, to assess the opportunities for enhancing nutrient use efficiency in maize and groundnut cropping systems for enhancing farm productivity.

Chapter eight provides a comprehensive synthesis of the key findings from Chapters four to eight. This final chapter concludes with a summary of the main conclusions, recommendations and future research and proposals, followed by the References and Appendices.

CHAPTER TWO:

LITERATURE REVIEW

2.1: Overview of maize production in Northern Ghana.

Maize is the main staple crop in northern Ghana, grown primarily by smallholder resource-poor farmers under rain-fed conditions and consumed by a large number of households. Coastal savannah zone, forest zone, transition zone, and Guinea savannah zone are a few of Ghana's agro-ecological zones where the crop thrives. The need for maize as a primary food crop is increasing as the world's population grows, and opportunities to extend the areas dedicated to its cultivation are rapidly dwindling.

Maize (zea mays) yields are well below attainable levels in Northern Ghana as a whole, so closing yield gap is critical for securing a sufficient and reliable food supply (Godfray et al., 2010; Van Ittersum et al., 2016). This is a problem where productivity is very unpredictable and maize yields are low, with many areas experiencing recent stagnation (MOFA, 2010). According to projections by (GYGA, 2018), just 20% of Ghana's out potential of 7 tons per hectare of maize (Zea mays) productivity could be achieved by 2050. The maize sector has seen a significant growth in output during the last few decades, however, rather than yield, the rise in recorded output can be attributable to greater area under cultivation. Despite various interventions by the government and stakeholders in the sectors, as well as improved varieties provided to farmers, maize yields have only grown modestly from 1.3 to 1.8 tons per hectare (MOFA, 2010). According to Beza et al., 2017, a review of yield gap explanation factors found that fertilization (time, rate, source, and place) often explained the yield difference for many crops in Sub-Saharan Africa (SSA), especially maize. However, according to Mueller et al., (2012) increasing fertilization alone might close the yield gap in Sub-Saharan Africa (SSA) by 50%. Increased fertilizer use has been demonstrated to boost yields in Ghana, however low soil fertility can limit yield response (Chapoto et al., 2015). Fertilizer use in Ghana is currently low (on average 5 kg N ha^{-1}), owing to the risk associated with relatively high fertilizer prices in relation to the unpredictability in yield improvements (FAO, 2018; Agyare et al., 2014; Sileshi et al., 2010).

Apart from fertilization, other factors that contribute to the yield gap include biotic and economic constraints (Kihara et al., 2015, Silva et al., 2018). Other studies have found that the factors driving the production difference might differ significantly between farms. Other factors that explain yield discrepancies among farmers, including seed input, agrochemicals, fertilization, labor, cultural practices, farmer experience, age, education and access to credit facilities.

According to (Van Ittersum et al., 2016), sustainable agricultural intensification is considered as one of the key techniques for improving maize output in densely populated areas where agricultural land expansion is constrained. Furthermore, as shown in Northern Ghana, arable farmland is becoming increasingly scarce as a result of population growth, agricultural modernization such as mechanized farming which led to the cultivation of large acreages of farm lands hence the demand, and competition from other economic activities.

Numerous methodologies can be used to analyze the causes of yield disparities, according to (Rattalino Edreira et al., 2017; Silva et al., 20 17, 2018). However, models and surveys have been the most often used. However, field investigations have yet to be combined with these methodologies. When these approaches are combined with different levels of research, such as field and farm level data, they should provide useful insight into the variables that explain yield disparities. As a result, two on-farm and two on-station experiments on agronomic survey, nutrient omission trials, secondary and micronutrient inclusion and cropping systems were important to investigate the reasons of yield differences and propose methods to bridge the gaps.

2.2: Maize as a mainstay crop in Northern region of Ghana

In the northern part of Ghana, where white maize is cultivated primarily for human food, very little yellow maize is produced. Roughly 87% of the maize produced is consumed locally, according to WABS (2008). In 2020, Ghana's per capita consumption of maize was 75.91 kg annually, up around 3% from the year before, according to a report released by the Ministry of Food and Agriculture's (MoFA, 2020), Statistics Research and Information Directorate (SRID). Forty percent of the harvest is traded, either formally or informally, while the remaining seventy-seven percent is consumed directly by farming households. Only a small percentage (about 13%) of the maize produced in the poultry industry gets fed to animals.

2.3: Economic importance and constraints of maize production in Ghana

The maize sector of Northern Ghana makes a considerable contribution to the country's economy, both upstream and downstream of the processing industries (MoFA, 2021). Producers or farmers, governmental entities, and agribusinesses make up the maize industry.

Maize's importance in Northern Ghana for both food security and income cannot be overstated. Although maize is mostly grown by smallholder farmers for household consumption, it has recently become a vital input for the poultry industry. Maize is a key source of calories in Ghana, and has even overtaken sorghum and pearl millet as traditional staple crops in the north (MoFA, 2020).

For the majority of Ghanaians, maize cultivation is a key source of food, making it crucial for maintaining household food security in Ghana (FAO, FAOSTAT, 2008). Maize ranks first as

Ghana's most important cereal produced and consumed. Food production in Ghana and Sub-Saharan Africa (SSA) as a whole should be tripled by 2050 to meet estimated food demand and therefore urgent measures are needed to bridge the yield gap.

In Ghana, practically, every portion of the maize crop is economically significant. That is, a variety of food and non-food items, such as a fire source for cooking, can be made from the grain, cob, leaves, tassel, and stalk of the plant. For most Ghanaians, maize is a staple food, hence its production is essential to the nation's household food security. A common grain for feeding livestock and poultry, maize also serves as a substitute in the brewing sector.

The yields from maize farms in northern Ghana are among the lowest, despite the industry's economic benefits. Ghana's current yields are 1.73 metric tons per hectare and 1.92 metric tons/ha, respectively, based on statistics from IFPRI and MoFA. Moreover, smallholders who produce more than 70% of Ghana's maize crop are disadvantaged by poor yields since they do not have access to the resources needed to boost productivity. Ghana's low maize yields lead to low output, which falls short of industry demand.

In an ideal world, this would lead to higher prices for farmers who grow maize; however, in Ghana, resource-poor farmers cannot hold onto their produce and wait for better prices in the future, which prevents them from making the most of the resources they invested in growing maize. This and other factors make producing maize undesirable to farmers, forcing them to scratch out a livelihood, restricting supply, and widening the already existing imbalance between the demand and supply of maize, especially for domestic use and the poultry industry. Due to Ghana's reliance on maize as a grain for food security, food insecurity would result from the ongoing supply shortage, making it impossible for the nation to achieve the Sustainable Development Goals (SDGs) of ending hunger and poverty. It is therefore decided to look at the profits and profit efficiency of Ghanaian maize farmers. In addition to price increases, resource-poor farmers should have other options to boost their profits and enhance production efficiencies. This is how maize production can become a source of jobs in Ghana.

2.4: Groundnut production in Northern Ghana

Ghana ranks among the top six African nations in terms of groundnut production (Essilfie et al., 2020). Nearly all farming communities in Northern Ghana and the transitional zone grow groundnut. According to estimates, more than 70% of farmers in Ghana's five Northern regions grow groundnuts, which together account for more than 85% of the country's output (Technoserve, 2009). Groundnut is known as the woman's crop in Ghana and the rest of West Africa due to the considerable contributions that women make to its production, selling, and processing. They engage in farming, trading, and sporadically physically demanding activities like planting, harvesting, and shelling (Dokurugu, 2015). Between 2003 and 2007, the nation produced 439,930 metric tons annually on average. It increased to 565,000 metric tons in 2020 (SRID 2021). Ghana's Upper East, Upper West, Northern including North East and Savanna regions and portions of the Bono region is notable groundnut-growing regions. These growing areas are the places with the highest rates of food insecurity, though 67% of the workforce are involved in agriculture. In the Brong Ahafo, Northern, Upper East, and Upper West regions, respectively, it is estimated that 17%, 57%, 72%, and 78% of households are involved in groundnut production. Therefore, any program for reducing poverty that incorporates groundnut promotion into its strategies may have a high chance of having greatest impact (ODI, 2005).

2.5: Economic importance and constraints of groundnut production in Northern Ghana

Groundnut is one of the most prominent edible crops in the world, and contains vegetable protein, fat and oil, and carbohydrates amounting to 20-50 %, 40-50 % and 10-20 % respectively (FAO, 2006). According to Mukhtar (2009), groundnut is the 6th most important oil seed crop in the world and contains 48-50 % oil. Most Ghanaian societies use groundnut in preparing stews, soups, and cereal mixtures (Asibuo et al., 2008). Groundnut is sometimes processed into groundnut cake by most industrial oil processing centers for human and livestock consumption (Awuah et al., 2009). Groundnut is a readily saleable crop that provides income and livelihood support to farmers. From the agro-ecological point of view, groundnut is cultivated largely in the northern savannah zone in Ghana. Groundnut production in Ghana is largely subsistence-based and usually cultivated by peasant farmers. The production of groundnut provides income to households (Abu, 2015) as well as multiple nutrients to consumers. Groundnut rotated with cereals such as sorghum reduces the density of striga infestation (Onwuema and Sinha, 1991). Groundnut as a legume, also has the ability to utilize residual fertilizers (Milla, 2003). Planting is done as soon as there is consistent/adequate moisture usually from late May to end of June (Dokurugu, 2015). According to statistics from MoFA (2021), there were 337,000 hectares of land cultivated with groundnut in Ghana in 2016 with a 565,000-ton yearly yield, resulting in a groundnut yield of 1.3 tonnes on average per hectare, which is less than the 2.5 tonnes per hectare target output.

Groundnuts are picked by hand using hoes to dig the nuts from the soil, which are then transported home with the vines. In situations where there are no rains or the rains stop too soon, pods are lost because the soil become hard and difficult to dig.

To minimize moisture and aflatoxin levels before storage (often in bags), the collected pods are sun dried (Tsigbey et al. 2003). According to Tanzubil (2016), key obstacles to groundnut farming in northern Ghana include pests and diseases, which cause significant output losses. Groundnut rosette viral disease (GRD), which causes yearly losses of US$156 million in Africa, is one of the main inhibitors of groundnut production (Nigam et al., 2012). The vegetative phase at which infection occurs determines the amount of yield loss caused by the rosette; if seedlings contract the infection, a 100% yield loss may result, however an insignificant effect may result if the infection occurs during the pod-filling phase (Waliyar et al., 2007). Spodoptera, thrips, and aphids are the main pre- and postharvest insect pests that significantly reduce groundnut production's economic gains. In Ghana's Tolon district, where farming is the primary economic activity, the majority of households grow groundnut as an important cash crop. Groundnut is crucial to reducing poverty since it supports household income and food security in the district. Despite its importance, the crop is not produced enough to meet market demand, and the current smallholder farming systems do not provide sufficient information on the crop's profitability. This condition is linked to several factors, including high production costs, a lack of awareness of cost structures, low per-capita income, bad storage, poor transportation, and subpar marketing services (Girei et al., 2013). Finding solutions to lower production costs and consequently raise the crop's profitability in the district will be made easier with a good understanding of the groundnut industry's cost structure if the cost of producing a product is constantly more than the profits it makes. This can be achieved by employing more efficient weed and pest management, improve your farm machinery, boost your yield gains, optimize your fertilizers and reduce disease with regular rotation. As a result, household income and food security will improve. Because groundnut fixes nitrogen, when added in crop rotation and mixed cropping systems, its cultivation enhances farming systems. Thus, the study's goals included estimating the costs and returns of groundnut production in order to assess profitability, and pinpointing issues that groundnut farmers faced in the study area.

CHAPTER THREE:

METHODOLOGY

3.1: Mixed-Methods Approach and Study Design

This thesis employed a mixed-methods research design, incorporating common methods used across the manuscripts. Specifically, Manuscript 4 utilized qualitative, whereas Manuscript 5 to employed qualitative. For a detailed description of these methods, please refer to the respective manuscripts.

3.2: Description of Study Areas and Agro-Ecological Setting

The on-farm study was conducted in farmer fields at Nanumba North, Nanumba South and Kpandai districts in Northern region as well as East Gonja district in the Savannah region of Ghana. The Savannah Agriculture Research Institute (SARI) experimental fields at Nyankpala and Damongo served as the site for the on-station studies.

Nyankpala is located in the Tolon district of the Northern region while Damongo found in West Gonja district of the Savannah region. All these districts were focal districts for the implementation of the 4R Nutrient Solutions Project (NSP) which had the ultimate aim of enhancing crop productivity in smallholder farming systems in Northern Ghana.

Small-scale crop production is practiced in these locations, with the primary staple crops of the area being groundnuts (*Arachis hypogea* L) and maize (*Zea mays* L.).

Due to mono modal rainfall patterns and very shallow soils, the agro-ecological potential for crop production is minimal. The erratic weather in this part of the nation has a detrimental effect on the efficiency of the agricultural sector. However, continuous farming practices that use little to no nitrogen input have caused a considerable nutrient depletion, which has had a detrimental influence on soil fertility over a wide area. Farmers also have limited market access and a little marketing margin share (Angelucci et. al, 2013). Low living standards have been influenced by several issues. Although poverty in Ghana is mostly a rural concern, Savannah's rural areas are the hardest hit. About two-thirds of the country's overall cases of extreme poverty were recorded by this region (GSS, 2005–2017).

CHAPTER FOUR

CHARACTERIZATION OF SMALLHOLDER MAIZE CROPPING SYSTEMS IN NORTHERN GHANA

Abstract

The study aimed to identify and quantify the primary factors limiting or enhancing maize yields in smallholder farming systems in Northern Ghana. Detailed socio-economic and agronomic surveys were conducted among households and farms, and data were collected from 240 maize farms across four districts - East Gonja, Kpandai, Nanumba North, and Nanumba South during the 2020 cropping season. The results showed that actual maize yields were low, with a mean of less than 1.5 tons ha $^{-1}$, and varied widely among farms (0.25 - 4.0 tons ha $^{-1}$). The exploitable yield gap at farm-level was up to 7 tons ha $^{-1}$, indicating significant potential for improvement. However, less than 1% of farms achieved yields above 4 tons ha $^{-1}$. Key management practices, such as land preparation, seed choice, planting timing, pest management, and nutrient management, were critical in bridging the yield gaps.

The study highlights a need for improved crop and nutrient management techniques to increase maize production, close yield gaps, and enhance food security in Northern Ghana's smallholder farming systems.

4.1: Introduction

Rural livelihoods in Northern Ghana are mainly agro-based and are highly reliant on crop output in the predominant smallholder farming systems (Owusu et al. (2011). But low yields in the common cereal-legume cropping systems characterize crop production in these farming systems (ISSER, 2006). For instance, actual yields of maize, one of the region's principal cereal crops, are often significantly lower than yields achievable with the best crop and nutrient management techniques. According to Owusu et al. (2020), mean actual yields of maize are 2 tons per hectare, whereas feasible yields are 7 tons per hectare. As a result, these cropping systems are characterized by large yield gaps, defined as the difference between real yield and achievable yield (Cassman et al., 2003). Low yields in these predominantly rain-fed cropping systems are related to low and variable rainfall, insufficient nutrient inputs, inefficient nutrient application methods, inadequate weed and disease management practices, and limited utilization of improved crop varieties (Docs et al., 2001). Existing yield gaps in these cropping systems indicate a large potential to substantially increase yields once key limiting agronomic constraints are addressed (Tollenaar and Lee, 2002). While the link between sub-optimal crop and nutrient management methods and final crop yields is generally acknowledged, a precise quantification of the exact influence of various yield-reducing factors on final yields is frequently lacking, especially among smallholder farmers (Cassman et al., 2003). Furthermore, the specific effects of such yield-reducing factors are likely to differ depending on crop type, cropping techniques, and farm-specific attributes. Given the resource constraints that majority of smallholder farmers in Northern Ghana face, implementing a full range of recommended crop and nutrient management strategies on a one-off basis is typically out of reach. A staggered adoption strategy whereby farmers address the main yield reducing factors first, then gradually embrace additional yield reducing factors as yields and incomes increase, may be a more practical method to increasing crop production in these farming systems. For such an approach to succeed, it is critical that the key nutrient and crop management factors limiting crop yields are first identified and quantified. This study therefore sought to use detailed socio-economic and agronomic surveys to characterize smallholder maize farming systems in Northern Ghana, and identify and quantify key farm level factors limiting maize productivity. The study specifically sought to: (i) characterize the socio-economic setting and structural composition of smallholder maize households in Northern Ghana, (ii) assess and quantify the frequency and size of yield gaps in smallholder maize cropping systems, (iii) document and quantify the influence of current crop and nutrient management practices in maize yields in smallholder farming systems, and (iv) identify opportunities for enhancing maize productivity.

4.2: Methodology

4.2.1: Study site

The study was carried out in the Northern region of Ghana, as part of the agronomic component of a project named “4R Nutrient Stewardship Project (4R NSP)”, and included sites in the districts of Kpandai, East Gonja, Nanumba North, and Nanumba South. The Kpandai district is centered in a latitude of 8.44°N, a longitude of 0.03°W, and an elevation of roughly 181 meters above sea level. East Gonja district is centred at a latitude of 8.57° N, a longitude 0.67° W, and at about 110 m above sea level. Nanumba North district is centred at a latitude of 8.97° N, a longitude 0.11° W, and at about 156 m above sea level. Nanumba South district is centred at a latitude of 8.81° N, a longitude 0.04° E, and at about 151 m above sea level. Each of the districts is further divided into lower administrative levels commonly referred to as “Communities”, with a total of 282, 72, 72, and 147 communities in Kpandai, East Gonja, Nanumba North, and Nanumba South respectively.

The region is characterized by high daytime temperatures throughout the year, with temperatures of up to 41°C recorded during the hottest months and 16oC during the night and mornings of the dry cold Harmattan. The region experiences mono-modal rainfall pattern between April and September with total annual rainfall ranging between 1,050mm to 1,500mm. The rainfall pattern is characterized by irregularity and variability in terms of onset, duration, and total amount of rainfall. Typical soil types within this region include ochrosols, savannah glycols and ground water laterite. The districts have a savanna vegetation characterized by: Grasslands with scattered trees, woodland savannas, shea butter, and mango trees, guinea savannas with mixed grasses and trees

In all the four districts, majority of the population practices a rural agricultural-based lifestyle, in which about 80% of households practice small-scale mixed farming as the main source of livelihood (Etwire et al., 2019). Typical agricultural farm holding per family is 6 ha, with land ownership typically passed down through inheritance, while additional land for cultivation can be obtained through allocations by community leadership. Key crops cultivated include cereals such as maize, sorghum, millet, and rice; root crops such as yam and cassava; legumes such as groundnuts; and tree crops such as cashew and mango. Crop production in the region is however largely characterized by minimal use of inputs, and limited mechanization, with hoes and cutlasses the primary tools used in farming after tractor or bullock has been used to till the land.

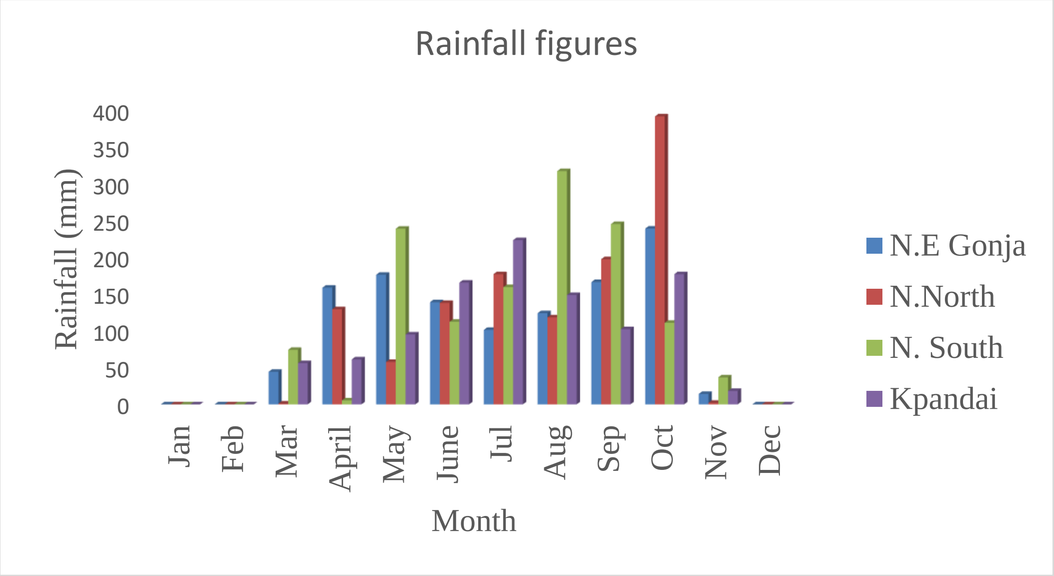

Figure 4. 1: Monthly rainfall in the four study districts in the 2020 cropping season.

Source: District Department of Agriculture meteorology stations.

4.2.2: Selection of survey households

The location of survey households was largely guided by the location of Nutrient Omission Trials (NOTs) previously established by the 4R NSP project within the target study districts. Before the 2020 cropping season began, NOTs were set up at 24 sites, six of which were in each of the four districts. These sites were indicative of the research area's overall agricultural conditions. Established NOTs aimed at assessing attainable maize yield, and the key nutrients limiting maize yields in the study area. In summary, the NOTs included a set of six treatments including a control (All nutrients omitted), P + K (N omitted), N + K (P omitted), N + P (K omitted), N + P + K (S, Mg, Zn & B omitted), and N + P + K + S + Mg + Zn + B (NPK + SMN) treatments (Table 1) established in plots measuring 10 m by 10 m. Each site served as a complete block (one farm-one replicate design).

Table 4.1: Treatment design and rates of fertilizer application in on-farm (n = 24) NOTs in the Northern Ghanaian districts of Nanumba North, Nanumba South, Kpandai, and East Gonja.

Treatment	Nutrient (kg ha^{-1})						
	N	P	K	S	Mg	Zn	B
Control	0	0	0	0	0	0	0
PK	0	60	60	0	0	0	0
NK	120	0	60	0	0	0	0
NP	120	60	0	0	0	0	0
NPK	120	60	60	0	0	0	0
NPK, S, Mg, Zn,	120	60	60	13.5	10	1	0.5

Selection of survey households was subsequently based on purposive stratified sampling with each NOT site serving as a reference site for the selection of a minimum of 10 and a maximum of 12 maize cultivating households within a 5 km radius of NOT site. This was aimed at ensuring similarities in growing conditions between surveyed farms and NOT sites, proving room for using yields attained under the full nutrient application treatment in the NOTs (NPK + SMN), as benchmark attainable yields. Stratified sampling of survey households was achieved by starting from the location of each NOT site, and then selecting maize cultivating households at a radius of 5 km from each 4R demo by skipping an initial five households from the NOT site, and another five households from the previously sampled household. Where the selected household did not have maize under cultivation, the next household with maize cultivated was selected. Selection of survey households was conducted in two opposite directions from the location of each NOT site to ensure that all selected households were within the 5 km radius. A total of 248 households were selected for the survey, including 60, 64, 64, and 60 households in Kpandai, East Gonja, Nanumba North, and Nanumba South districts respectively.

4.2.3: Socio-economic and agronomic surveys

For each selected farm, a detailed socio-economic and agronomic survey was conducted in the main field where maize was cultivated. Relevant data was collected using questionnaires and observations by trained enumerators conversant with local farming systems and languages. Data collection was conducted over the course of two visits by the survey team between September to November 2020. To obtain reliable information, the first visit was conducted a few weeks after all crop and nutrient management practices had been completed, with the second visit coinciding with harvesting. Data was collected relating to sections of the farm identified by the farmer as their main maize field.

Socio economic data collected aimed at household characterization based on the demographic composition and key economic activities of surveyed households. Agronomic data collected aimed at characterizing the cropping systems based on typical agronomic practices conducted, and on key farm level constraints to maize production. In addition, the agronomic survey also included yield measurements by the survey team. This was conducted during the second visit which was timed to coincide with the harvesting period. During the first visit, data related to the following categories was collected;

1. Farm household characteristics such as, farm location (District and community), farmer details (name, age, marital status, gender, occupation), GPS coordinates of the field.
2. Farm characteristics and farming systems, such as, total field size, and major constraints to maize production.
3. Crop management practices conducted in the current season such as manure and fertilizer application patterns (types, quantities, and application frequency), weeding methods and frequency, herbicide application patterns (type and frequency), pesticide application patterns (type and frequency), other local disease and pest control patterns employed.
4. Status of current maize crop in terms of disease, weeds, and pest infestation based on a pre-set ranking schedule in the questionnaire.

Data collected to characterize households and cropping systems was informed by the results of prior studies e.g., (Timler et al., 2014), the knowledge of local experts, study objectives, and overall goals of the main project.

4.2.4: Collection of soil samples and analysis

A general assessment of the important physical and chemical characteristics of the soils in the study site was intended by the soil sample collection and testing. This was conducted for a subset of twelve randomly chosen fields where the agronomic survey was implemented, with three fields selected in each of the four study sites. Selected fields represented about 5 % of all surveyed fields. This relatively small sample was influenced by limitations in resource for supporting soil analysis. The sample was however deemed adequate for general characterization. Soil sampling was conducted by collecting five sub-samples from the demarcated section in each field following the ‘zigzag sampling approach’ described by (Smith, J., & Atkinson, D. (1975)). An Edelman auger was used for sampling, and the depth ranged from 0 to 20 cm. To make a composite sample, all five sub-samples were put in a basin and well mixed. Two 500 g subsamples were then gathered and put in sampling bags with labels plainly visible. Composite samples were air dried and passed through a 2 mm sieve prior to analysis at the Soil Research Institute in Kumasi, Ghana. The pH electrode method was used to measure the pH of the soil in water at a ratio of 1:2.5, and the modified hydrometer method was used to measure the soil texture (Van Reeuwijk, 1995). Soil organic carbon was determined using the Walkley-Black Method (Walkley and Black, 1934), while available P was determined using the Bray 1 method. Exchangeable K was determined by flame photometry, while exchangeable Ca and Mg were determined by the EDTA complexometric titration method.

4.2.5: Management of NOT sites

All NOT sites were researcher established and managed. N was given in the form of urea in two equal portions, two weeks and six weeks after planting. At two weeks following planting, P and K were added in the forms of triple superphosphate (TSP) and muriate of potash (MoP), respectively. Sulphur and Magnesium, and micronutrients such as Zinc and Boron were supplied at two weeks after planting in the form of Magnesium Sulphate (MgSO4), Zinc Sulphate (ZnSO4), and Borax. The hybrid lake maize variety was planted at each site with two seeds per hole at the prescribed spacing of 80 by 40 cm, resulting in a planting population equal to 62,500 plants Per hectare. Experimental plots were kept weed free through two weeding operations using pre-emergence herbicide immediately following sowing, and through manual weeding at approximately six weeks after planting (prior to top dressing).

4.2.6: Yield assessment

Yield assessment aimed at determining the actual maize yields attained by farmers in surveyed fields, and the attainable yields in the study area following best nutrient and crop management techniques in NOT plots with all nutrients supplied (NPK + SMN). For the surveyed fields, two 4m X 4m areas of the field with maize that were grown in a way that was typical of overall growth conditions in the entire maize field were identified during the first visit and demarcated using twines. During this first visit, visual assessment of the status of the crop in each of the two demarcated sections was conducted to quantify aspects such as: weed severity, disease and pest infestation status, and general status of crop growth using ranking scores provided in the survey tool. Farmers were subsequently, requested to reserve the demarcated sections for joint harvesting with researchers during the second visit. For the NPK + SMN treatment plot, a 3.2 m by 3 m net plot with four center rows was marked out. Harvesting for both the survey fields and NOT plots was conducted following physiological maturity of maize. Harvesting was conducted by cutting all plants at the ground level. Following harvesting, the overall weight of the cobs was calculated and the number of plants and cobs totalled and recorded. Five representative cobs were then shelled, and the grain moisture content determined by drying the grain to a constant moisture content of 12 percent. For the surveyed fields, data from the two harvest sections were then aggregated, and variables such as dry matter yield and planting density at harvest were computed on a per hectare basis. The same variables were also determined for the NPK + SMN plot based on data collected from the net plot.

4.2.7: Data Analysis

Data analysis was conducted using the Statistical Package for Social Science software, (SPSS, Version 19) based on quantitative analytical techniques such as descriptive statistics, frequencies, percentages, and cross-tabulation. All output indicators were estimated using summation. The baseline values for all other intermediate indicators were estimated using either arithmetic mean as a measure of central tendency or ratios expressed as a percentage. Data visualization was conducted using figures developed in R (R Core Team 2022).

To evaluate actual farm level maize yields, farm level yield data was sorted in increasing order and plotted per district. Lines showing the mean attainable yields for each district were superimposed on the yield graphs to illustrate the frequency and magnitude of yield gaps under current cropping practices. To assess the influence of crop and nutrient management practices employed by farmers on maize yield, linear mixed effects approaches with maize grain yield as the dependent variable and crop and nutrient management practices as response variables were constructed using the 'lme4' package in R, with community included as a random factor. Response variables included variety, planting time, fertilizer use, fertilizer application frequency, weeding frequency, and cropping practice. To assess the utility of select crop growth status parameters in explaining observed maize yields, The R software's "rpart" (Therneau et al., 2017) and "rpart.plot" (Milbrow, 2017) packages were used to perform classification as well as regression tree (CART) analysis, with anova selected as the method of splitting branches. For these regression models, maize yield data was subset into data from monocrops or intercrop systems to account for differences in cropping practices. These datasets were then sequentially used for the CART analysis with maize yield set as the dependent variables, while select crop growth and status parameters assessed or measured prior to or at harvesting included as explanatory variables. Variables used included weed, pest and disease status, the number of plants at harvest, as well as the cob to plant ratio. The regression analyses were set up to include only the factors that significantly ($p<0.05$) influenced yield in the final CART models results

4.2.7.1: Principal component analysis

For the classification, a selection of candidate variables, including those related to households, employment, land use, food security, and income, was obtained using principal component analysis (PCA) (Table 1). PCA is a method often use to reduce large data into smaller one that still contains most of the necessary information in the larger set. The dataset based on candidate variables was carefully checked by analyzing missing data and identifying probable outliers to avoid distortions in the statistical analysis.

4.3: Results

4.3.1: Socio-economic setting and composition of surveyed households

4.3.1.1: Household characterization

Majority (>87%) of surveyed households were male-headed with minimal variation between districts (Table 4.2). Household heads were generally middle aged with about 58% of household heads in the age bracket 31 – 50 years. Younger (18 – 30 years) household heads constituted 12% of the surveyed household heads, with a similar proportion for those aged over sixty years. Majority (75%) of household heads had no formal education, with only 22% having accessed post primary education (Table 4.2). About half of surveyed households (48%) had a household size of 6 – 10 members, though about 30% of households comprised more than ten members. Almost all household heads considered farming as their main occupation, with only 3 % of household heads engaged in other activities as the main form of occupation. Similar observations were made for spouses of household heads. Majority of households (84 %) also had no off-farm income sources. Household heads however generally had many years of farming experience with over 57% of household heads having more than 20 year of farming experience (Table 4.2).

Table 4.2: Socio-economic and demographic setting of surveyed smallholder farming households (n = 240), in select districts in Northern Ghana.

Variable	East Gonja	Nanumba North	Nanumba South	Kpandai	Combined
Gender (%)					
Male heads	87	91	87	88	88
Female heads	13	9	13	12	11
Age (%)					
18-30	7	19	13	5	12
31-40	35	25	31	39	32
41-50	35	26	17	29	27
51-60	12	19	26	12	17
>60	12	11	13	14	12
Household size (%)					
1-5	25	20	13	26	21
6-10	50	41	52	54	49
11-15	12	20	13	12	15
16-20	5	6	9	4	6
Above 20	8	11	13	4	9
Educational level (%)					
None	72	80	83	61	75
primary	7	3	2	2	3
JHS	5	5	8	16	8
SHS	13	13	6	8	10
Tertiary	3	-	2	14	4
Main occupation of the household head					
Farming	97	100	98	90	97
Business	0	0	0	2	1
Off-farm employment	3	0	0	2	1
Other	0	0	1.85	5.88	2
Ownership of off-farm income source					
No	95	82	89	67	84
Yes	5	18	11	33	16
Years of farming					
1-10	24	24	17	14	20
11-20	19	25	28	16	22
21-30	44	34	33	47	39
>30	14	17	22	24	19

Source: the survey data analyzed by the authors. Unless otherwise noted, all of the following Tables and Figures use the authors as the source.

4.3.1.2: Membership of association, access to credit and extension information

About 46% of farmer’s surveyed farm belonged to Farmer Based Organization (FBOs) (Table 4.3). Membership in FBOs was however notably lower in East Gonja district (22%), with Nanumba South district having the highest membership (62%). The FBOs that farmers were involved in were generally unregistered, and mostly made up of both men and women (Table 2.3). Access to credit was generally low with most of surveyed farmers reporting no access to credit, and only 15% of surveyed farmers reporting having borrowed some credit during the survey period. Access to extension information was however high, with about 78% of surveyed farmers reporting they received extension advice from Agriculture Extension agents (AEAs), demonstration sites, field days, Agro-dealers, research projects, fellow farmers NGOs, Booklets and posters advice.

Table 4. 3: Membership to farmer-based associations, and access to credit and extension information among smallholder farming households (n = 240), in select districts in Northern Ghana.

Variable	East Gonja	Nanumba North	Nanumba South	Kpandai	Combined
Membership of FBO					
No	78	46	37	57	54
Yes	22	54	63	43	46
Access to credit					
No	92	84	81	81	84
Yes	8	16	19	19	16
Borrowed credit (%)					
No	94	85	72	92	86
Yes	6	15	28	8	15
Receipt of extension advice (%)					
No	37	8	21	26	22
Yes	63	92	79	75	78
Source of information (%)					
Extension staff	4	16	18	20	4
Demonstration site	8	12	11	10	8
Field days	10	11	11	17	10
Agro-dealers	10	4	5	4	10
Research Projects	5	13	17	8	5
Fellow farmers	24	13	9	13	24
Media (Radio, TV)	18	15	12	6	18
Booklets and posters	6	3	5	2	6
NGOs	16	10	12	20	16
Total	100	100	100	100	100

Source: the survey data analyzed by the authors. Unless otherwise noted, all of the following Tables and Figures use the authors as the source.

4.3.1.3: Characterization of farming systems

4.3.1.4: Cropping systems characterization

Findings from the survey showed that about 60% of surveyed households grow maize as a monocrop, with the rest growing maize as an intercrop (Table 4.5). The proportion of households practicing maize monocropping was however substantially larger in East Gonja district (85%). The average size of maize monocrop fields was also notable larger in this district (4.4 acres), compared to less than 2.5 acres in the other three districts (Table 4.4). Where maize was grown as an intercrop, it was in all surveyed cases intercropped with groundnut. Maize monocrop fields are mostly managed by male members of the household (62%) where maize and groundnut are intercropped, such fields are mostly managed by female members of the household (54%). When maize and groundnut are intercropped, majority (54%) of farmers considered groundnut as the most important crop in the intercrop, with only 18% considering maize as the most important crop in the intercrop. However, 29% of surveyed farmers considering both maize and groundnut to be equally important. Notable differences in crop importance were observed between surveyed districts, with more than 70% of surveyed farmers in East Gonja and Kpandai considering groundnut as the most important crop in the intercrop, compared to 43% in both Nanumba North and Nanumba South districts.

Table 4. 4: Characterization of farming systems in smallholder farming households (n = 240), in selected districts of Northern Ghana.

	East Gonja	Nanumba North	Nanumba South	Kpandai	Combined
Maize cropping system (%)					
Mono crops	85	55	59	45	61
Intercrops	16	45	41	55	39
Size of maize mono cropped (Acres)	4	2	2	2	3
Main person in charge of maize mono cropped field					
Female	19	36	46	8	29
Male	78	58	52	64	62
Both	4	7	3	28	9
Size of maize-groundnut intercrop field (Acres)	2	3	2	2	2
Main person in charge of the groundnut intercrop field					
Female	38	56	60	50	54
Male	63	31	28	21	30
Both	0	13	8	21	15
Other	0	0	4	0	1
Crop considered most important for intercropping					
Groundnut	78	43	43	71	54
Maize	22	24	38	0	18
Both	0	33	19	29	28
Is this field always under maize and Groundnut intercropping?					
Maize and groundnut intercropping	33	43	50	79	53
Sometimes under maize mono cropping	11	28	14	7	18
Sometimes cropped with other crops	44	28	23	7	23

Source: the survey data analyzed by the authors. Unless otherwise noted, all of the following Tables and Figures use the authors as the source.

2.3.1.5 Cropping systems practices in maize

Farmers considered ease of crop management, higher yields, and ease of harvesting as the main reasons for practicing maize mono cropping (Figure 4.2). On the other hand, farmers who practiced intercropping highlighted higher total yields, lack of sufficient farmland, reduced cost of production and enhancement of soil fertility as the key reasons for intercropping.

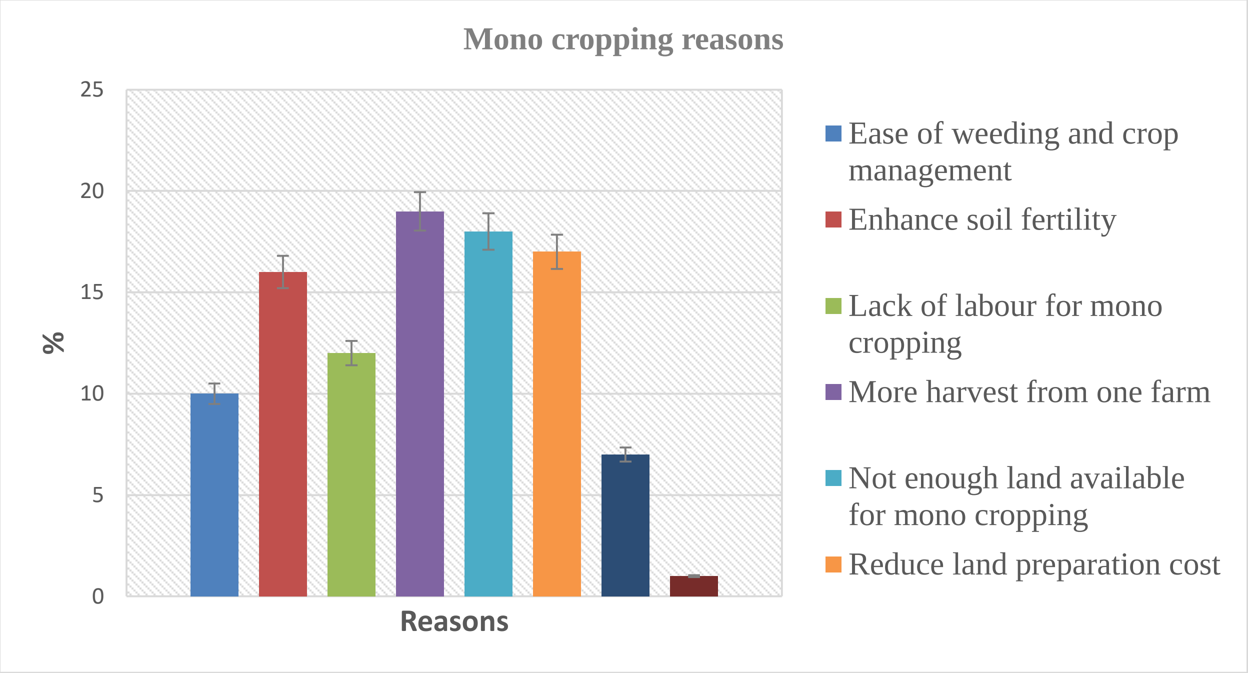

Figure 4. 2: Cropping systems practices in maize (Mono cropping)

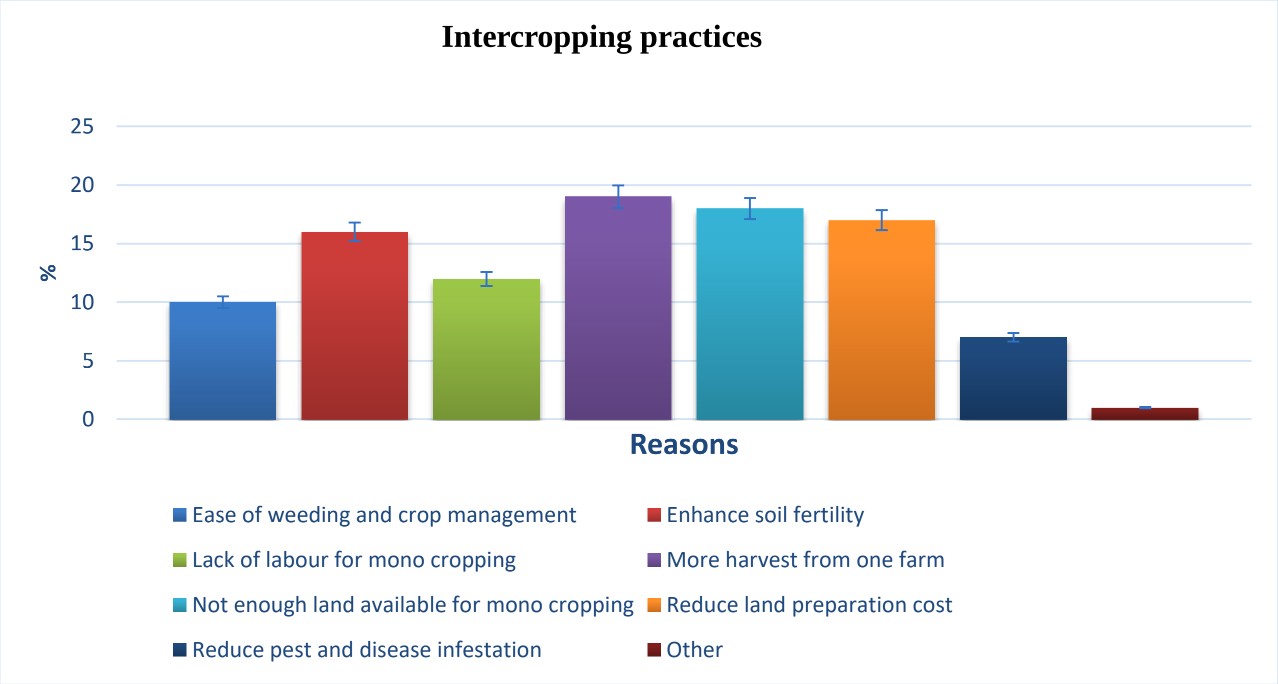

Figure 4. 3: Cropping systems practices (intercropping)

4.3.1.6: Fertilizer use in maize

Findings from the survey indicated that farmers generally consider fertilizer to be useful for attainment of good maize yields, with almost all surveyed farmers having a better perception of the importance of applying fertilizer for enhancing yields in maize (Table 4.5). However, farmer's awareness of recommended fertilizer use practices was low, with only 31% awareness of the recommended fertilizer type for maize, 35% awareness of the recommended quantity of fertilizer to apply in maize, and 55 and 47 % awareness of the recommended time and method of fertilizer application respectively. Findings from the survey further indicated that only 37% of the respondents applied fertilizer to their current maize crop, with 56% of those who applied fertilizer only applying once (basal application) while the rest applied twice, i.e., basal and top dressing (Table 4.5). Among farmers who applied fertilizer, basal fertilizer application was predominantly done after planting (99%), generally at two weeks after planting. Compound NPK fertilizers were the main type of basal fertilizers applied, with 48% of the farmers applying NPK 15:15:15, while 27 % applied NPK 15:10:10 (Table 4.6). Notable differences in the most popular NPK fertilizer were observed between the three districts, with NPK 15:15:15 being the most used fertilizer in East Gonja and Kpandai, while NPK 15:10:10 and NPK 23:10:5 + TC where the most used fertilizers in Nanumba North and Nanumba South respectively. Lack of financial means for fertilizer purchase was identified as the main reason (Table 4.6) for lack of fertilizer application among farmers who did not apply any fertilizer (92%).

Table 4. 5: Awareness of fertilizer use recommendations and fertilizer use practices among in smallholder maize farming households (n=240), in select districts in Northern Ghana.

	East Gonja	Nanumba North	Nanumba South	Kpandai	Total
Perception about fertilizer use					
Important for good yield	100	99	94	100	98
None	0	1	6	00	2
Awareness of recommended application of fertilizer					
Yes	27	31	32	35	31
No	73	69	68	65	69
Awareness of recommended quantity use of fertilizer					
Yes	41	40	15	48	36
No	59	60	84	52	64
Awareness of recommended time of applying fertilizer					
Yes	57	41	38	50	55
No	43	59	62	50	45
Awareness of recommended method of applying fertilizer					
Yes	56	47	40	51	47
No	44	54	60	49	53
Applied fertilizer					
Yes	64	44	13	36	37
No	36	56	87	64	63
Number of times applied fertilizer					
Once	78	63	57	22	56
Twice	22	37	43	78	44
Time of first fertilizer application					
During planting	0	4	0	0	1
Two weeks after planting	56	43	86	53	53
Three weeks after planting	31	21	0	32	24
Other	13	32	14	16	21
Type of fertilizer (First application)					
NPK 15:15:15	72	22	29	68	48
NPK 15:10:10	11	44	14	21	27
NPK 11:22:21 + TC	0	4	0	5	3
NPK 23:10:5 + TC	0	19	43	0	11
Other	17	11	14	5	11
Quantity of fertilizer applied (kg)	317	82	357	125	176

Reasons for not applying fertilizer					
Fertilizer not available in market	0	0	2	0	1
No money for fertilizer purchase	80	93	98	88	92
Did not want to apply fertilizer	0	0	0	13	3
Farm is fertile enough	10	4	0	0	2
Other	10	2	0	0	2
Use of organic fertilizer					
Yes	20	25	15	30	28
No	80	75	85	70	72

4.3.1.7: Constraints to maize production

Surveyed farmers identified low soil fertility as the main constraint (16%) to maize productivity. Lack of good varieties, pest attack which include weeds and insects, lack of fertilizer (the right and the high cost) were also identified as major factors that contribute to low maize yield of maize (Figure 4.4).

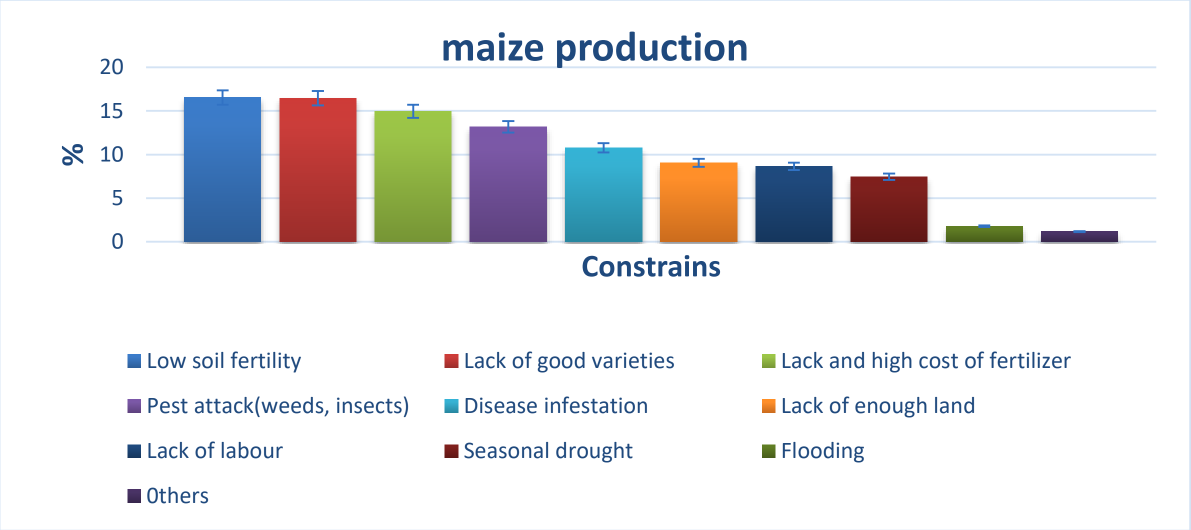

Figure 4. 4: Constraints to maize production

4.3.1.8: Characterization of soils in the study site

Soils in the study site are sandy loams with high sand contents (Table 4.6). Based on interpretation guidelines by Hazelton and Murphy (2016), these soils are moderately to strongly acidic as indicated by the measured pH range of 4.8 – 5.7. According to Manevski et al. (2015), sandy soils often have a low retention of nutrients, with a high leaching potential of applied nutrients. Very low levels of soil organic matter (SOM) were indicated by general values of organic carbon (OC) <=1. SOC is a spatially variable metric of soil productivity, according to Wang et al. (2010). SOC depletion results in decreased water-holding capacity, poor soil aggregation and stability, fertility, enzymatic activity, and soil biology.

In 9 out of twelve sites, measured soil available P values were <5 mg kg^{-1}, indicating very low soil P stocks and general low soil fertility, given the critical value of 10 kg mg^{-1} for soil available P. Such low soil available P values are indicative of continuous cultivation with minimal usage of inorganic and natural resources (Zou et al. 2022, Helin and Weikard, 2019). Measured values of the major exchangeable cations measured (K, Mg, and Ca) were also indicative of low soil potassium (K), magnesium (Mg), and calcium (Ca) contents, confirming the low fertility status of these soils.

Soil chemical and physical properties (0 - 20cm) from selected sites (n = 12) included in an agronomic and socio-economic survey of smallholder maize cultivating households in East Gonja, Kpandai, Nanumba North and Nanumba South districts of the northern region in Ghana (Table 4.6).

Table 4. 6: Soil chemical and physical properties

District	Community	Soil Properties											
		pH (1:2.5)	OC (%)	P (mg/kg)	K (cmol/kg)	Mg (cmol/kg)	Ca (cmol/kg)	Fe (mg/kg)	Cu (mg/kg)	Zn (mg/kg)	CEC me/100g	Clay (%)	Sand (%)
East Gonja	Klinkin	5.7	0.9	4.4	0.13	3.3	6.2	149	3.8	4.9	9.9	6	76
	Kuwani	5.5	1.0	3.1	0.12	0.9	2.8	94.4	1.4	0.9	4.1	6	78
	Yahayali	5.4	0.8	3.4	0.12	1.1	3.4	72.8	1.2	1	5	6	72
Kpandai	Kategeli	5.5	0.5	17.1	0.08	0.4	1.7	77.2	1.1	1	2.6	8	84
	Kumidi	5.3	0.5	11	0.07	0.9	2.1	85.6	1.3	1.1	3.5	10	78
	Jamboi	5.4	0.6	4.7	0.12	1.4	2.3	65	1.4	1.1	4.3	6	62
Nanumba North	Manchoni	4.8	0.7	3.6	0.15	1.3	2.3	73.5	0.9	0.8	4.3	6	76
	Lifado	4.9	0.9	4.7	0.09	0.8	3.2	75	1.5	1.4	4.5	10	66
	Zibaga	5.7	0.6	2.7	0.12	0.6	2.1	65.2	1.3	2.2	3.2	8	72
Nanumba South	Maggido	5.7	0.9	4.6	0.21	0.4	3.2	67.	1.3	0.9	4.1	6	80
	Sakpe	5.5	1.0	20.9	0.11	1.3	4.2	118.2	2.4	1.9	6.1	10	66
	Kotoya	5.2	0.6	4.3	0.16	0.3	2.1	68.9	1.1	0.7	3.1	6	76

4.4: Maize productivity patterns

The proportion of farmers practicing mono cropping in all the four district is about 60 % with highest number of about 94 % in East Gonja district while Kpandai district lead with the practice of intercropping (Table 4.8). The mean grain yield of maize obtained from all the four districts was about 1.4 t ha^{-1} (Table 4.8). Wide variation at a farmer level was observed, with minimum yields < 0.5 t ha^{-1}, and maximum yields of 5.8 t ha^{-1}. Nanumba North recorded higher yield of 2.4 t ha^{-1} and East Gonja recorded lowest yield of 1.1 t ha^{-1}. On average, variability was greatest in the Kpandai district followed by Nanumba North, Nanumba South and least in the East Gonja. Only Nanumba North recorded the potential for attaining yields >3 t ha^{-1} with 35%. Variation in yield was highest in Kpandai district with 76% and probability of obtaining yield >3 t ha^{-1} was highest in Nanumba North district by 35% (Table 4.8).

Maize yield was significantly increased with an increase in density as the average cob number per square meter increased along with density and showed the highest value in (Figure 4.5 a). Each plant may grow to its full potential when the plant density is too low, but there aren't enough plants overall to produce the maximum amount. Maize yields declines when plant density increased beyong the optimum plant density. The the cob size to plant ratio decrease with an increased in plant density (Figure 4.5 b).

Proportion of farms practicing maize monocropping or intercropping, mean actual maize yields, the variation in maize yields, and probability (%) of attaining yields (>3 t ha^{-1}) as determined following an agronomic in farmer's fields (n = 218) across four districts in northern Ghana.

Table 4. 7: Proportion of farms practicing maize monocropping or intercropping

District	Cropping system (%)		Yield (t/ha)	Production risk	
	Mono	Intercrop		CV	ϕ >3
East Gonja (n=32)	94	6	1.1ab (0.5, 2.7)	53	0
Kpandai (n=63)	46	54	0.8a (0.03, 2.3)	76	0
Nanumba North (n=63)	51	49	2.4c (0.4, 5.8)	63	35
Nanumba South (n=60)	65	35	1.2b (0.2, 3.7)	54	0
All Districts (n=218)	60	40	1.4 (0.03, 5.8)	83	9

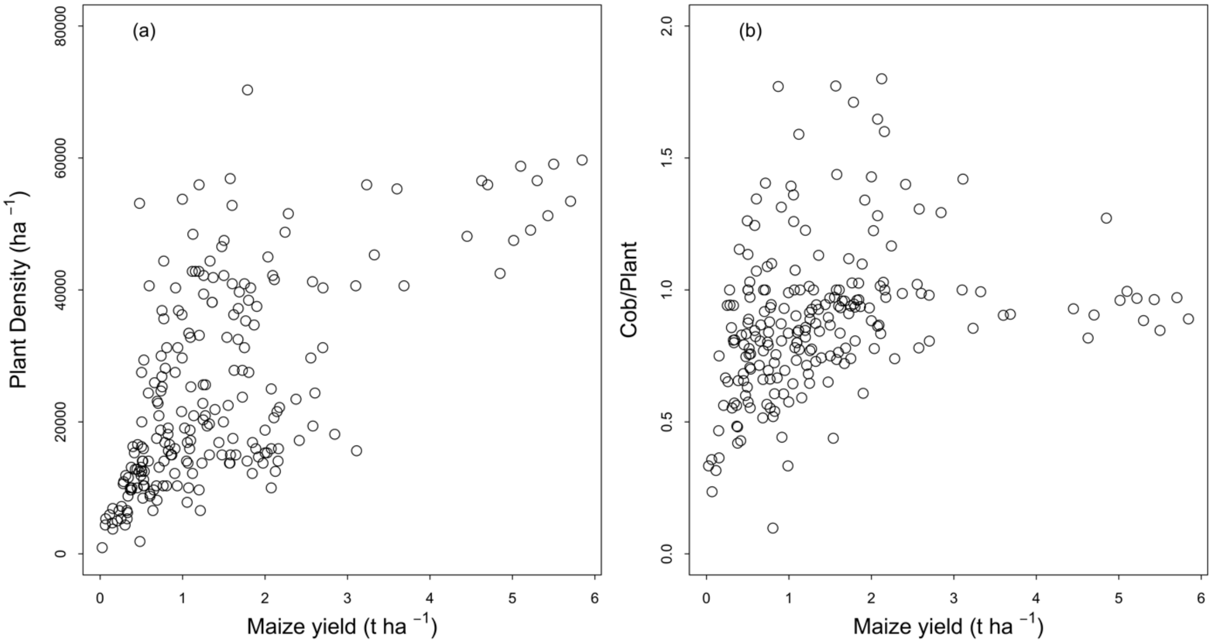

Figure 4. 5: Relationship between; (a) plant density at harvest, and (b) the cob to plant ratio, and measured actual maize yields in farmer's fields (n = 218) in East Gonja, Kpandai, Nanumba North and Nanumba South districts of northern Ghana.

4.5: Attainable yields with optimum crop and nutrient management practices

The highest mean grain yield of 4.4 t ha^{-1} was achieved from Nanumba North which was not significantly different from Nanumba South (Table 2.9). The lowest yield of 2.2 t ha^{-1} was achieved from East Gonja districts which was not also statistically different from Kpandai. However, wide variation at a farmer level was observed, with minimum yields of 1.6 t ha^{-1}, and maximum yields of 5 t ha^{-1} (Table 4.9). Variability was greatest in the East Gonja district followed by Nanumba North, Nanumba South and least in the Kpandai (Table 4.9). Nanumba North recorded the highest potential for attaining yields >3 t ha. with 96% followed by Nanumba South with 91%, Kpandai with 53% and East Gonja recorded 14%.

Mean and range of measured maize yields (t ha^{-1}), the variation in maize yields, and probability (%) of attaining yields (>3 tons ha^{-1}) in on-farm experimental plots (n = 24) with best management of crop and nutrient practices across four districts in northern Ghana.

Table 4. 8: Mean and range of measured maize yields (t ha^{-1})

District	Yield (t ha^{-1})	Production risk	
		CV	ϕ >3
East Gonja (n=6)	2.2a (1.6, 3.4)	32	14
Kpandai (n=6)	3a (2.2, 3.6)	18	53
Nanumba North (n=6)	4.4b (2.8, 5)	22	96
Nanumba South (n=6)	4.2b (2.7, 5.4)	19	91

4.9.3: Frequency and magnitude of yield gaps

The frequency distribution of relative mean yield of maize obtained from all the four districts was about 1.0 t ha^{-1} (Fig. 4.6). Wide variation of exploitable yield gap at a farmer level was observed, ranging from 0.23 tons ha^{-1} at Nanumba South and 5.0 tons ha^{-1} at Nanumba North (Fig. 4.6). Generally, yields at farmer level in all the districts were below attainable yield of 6 t ha $^{-1}$

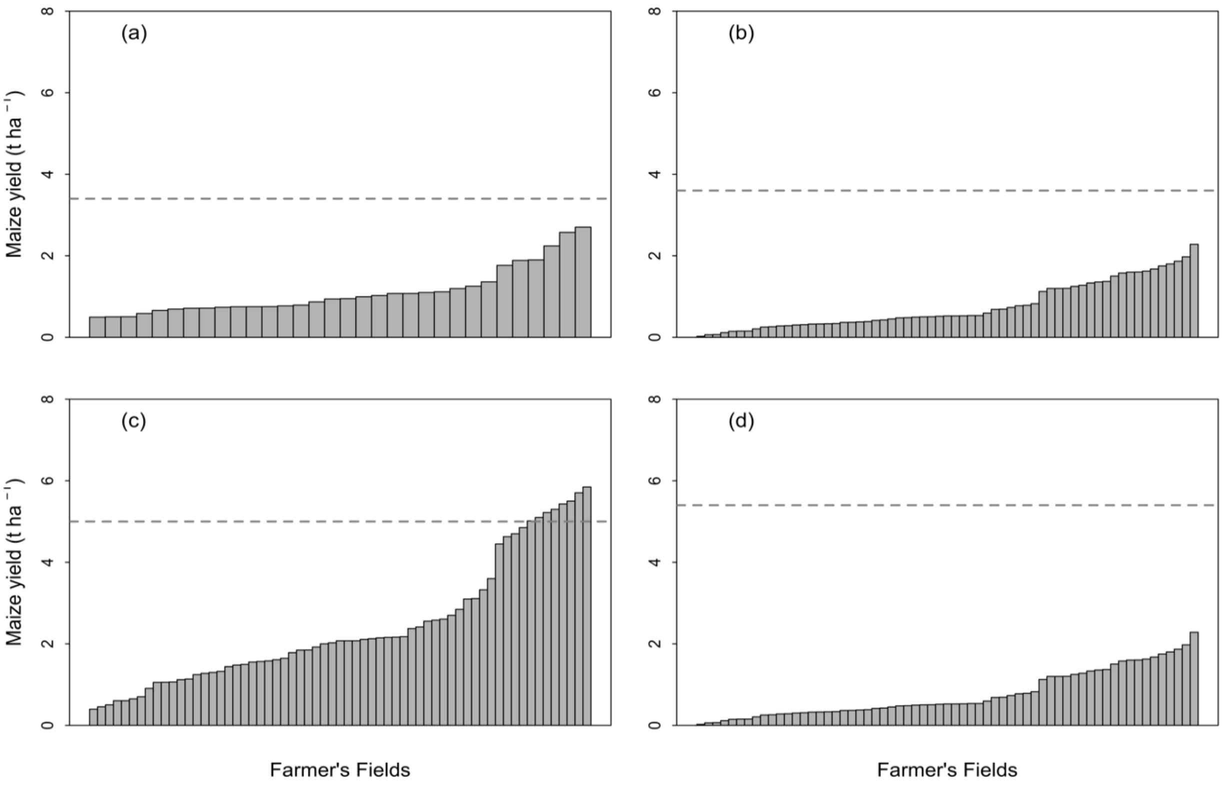

Figure 4. 6: Actual maize yields measured in the 2020 cropping season

During an agronomic survey of farmers' fields (n = 218) in the northern Ghana districts of; (a) East Gonja, (b) Kpandai, (c) Nanumba North, and (d) Nanumba South. Dotted lines represents the highest yield recorded with best crop and nutrient management practices in on-farm trials established in each of the districts in the same cropping season.

4.9.4: Key factors explaining maize actual maize yields

Mean estimate of local variety intercept over the seasons was 1.0 t ha^{-1} (Table 4.9). This did not vary significantly over time as indicated by the estimate and p value associated with the season (P <0.05). All the model results showing influence of management factors on maize were not significant (P <0.05).

Mixed-effects model results showing influence of management factors on maize grain yields in surveyed fields (n = 218) in East Gonja, Kpandai, Nanumba North, and Nanumba South Districts of northern Ghana during the 2020 cropping season (table 4.9)

Table 4. 9: Mixed-effects model results showing influence of management factors on maize grain yields in surveyed fields

Explanatory variable	Estimate (t ha^{-1})	S.E.	*P* value
Variety: local (intercept)	1.0	0.35	<0.05
Variety: Improved	-0.24	0.17	ns
Planting Time: Start of rains	-0.12	0.17	ns
Planting Time: After start of	0.04	0.21	ns
Fertilizer Use: Yes	0.12	0.22	ns
Fertilizer Use Frequency: Once	0.15	0.23	ns
Fertilizer Use Frequency: Twice	-0.04	0.25	ns
Weeding Frequency: Once	-0.01	0.20	ns
Weeding Frequency: Twice	-0.17	0.18	ns
Weeding Frequency: Thrice	-0.07	0.29	ns
Cropping system: Mono	0.8	0.12	<0.001

4.9.5: Key parameters explaining actual maize yields

Key crop growth status characteristics that explained real maize yields were identified using regression trees and classification (Figs. 4.7 & 4.8). Deviations from average yield in the first node indicate the influence of model parameters on yield at various levels of model parameters. For monocropped maize, the planting density at harvest was the most important factor explaining actual yields, with the cob/plant ratio the second most factor (Fig. 4.7). Where planting density at harvest was lower than 47,000 plants ha^{-1}, average yields were 1.3 t ha^{-1}. On the other hand, where planting density at harvest was greater or equal to 47,000 plants ha^{-1}, average yields were 3.5 t ha^{-1}. At planting density greater or equal to 47,000 plants ha^{-1}, instances where the cob to plant ratio was greater than or equal to 0.83, average maize yields increased further to 4.5 t ha^{-1}, with a decrease to 1.8 t ha^{-1} in cases where the cob to plant ratio was less than 0.83.

For intercropped maize, the cob/plant ratio was the most important factor explaining differences in actual maize yields, with the planting density at harvest the second most important factor (Fig. 4.8). Where the cob/plant ratio was greater or equal to 0.88, maize yields increased from a mean of 1 t ha^{-1} to 1.6 t ha^{-1}, while a decrease in mean yields to 0.59 t ha^{-1} was observed when the cob/plant ratio was less than 0.88. Further improvements or reductions in mean yield were associated with higher or lower plant densities respectively. The highest mean yields for intercropped maize (2.2 t ha^{-1}) observed in instances where the cob/plant ratio was greater or equal to 0.88 and plant density at harvest greater or equal to 22,000 plants ha^{-1}. Conversely, the lowest average yields were noted in situations when the plant density at harvest was less than 6,406 plants ha-1 and the cob/plant ratio was less than 0.88 (Figure 4.7).

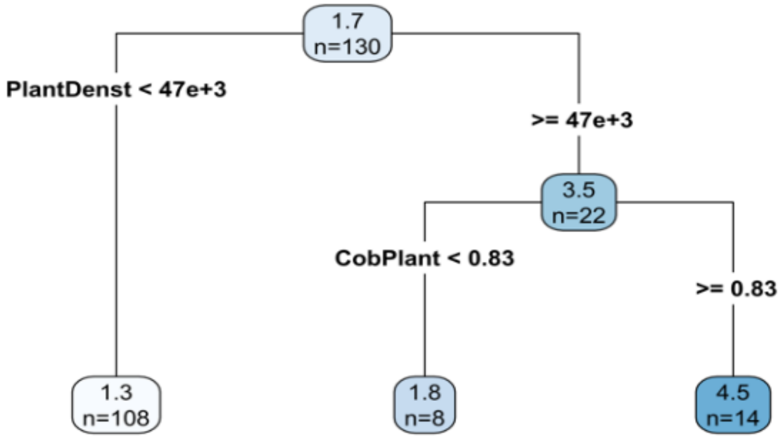

Figure 4.7: Classification and regression tree model demonstrating association between key factors explaining maize grain yield in farmer fields under maize monocropping (n = 130).

The average yield is represented by the first value in each node (t ha^{-1}) under the conditions indicated. The second value indicates the number of farms under each condition/category.

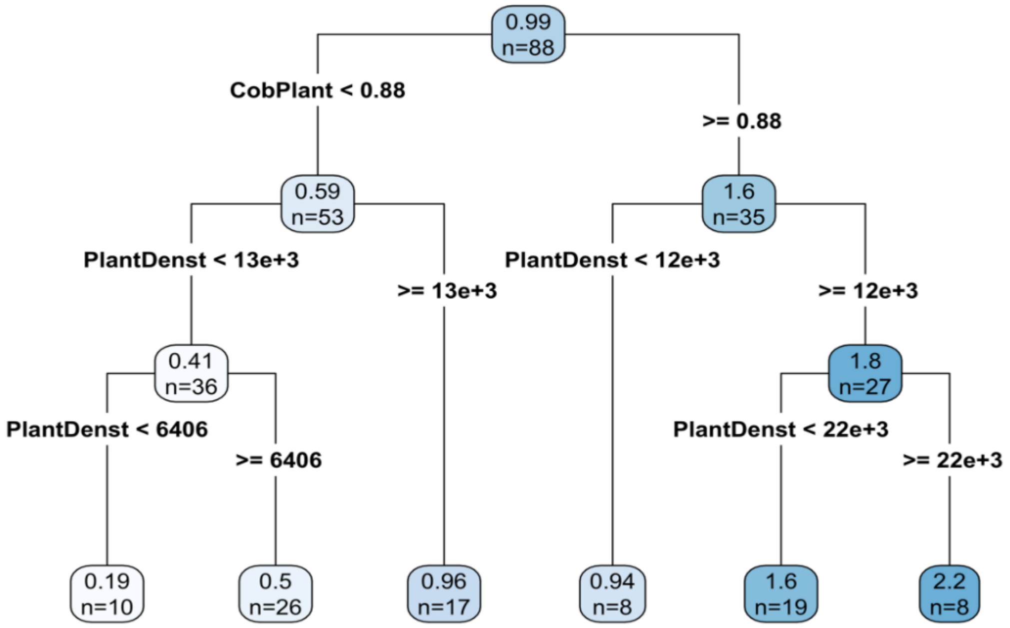

Figure 4. 8: Classification and regression tree model demonstrating association between key factors explaining maize grain yield in farmer fields under maize intercropping (n = 88).

The average yield is represented by the first value in each node (t ha^{-1}) under the conditions indicated. The second value indicates the number of farms under each condition/category.

4.10: Discussion

In the majority of production systems, sustainable intensification is seen as a primary objective but for it to be realized, a number of production factors must be optimized (UN, 2015). For such an approach to succeed, it is critical that the key nutrient and crop management factors limiting crop yields are first identified and quantified. This study therefore sought to use detailed socio-economic and agronomic surveys to characterize smallholder maize farming systems in Northern Ghana, and identify and quantify key farm level factors limiting maize productivity. The study specifically sought to: (i) characterize the socio-economic setting and structural composition of smallholder maize households in Northern Ghana, (ii) assess and quantify the frequency and magnitude of yield gaps in smallholder maize cropping systems, (iii) document and quantify the influence of current crop and nutrient management practices in maize yields in smallholder farming systems, and (iv) identify opportunities for enhancing maize productivity.

With regard to socio-economic setting and structural composition of smallholder maize households in Northern Ghana, there is a low level of literacy with farm households having a formal educational background (MOFA). (2019). The proportion of male headed households (87**%)** is higher than that of females. The survey result is similar to Ghana Living Standards Survey (GLSS6) which was conducted in (2005-2017). Household heads were generally middle aged with about 58% of household heads in the age bracket 31 – 50 years (Table 4.2). Younger (18 – 30 years) household heads constituted 12% of the surveyed household heads, with a similar proportion for those aged over sixty years. This focuses on the household as a key socio-economic unit and provides valuable insights into living conditions of the house. Majority (75%) of household heads had no formal education, with only 22% having accessed post primary education (Table 2.2). About half of surveyed households (48%) had a household size of 6 – 10 members, though about 30% of households comprised more than ten members. Almost all household heads considered farming as their main occupation, with only 3 % of household heads engaged in other activities as the main form of occupation (MoFA, 2019). Similar observations were made for spouses of household heads. Majority of households (84 %) also had no off-farm income sources. Household heads however generally had many years of farming experience with over 57% of household heads having more than 20 year of farming experience (Table 4.2).

About 46% of surveyed belonged to Farmer Based Organization (FBOs) (Table 4.3).

Regarding the relative mean yield of maize, the frequency distribution across all four districts was around 1.0 t ha^{-1} (Fig. 4.6). The exploitable yield difference at the farmer level varied noticeably, ranging from 0.23 tons ha-1 at Nanumba South to 5.0 tons ha-1 at Nanumba North (Fig. 4.6). In each district, yields at the farmer level were generally less than the 6 t ha-1 attainable yield. This is in line with findings that show an average yield gap of 80% for the entire country of Ghana (GYGA, 2018).

The most significant factor in determining actual yields for monocropped maize was the planting density at harvest, followed by the cob/plant ratio (Fig. 4.7). Where planting density at harvest was lower than 47,000 plants ha^{-1}, average yields were 1.3 t ha^{-1}. Conversely, average yields were 3.5 t ha-1 in areas where planting density at harvest was more than or equivalent to 47,000 plants ha-1. Average maize yields improved further to 4.5 t ha-1 at planting densities greater or equal to 47,000 plants ha-1 in situations where the cob to plant ratio was greater than or equal to 0.83. In contrast, average yields decreased to 1.8 t ha-1 in cases where the cob to plant ratio was less than 0.83. Similar research conducted by Meng et al., (2013) somewhere in China showed that maize yields could be increased by 20 to 40% by simply increasing the plant density to the optimum.

According to Tollenaar et al. (1997), plant density that is also higher than the optimal plant density reduces maize grain output mainly due to increased stem lodging and a decrease in the harvest index. These situations show fierce competition between plants for soil nutrients, water, and incident photosynthetic photon flux density. As a result, there are less carbon and nitrogen resources available, increasing the amount of barrenness and decreasing the size and number of kernels produced by each plant (Lemcoff & Loomis, 1994). According to Chen et al. (2012), close-planting is with optimum density is crucial for the high yield of modern maize cultivars. It was demonstrated by Tokatlidis and Koutroubas (2004) that increasing output from nearby plants could not effectively make up for production losses caused by missing plants.

Smallholder farmers in northern Ghana use intercropping (IC) as in other developing countries, an age-old multiple-cropping technique that is recognized for its superior economic benefits (Mucheru-Muna et al. 2010; Van Asten et al. 2011), reduced incidence of pests and diseases (Zhu et al., 2000), and increased efficiency in using land and nutrients (Agegnehu et al., 2006; Li et al., 2007). For intercropped maize, the cob/plant ratio was the most important factor explaining differences in actual maize yields, with the planting density at harvest the second most important factor (Fig. 4.8). Where the cob/plant ratio was greater, maize yields increased from a mean yield while a decrease in mean yields was observed when the cob/plant ratio was less. Further improvements or reductions in mean yield were associated with higher or lower plant densities respectively. The highest mean yields for intercropped maize (2.2 t ha^{-1}) observed in instances where the cob/plant ratio was greater and plant density at harvest greater. However, the lowest mean yields were noted in cases where the cob/plant ratio was less and plant density at harvest was low (Figure 4.7). According to this research, small-scale, resource-poor farmers' intercropping practices need to be improved further, particularly in the area of plant population density of the component crop or crops, as this can guarantee higher income and sustained productivity.

4.11: Conclusion

We have shown how to use agronomic survey to evaluate yield gaps and gather knowledge of small-scale farmer management techniques and their effects on yields. To retrieve data and provide insights, we also present various analytical methodologies. Reducing yield gaps requires increasing fertilizer frequency to lesson nutrient mining, adhering to the 4R principles (the correct source of fertilizer, the right rate, the time and method of application), maximizing the number of plants in farmer fields and all the good agronomic practices. Improving manure handling and evaluating fertilizer quality will require more effort.

CHAPTER FIVE

MAIZE PRODUCTIVITY IN NORTHERN GHANA: SECONDARY AND MICRONUTRIENT INCLUSION

Abstract

Developing recommendations for the right fertilizer to use for maize production in smallholder farmers of Northern Ghana is hampered by the significant variability in maize responses to the application of macro, secondary, and micronutrients. We examined how NPK and SMN application affected maize production and the connections between crop responses to the treatments. NOTs were established on 24 farms located in East Gonja, Kpandai, Nanumba North and Nanumba Sourth chosen to serve as a representative sample of the primary soil and management components in systems based on maize of Northern Ghana. Treatments comprised PK, NK, NP, NPK, and NPK plus SMN administrations in addition to a control (no fertilizer). The studies covered three cropping seasons without altering treatment plans or plot locations for 2020 to 2022. The responses of maize yield to NPK plus SMN treatments showed clear spatial-temporal patterns. The first cropping season had average maize yields of 0.9, 1.2, 1.9, 3, 2.9, and 3.6 t ha^{-1}, whereas the second cropping season saw average yields of 0.4, 0.8, 1.2, 31.9, 2.5, and 3.1 t ha^{-1} across the control, PK, NK, NP, NPK, and NPK + SMN treatments. In comparison, values of 0.5, 0.6, 0.8, 1.2, 1.6, and 1.9 t ha $^{-1}$ were recorded in the third season. Overall, the NPK plus SMN treatment demonstrated a consistent and superior maize yield performance across three cropping seasons, with average yields ranging from 1.9 to 3.6 t ha−1, highlighting its potential for improved maize productivity.

In the first cropping season, mean relative (RY) yield for RYPK, RYNK, RYNP, and RYSMN was 0.48, 0.69, 1.12, and 0.93; in the second cropping season, it was 0.36, 0.53, 0.85, and 0.78;

and in the third, it was 0.37, 0.53, 0.85, and 0.89. The substantial spatial-temporal patterns shown provide significant barriers to producing site-specific fertilizer recommendations, possible avenues for further research, and substitutes for more effective intensification strategies.

5.1: Introduction

Maize (*Zea mays* L.), a major staple crop that was largely cultivated in southern Ghana was extended to the northern regions, due to breeding efforts that targeted yield response to small amounts of fertilizer, among others (MacCarthy et al., 2017). While current yields in smallholder farms in northern Ghana is approximately 1.6 t/ha, studies have shown that with good crop and nutrient management, a yield potential of up to 5.5 t/ha is possible (Rahman et al., 2022), indicating huge opportunities for farmers to sustainably enhance maize productivity. Indeed, in northern Ghana, maize yields reached 4.5 t/ha with enhanced nitrogen application of 90 kg N ha^{-1} or higher under favorable rainfall conditions (Naab et al., 2015).

Maize productivity in northern Ghana is frequently hampered by factors such as poor soil fertility, low soil water storage capacity, erratic rainfall, limited use of improved maize varieties, prevalence of pests and diseases, sub-optima agronomic practices, and limited use of yield- enhancing inputs such as fertilizers and agrochemicals (MacCarthy et al., 2017; Sserunkuuma et al., 2001). Low soil fertility associated with continuous cropping with minimal or no application of external nutrients in these farming systems is further exacerbated by traditional practices such as annual burning of harvested fields, which leads to loss of soil organic matter (SOM) (Bationo et al., 2018). The loss of SOM which is a reserve for soil N, P and S translates to reduced availability of important nutrients for crops, resulting in strong macronutrient limitations. Besides this, the loss of SOM reduces the efficacy of applied mineral fertilizers, as the presence of SOM has been found to improve the performance of applied mineral fertilizers (Kihara et al., 2016). Burning of fields also raises soil pH to high levels that often induce deficiencies of iron and other micro-nutrients (Agyare et al., 2006).

Soils in northern Ghana have been reported to be critically low in organic C, N, P and K, with Mg, S, Zn, B, Fe and Zn levels varying from low to very low (Asei et al., 2021). Furthermore, in northern Ghana, agronomical trials carried out by the N2Africa initiative putting nitrogen fixation to use found that 28% of areas had poor crop response to P fertilizers (Woomer et al., 2009, 2013). Studies have shown that the presence of non-responsive soils increases the variability of crop responses to best management practices that widening the yield gap, and lack of secondary and micronutrients (Ca, Mg, S, Cu, Zn, B) have been named as a significant cause of this non-responsiveness of crops to fertilizer inputs (Kihara et al., 2016; Nziguheba et al., 2009). On the other hand, little systematic and thorough information exists regarding non-responsive soils, their limitations, and how to manage them to maximize crop response to fertilizer inputs. Appropriate fertilizer management techniques are necessary and should be taken care of in order to maximize crop response and nutrient efficiency. This can be achieved by creating fertilizer recommendations that are site-specific and take into account how variations in farm circumstances and soil fertility affect the anticipated crop yield response to nutrient treatments. The concept of 4R Nutrient Stewardship which emphasizes using the Right source of nutrients, at the Right rate, applied at the Right time, and in the Right place is considered a credible option towards this. This study therefore aimed to: (i) quantify the effect of imbalanced and balanced nutrient applications on maize yields and production risks; (ii) assess improvements in nutrient use efficiency associated with balanced nutrient applications; (iii) determine the extent and temporal-spatial patterns of maize yield responses to nutrient treatments; and (iv) assess the relationship between field quality and reactions of maize yield to nutrient treatments

We hypothesized that: (i) balanced NPK treatments enhance yields and reduce production risks; and (ii) inclusion of secondary and micronutrients to combined NPK applications further enhances yields and reduces production risks.

5.2: Materials and methods

5.2.1: Study sites

The study was conducted in the northern region of Ghana, as part of the agronomic component of a project named “4R Nutrient Stewardship Project (4R NSP)”. The study included sites in the districts of Kpandai, East Gonja, Nanumba North, and Nanumba South, characterized as shown in

Table 5.1: Site characteristics

District	Latitude	Longitude	Above sea level
Kpandai	8.44° N	0.03° W	181m
East Gonja	8.57° N	0.67° W	110m
Nanumba North	8.97° N	0.11° W	156m
Nanumba South	8.81° N	0.04° W	151m

Source: Google map

Each of the districts is further divided into lower administrative levels commonly referred to as “communities. All four districts lie within the Guinea Savannah Agroecological zone with the region also influenced by the wet south-west monsoon and the dry north-east trade winds. Subsequently, the region is characterized by high daytime temperatures throughout the year, with temperatures of up to 41^{o}C recorded during the hottest months. However, during Harmattan period, temperature can fall to as low as 16^{o}C during the night and mornings. The region has a uni-modal rainfall pattern with total annual rainfall ranging between 1,050 mm to 1,500 mm. While most of the rainfall falls within a six-month period (April – September), the rainfall pattern is often characterized by irregularity and variability in terms of onset, duration, and total amount of rainfall.

In all the four districts, majority of the population practices a rural agricultural- based lifestyle, with about 80% of households involved in small-scale mixed farming as the main source of livelihood (Etwire *et al.*, 2019). Typical agricultural farm holding per family is 6.0 ha, with land ownership typically passed down through inheritance, while additional land for cultivation can be obtained through allocations by community leadership. Key crops cultivated include cereals such as maize and rice, root crops such as cassava, legumes such as groundnuts, and tree crops such as cashew nuts. This zone has a mix of open grasslands and wooded areas, with vegetation that's adapted to the dry and wet seasons Crop production in the region is however largely characterized by minimal use of inputs, and limited mechanization].

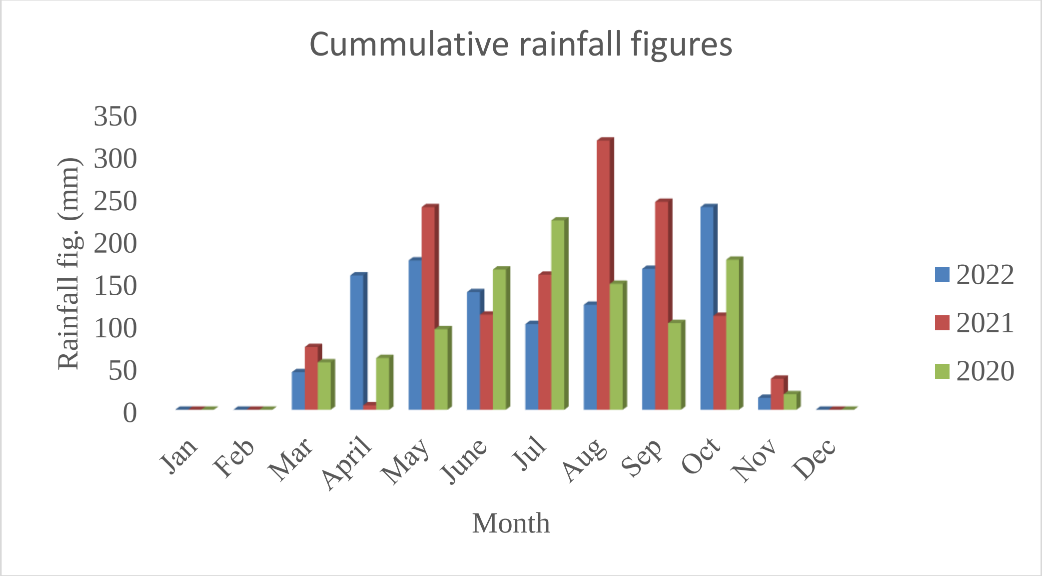

Figure 5.1: Cumulative monthly rainfall in the study area during the three growing seasons. Source: District Department of Agriculture meteorology stations.

5.2.2: Choosing of experimental location

On-farm NOTs were established in 2020 across 24 sites representative of general farm conditions in the study site, with six sites established in each of the four districts. Site selection was largely based on findings from a baseline study conducted prior to the start of the aforementioned 4R Nutrient Stewardship Project (Etwire *et al.*, 2019). The baseline study aimed at among other things documenting and characterizing typical farming practices among smallholder farmers in the study area. The study was conducted in 56 communities, with 14 communities within each district selected through simple random sampling, and included the 1,008 farm household interviews and 56 focus group discussions (Etwire et *al.*, 2019). Findings from this survey indicated that maize was the main cereal crop cultivated in the study area. Cultivation is however primarily under rainfed farming, with sub- optimal use of required inputs such as fertilizers, and inadequate agronomic practices, resulting in mean maize yields of roughly 0.7 t ha^{-1} (Etwire *et al.*, 2019), compared to potential yields of 5.5 t ha^{-1} (MoFA, 2016).

As a starting point for site selection, a list of the 56 communities within which the baseline survey was implemented was created. From this list, random selection using Excel was used to randomly select a sample of six communities out of 14 communities in each of the four districts for establishment of NOT sites. From each of the selected communities, to choose an initial sample of three farms per community, staggered random sampling was used that were generally representative of the study area in terms of history of cultivation, total land size, main crop cultivated, past nutrient management practices, and households' main economic activity in line with findings from the baseline survey. From these three sample fields per community, a site validation exercise to select one field in each of the six communities per district was conducted, resulting in a total of 24 fields selected for establishment of nutrient omission trials. This final validation and site selection was based on several aspects. These included availability of land for experimental set-up for three consecutive years, general uniformity in soil type and fertility status, and ease of access for crop monitoring and data collection.

Prior to establishment of the trials, selected sites were characterized through documentation of exact site location including GPS coordinates, and documentation of site cropping history for the past 3 seasons, e.g., crops grown in each of the seasons, fertilizer use practice, organic resources use history, crop residue management practices used, and fallow periods.

5.2.3: Soil sampling and analysis

Soil sampling was carried out prior to the establishment of the experiment during the final site selection exercise. Prior to collection of soil samples, the section of a selected field to be used for establishment of the experiment was identified and demarcated. Five sub-samples were then collected from this demarcated section in each field following a ‘zigzag sampling approach’ described by Smith and Atkinson (1975). Five sub-samples totaling approximately 500 g were collected and deposited in clearly labeled sampling bags after the sample was taken using an Edelman auger at a depth of 0–20 cm. The five sub-samples were combined and thoroughly mixed in a basin to form a composite sample. Composite samples were air dried and passed through a 2 mm sieve prior to analysis at the Soil Research Institute in Kumasi, Ghana.

The pH electrode method was used to measure the pH of the soil in water at a ratio of 1:2.5, and the modified hydrometer method was used to measure the soil texture (Van Reeuwijk, 1995). Soil organic carbon was determined using the Walkley-Black Method (Walkley and Black, 1934), while available P was determined using the Bray 1 method. Exchangeable K was determined by flame photometry, while exchangeable Ca and Mg were determined by the EDTA complexometric titration method.

5.2.4: Experimental set-up and management

The first set of nutrient omission experiments was established in June 2020, at the onset of the rainy season. The experiment included a set of six treatments, to assess maize response to NPK and secondary and micronutrients application. These treatments included a control, PK, NK, NP, NPK, NPK+SZnB (NPK + SMN) treatments (Table 3.1). The treatments were established in plots measuring 10 m by 10 m, with each site serving as a complete block with RCBD design. Each farm was used as a replicate. N was supplied as urea in two equal splits: at 2 WAP and at 6WAP. P and K were applied at 2 WAP in form of triple superphosphate (TSP), and muriate of potash (MOP), respectively. Sulphur and micronutrients such as Zinc and Boron were also supplied at 2 WAP in the form of Magnesium Sulphate (MgSO4), Zinc Sulphate (ZnSO4), and Borax. Throughout the course of the study, the trial plot sites and treatments were kept constant

In the first year, land preparation (ploughing and harrowing) was conducted using tractors. Plots measuring 10 × 10 m were delineated at planting, and paths measuring 1 m wide left in between plots, while paths measuring 2 m wide were left in between the experimental plots' area and the rest of the farmer's field. Land preparation in the subsequent seasons was conducted through manual hand tillage, to maintain plot locations/ boundaries. The hybrid, lake maize variety was planted at the prescribed spacing of 80 by 40 cm during the trial period. Two seeds were placed in each hole to provide a planting population equal to 62,500 plants ha^{-1}.

All trial sites were researcher- established and managed. Experimental plots were kept weed free through two weeding operations. The first weed control operation involved applying the appropriate pre-emergence herbicides to every experimental plot right after the maize seeds were sown. While, the second weed control operation was conducted manually, approximately six weeks after planting, prior to top dressing. Chemical pest control was used, as per need basis.

Table 5.1: Treatment structure for on-farm (n = 24) NOTs established in Nanumba North, Nanumba South, Kpandai, and East Gonja Districts of northern Ghana.

Treatment	Nutrient						
	N kg	P kg ha^{-}	K kg	S kg ha^{-}	Mg kg	Zn kg	B kg
Control	0	0	0	0	0	0	0
PK	0	60	60	0	0	0	0
NK	120	0	60	0	0	0	0
NP	120	60	0	0	0	0	0
NPK	120	60	60	0	0	0	0
NPK, S, Mg, Zn,	120	60	60	13.5	10	1	0.5

5.2.5: The collection of yield data

All maize plants were harvested when they reached physiological maturity within a net plot measuring 3.2 m by 3 m, with four center rows in each plot. To reduce edge effects, at least 2 m were left on each side of the center rows. The net plot's precise location was selected so that it would visibly depict the general growth conditions inside the central rows.

Harvesting was conducted by cutting all plants at the ground level. The total number of plants and cobs were noted after harvest and total cob weight determined in the field using a digital scale accurate to 2 decimal places. Additionally, the total weight of all the stover from the net plot was weighed and recorded. Five (5) representative cobs and stovers were randomly chosen from the total number of cobs and stovers measured, and new weights were collected. A sub-sample consisting of five cobs was obtained by separating the grains and corbs and determining the fresh weights of each individually. A 200 g sub-sample of the chosen stovers was taken after they were sliced into 5 cm strips and well mixed. The three sub-sample plant parts, grain, corbs, and stover were then placed in bags with obvious labels, and they were oven dried for 48 hours at 60 degrees Celsius. In order to determine the dry matter yield, oven-dried samples were reweighed and their dry weights recorded. The grain yields were then adjusted for a moisture content of 12.5%.

5.2.6: Partial Factor Productivity

Partial factor productivity (PFP) was used to assess difference in nutrient use efficiency between imbalanced and balanced nutrient applications for the primary macronutrients (N, P and K), and was calculated as follows:

$$PFP = GY/N_x$$

Where GY is the grain yield (kg ha^{-1}) while N_x represents the applied nutrient N, P or K (in kg ha^{-1}).

5.2.7: Relative yield

The ratio of yield in a treatment where a specific nutrient is omitted to yield in the NPK plot in the same field and season for N, P, and K is known as relative yield (RY), which is used to quantify the yield responses to N, P, K, secondary, and micronutrients.

Relative yield for secondary and micronutrients was determined by dividing the yield in the NPK treatment by the yield in the NPK plus SMN treatment in the same field and during the same season. Relative yield values less than or equal to one signify a reaction to the applied nutrient, whilst values greater than or equal to one suggest no response.

5.2.8: Absolute yield response

The real yield response to the application of a specific nutrient or nutrients in tons per hectare was measured using the absolute yield response. The yield difference between the NPK treatment and a treatment in the same field and season that omitted either N, P, or K was used to compute this for N, P, and K. For instance, the following was found to be the absolute yield response to N:

$N\ Response = NPK_{yield} - PK_{yield}$

Where;

NPK_{yield} = Yield in the NPK treatment plot in tons per hectare

PK_{yield} = Yield in the PK treatment plot in tons per hectare

Yield response to application of secondary and micronutrients was determined as the yield variation between the NPK treatment and the NPK plus SMN treatment.

5.3: Statistical analysis

Data from 22 fields during the year one, 23 fields during the year two, and 19 fields during the year three made up the final dataset that was used in the analysis. Missing data from the first two seasons was due to crop damage by livestock, while in the third seasons, missing data was related to crop failure due to season drought in five sites in East Gonja district. Using the "lme4" package in R software (www.r-project.org), the impact of treatment on grain production in each season was examined using a generalized linear model with grain yield as the response variable and treatment as the explanatory component. The significance of the differences in treatment means was then assessed using an LSD test with the R package "predictmeans." The production risk associated with varied nutrient applications was evaluated by assessing treatment level yield variability and downside risk. Yield variability was assessed by calculating the coefficient of variation (CV) using the '*raster*' package in R, for each treatment in each season. A higher CV indicates increased variability and, hence, increased risk of production (Kiwia et al., 2019). According to Zingore et al. (2022), downside risk is the likelihood that yields will fall short of a set yield objective. Downside risk was determined by calculating the likelihood that treatment yield would fall short of the 3 t ha-1 African Green Revolution target yield (Zingore et al., 2022). Using the R software's "lme4" package, a generalized linear model with PFP as the response variable and treatment as the explanatory factor was used to analyze the impact of nutrient combinations on partial factor productivity (PFP) for the macronutrients N, P, and K at the seasonal level. The "predictmeans" tool in R was used to run an LSD test to determine the significance of PFP differences between treatments.

To assess the influence of soil chemical and physical properties, on yield responses to nutrient applications, absolute yield responses and actual yields in the control, NPK, and NPK inclusion of micro and secondary nutrients were individually included as response variables in decision tree analysis with site- level soil physical and chemical data collected during experimental variables used as explanatory factors. For this, conditional inference tree (CTREE) analysis which recursively partitions yield responses following permutation and tests the significance of splitting variables (Hothorn *et al.*, 2006; Roobroeck *et al.*, 2021) was implemented using the '*party*' package in R. For all sites, soil data used included pH, proportions of sand and clay, organic carbon contents, available P, exchangeable K, Ca, Mg and their ratios, Na, Fe, Cu and Zn contents, and ECEC. This analysis was run twice: first using a dataset including data from all three seasons, and then using a dataset with only the first and second seasons where yields were not constrained by an in-season drought as experienced in season three.

Boundary line analysis was applied to assess the relationship between field quality and yield reactions to the addition of nutrients. Maize grain yields in control treatments were used as a proxy of field quality with the assumption that nutrient uptake, and subsequently plant growth and yields in these plots were solely based on conditions inherent to these plots. Subsequently, yields from those treatment plots are expected to serve as a good indication of the 'quality' of the field. Boundary lines represent the maximum value of a dependent variable that can be achieved at different values of the independent variable (Shatar and McBratney, 2004), and have previously been used to assess relationships between yield responses and field quality (Kihara *et al.*, 2015).

To construct the boundary lines, respective yield response data were plotted and classified into groups of 0.5 t ha-1 categories according to the control yield and the three observations with the highest treatment yield in each control yield class mean. These average values for each class were then used for boundary line fitting. The boundary lines were fit for both the treatment with all of N, P and K applied, and treatments with nutrients omitted, or the treatment with additional secondary and micronutrients applied. The boundary lines were fit to the data as non-linear 3-parameter log logistic models using the package '*drc*', a general dose response curve fitting function in R software.

5.4: Results

5.4.1: Soil description

Soils in the study site are sandy-loams with high sand contents (Table 5.2). Interpretation of soil analysis data was based on the guidelines provided by Hazelton and Murphy (2016). Soil pH ranged from 4.9 – 5.9 for most of the sites, indicating moderately to strongly acidic soils. Measured organic carbon (OC) values <1%, and soil available P contents <10 mg kg^{-1} in most of the sites were indicative of soils with low soil organic carbon (SOC) contents, and low available P respectively. These soils were also very low in CEC, with majority of sites showing CEC values <6 me/100g. Values of the major exchangeable cations measured (K, Mg, and Ca) were also indicative of low contents of exchangeable K, Mg, and Ca, a common characteristic of acidic sandy soils.

5.4.2: Rainfall patterns during the experimental period

Rainfall during the three growing seasons was characterized by variability in both total rainfall and distribution of rainfall across the growing seasons (Fig. 5.1). The highest cumulative rainfall was recorded during the second growing season (2021), with the lowest recorded during the third growing season (2022). The third growing season also suffered from an in-season dry spell during the period July to August as indicated by the marginal increase in cumulative rainfall between these two months (Fig. 5.1). In contrast, the first growing season in 2020 was characterized by relatively high rainfall during the first two months of the growing season, while the second growing season was characterized by initial low rainfall in the first month, but with notable improvements in the subsequent months (Fig.5.1).

Table 5.1: Soil chemical and physical properties (0 - 20cm) in sites (n = 24) chosen for establishment of NOTs in East Gonja, Kpandai, Nanumba North and Nanumba South districts of the northern region in Ghana.

District	Community	Soil Properties											
		pH (1:2.5)	OC (%)	P (mg/kg)	K (cmol/kg)	Mg (cmol/kg)	Ca (cmol/kg)	Fe (mg/kg)	Cu (mg/kg)	Zn (mg/kg)	CEC me/100g	Clay (%)	Sand (%)
East Gonja	Kulpi	5.5	0.64	0.8	0.2	1.1	1.9	62.6	1.0	1.2	3.6	8	72
	Grushie-Zongo	5.5	1.01	4.5	0.3	1.3	3.6	97.1	1.7	4.5	5.5	8	76
	Upando	5.6	0.96	3.0	0.2	1.4	4.2	106.2	1.7	0.7	6.1	6	72
	Katanga	5.3	1.12	12.9	0.2	1.3	4.3	111.9	2.3	1.1	6.3	8	78
	Naamu	5.6	0.64	5.3	0.2	0.9	2.8	58.2	1.0	0.6	4.2	8	80
	Bunkpa	5.3	0.8	4.3	0.2	1.1	3.8	53.4	1.3	1.1	5.5	8	80
Kpandai	Bingali	5.3	0.96	5.3	0.1	1.0	2.6	101.9	1.3	3.3	4.0	6	82
	Wiae	5.9	0.8	4.4	0.2	1.7	2.6	102.5	1.3	1.1	4.7	8	76
	Bankamba	5.9	0.8	4.7	0.1	1.4	2.5	91.5	1.2	1.2	4.2	8	64
	Lonto	5	0.32	4.1	0.0	0.6	1.1	71.4	1.1	0.6	2.2	8	80
	Balai	4.9	0.72	4.4	0.0	2.8	1.9	66.9	1.4	0.5	5.2	8	78
	Nkanchina	5.4	0.56	3.9	0.1	0.6	1.9	78.3	1.2	0.5	3.1	8	80
Nanumba North	Tonayili	5	0.72	4.6	0.2	1.6	2.5	76.2	0.9	0.8	4.7	6	78
	Demonayili	5.3	0.72	4.3	0.2	0.8	1.9	61.7	1.4	1.5	3.3	8	72
	Bolni	5.3	0.8	6.2	0.1	0.9	3.4	149.9	1.7	2.1	4.8	10	76
	Kpaturi	5.6	1.05	2.6	0.1	1.0	4.3	69.8	2.0	1.4	5.7	8	78
	Karaga	5.4	0.64	5.0	0.3	1.5	2.8	89.1	1.4	1.2	5.0	6	80
	Jilo	5.3	0.96	6.0	0.1	1.4	2.8	67.6	1.6	1.1	4.7	10	62
Nanumba South	Juali	5.1	0.8	5.1	0.1	0.9	2.2	84.8	1.5	1.0	3.6	4	82
	Kpansu	5.1	0.4	5.1	0.1	0.3	1.7	58.2	1.0	0.6	2.5	10	78

	Kpabudo	5.3	0.56	3.8	0.2	0.5	1.7	43.5	0.9	1.0	2.8	6	76
	Nassamba	5	0.4	3.3	0.1	0.4	1.5	45.8	1.0	0.6	2.5	6	84
	Kajesu	5.4	0.96	5.0	0.3	1.5	3.0	65.1	1.5	0.9	5.1	6	80
	Nakpayili	6.4	0.96	4.9	0.2	0.4	4.7	69.1	1.8	2.0	5.4	8	76

5.4.3: Effect of imbalanced and balanced nutrient applications on yield and production risk

Variations in nutrient applications significantly affected mean maize yields, yield variability, and the probability of attaining yields >3 t ha^{-1}across all three cropping seasons (Table 5.3). On average, all applications including the combined application of NPK outperformed those with N, P or K omitted. Yields were generally largest with application of NPK plus secondary and micronutrients, with mean yields of 3.9, 3.5 and 1.9 t ha^{-1} recorded in the three consecutive seasons, respectively. These yields were at least three times larger than yields attained under no nutrient application in all three cropping seasons, as shown by mean yields of 0.9, 0.4 and 0.5 t ha^{-1} respectively. Mean yields in all other treatments were also significantly ($p<0.05$) less than yields attained with NPK + SMN in the first two cropping seasons. In the last cropping season, mean yields in the control, PK, NK and NP treatments were significantly smaller than those in the NPK and NPK + SMN treatments, while yield with NPK was not significantly different from that with NPK + SMN, though larger yields were recorded in the latter treatment (Table 3.3). Across all treatments, substantially lower yields were recorded in the third season relative to yields in the first two cropping seasons.

The co-application of NPK and secondary and micronutrients also reduced yield variability, and increased the probability of attaining yields >3 t ha^{-1} (Table 3.3). Application of NPK had the second highest probability of attaining yields >3 t ha^{-1}, though yield variability was larger than with NPK + SMN (Table 3.3). Similarly, omission of N, P or K resulted in higher yield variability, and reduced probability of attaining yields >3 t ha^{-1} (Table 3.3). For example, N omission resulted in a CV >60 in all three cropping seasons, with no probability of attaining yields >3 t ha^{-1} (Table 5.3). P omission also resulted in high yield variability with CVs of 50.2, 76.8 and 75.4, while the probability of attaining yields >3 t ha^{-1} was only 0.12, 0.03 and zero in the first, second, and third cropping season respectively. Yield variability with K omission was generally lower in the first two cropping seasons, but increased markedly in the third cropping season, with similar effects on the probability of attaining yields >3 t ha^{-1} (Table 5.3).

5.4.4: Effect of imbalanced and balanced nutrient applications on nutrient use efficiency

Imbalanced nutrient applications significantly ($p<0.05$) reduced the use efficiency of applied nutrients as indicated by differences in PFP between treatments (Table 5.3). Across all three cropping seasons, the highest PFPN, PFPP, and PFPK were recorded in the NPK + SMN treatment. In two out of three seasons, PFPN, PFPP, and PFPK in the NPK + SMN treatment were significantly ($p<0.05$) higher than with only NPK applied. In all three seasons, PFPN was lowest in the NK treatment, with all treatments where N was applied together with P recording significantly higher PFPN. Similarly, PFPP was lowest when P was applied without N (PK), with significantly ($p<0.05$) larger PFPP values recorded in treatments including the co-application of N and P across all three growing seasons (Table 5.3). PFPK was also lowest when K was applied without N (PK treatment). However, PFPK with NK was only significantly larger than with PK in the first season, whereas PFPK values with NPK or NPK + SMN were always significantly larger than with PK and NK (Table 5.3).

Table 5.3: Effect of varied nutrient applications on yield of maize grain (t ha^{-1}), production risk, and partial factor productivity (kg grain kg^{-1} nutrient), across on-farm nutrient omission trials sites (n = 23), conducted over consecutive growing seasons, in the Kpandai, Nanumba North, Nanumba South, and East Gonja districts of the northern region in Ghana.

Season system	Treatment[†]	Mean grain yield	Production risk		Partial factor productivity		
			CV	$\phi < 3$	N	P	K
2020	Control	0.9^{a}	57.4	1	--	--	--
	PK	1.2^{a}	60.2	0.99	--	20.8^{a}	20.8^{a}
	NK	1.9^{b}	50.2	0.88	15.8^{a}	--	31.5^{b}
	NP	3^{c}	31.1	0.49	25.2^{b}	50.4^{b}	--
	NPK	2.9^{c}	33.6	0.53	24.4^{b}	48.8^{b}	48.9^{c}
	NPK + SMN	3.6^{d}	32.6	0.32	29.6^{c}	59.2^{c}	59.2^{d}
2021	Control	0.4^{a}	72.2	1	--	--	--
	PK	0.8^{b}	70.3	1	--	13.9^{a}	13.9^{a}
	NK	1.2^{c}	76.8	0.97	10.3^{a}	--	20.5^{a}
	NP	1.9^{d}	47.6	0.9	15.6^{b}	31.3^{b}	--
	NPK	2.5^{e}	48.4	0.68	20.4^{c}	40.9^{c}	40.9^{b}
	NPK + SMN	3.1^{f}	32.2	0.45	26.0^{d}	51.9^{d}	51.9^{c}
2022	Control	0.5^{a}	77.6	1	--	--	--
	PK	0.6^{ab}	68.0	1	--	9.0^{a}	9.0^{a}
	NK	0.8^{b}	75.4	1	7.6^{a}	--	15.2^{a}
	NP	1.2^{c}	64.1	0.98	11.5^{b}	23.1^{b}	--
	NPK	1.6^{d}	61.1	0.9	14.4^{bc}	28.8^{bc}	28.8^{b}
	NPK + SMN	1.9^{d}	47.5	0.86	16.6^{c}	33.2^{c}	33.2^{b}

Significant differences are observed at P<0.05 for values in the same column within each season, denoted by a distinct superscript.

5.4.5: Responses of maize grain yield to fertilizer treatments

In the first season, mean RY_{PK}, RY_{NK}, and RY_{MN} were all significantly lower than 1 (Table 5.4), demonstrating fast, effective responses to N, P, and application of secondary and micronutrients. In the second seasons, the response to K was additionally significant, while in the third season, significant responses were observed for N, P, and K. Across all three seasons, the strongest yield responses were observed for N followed by P, indicating that these are the most restrictive nutrients in the experiment site. Mean RY_{MN} values were smaller than mean RY_{NP} in two out of three cropping seasons (, indicating that secondary and micronutrients could be more limiting than K in the study area. Seasonal trends in RY showed no significant differences in mean RY_{PK}, RY_{NK}, and RY_{MN} values between seasons, suggesting minimal changes in responses to N, P and secondary and micronutrients, through declining RY values over time indicated increasing limitations. On the contrary, mean RY_{NP} values in the second and third seasons were significantly lesser than that in the first year (Table 5.4), suggesting strong short-term changes in response to K.

Table 5.2: Seasonal variation in the relative grain yields of maize across on-farm (n=24) nutrient omission trials conducted in northern Ghana over three consecutive growing seasons.

Relative Yield[†]	Season[‡]			
	2020	2021	2022	*LSD*
RY_{PK}	0.48^a	0.36^a	0.37^a	0.17
RY_{NK}	0.69^a	0.53^a	0.53^a	0.19
RY_{NP}	$\mathbf{1.12}^a$	0.83^b	0.85^b	0.21
RY_{MN}	0.87^a	0.78^a	$\mathbf{0.89}^a$	0.29

Bold values are not significant from a value of 1.
There is a significant difference at P<0.05 between values in the same row that have a different superscript.
The means for the ratios of NPK treatment yield in a given season to that of PK, NK, and NP treatment yield are RYPK, RYNK, and RYNP, respectively. In a given season, RYMN represents the average of the yields from NPK treatment and NPK+MN treatment.

5.4.6: Patterns of yield response to fertilizer applications in space and time across fields

Plotting relative yield cumulatively showed differences in responses to nutrient applications between fields in a season, and across seasons (Fig. 5.2). Approximately 60% of fields responded significantly to N in each of the three seasons ($RY_{PK} < 0.5$). Strong between fields differences in responses to N were however observed across all seasons as shown by the spread of RY_{PK} figures (Fig. 5.2a). The reactions to N did not alter much over time as demonstrated by the similarity in the shape and locations of the cumulative frequency curves for the three seasons (Fig. 5.2a), suggesting immediate strong and persistence N limitations. During the initial season, only 26% of fields had strong responses to P (RYNK < 0.5) (Fig. 5.2b). However, in the subsequent two seasons, about 50% of fields were effectively responded to P, indicating low P stocks in majority of fields. Strong between field differences in response to P were observed across all three seasons as demonstrated by the spread of RY_{NK} values, suggesting strong and persistent difference in P limitations between fields. There was a movement in the cumulative frequency curve from the first season to the next two seasons, to the left, indicating that P limitations increased after continued cropping with no P applications (Fig. 3.2b). In the first cropping season, only about 50% of fields were responsive to K (Fig. 5.2c). These responses were however moderate to minimal, with none of the fields recording RY_{NP} values < 0.5. Strong between fields differences in reaction to K were however noted, with RY_{NP} values > 1.5 recorded in two experiments. In the next two seasons, more than 60% of the fields responded to K, with almost 10% of the total fields exhibiting a strong reaction (RYNP < 0.5). No responses to K were however observed in about 20% of fields across these two cropping seasons, indicating adequate K stocks in some of the fields in this study. Similar to P, strong temporal differences in response to K were observed between the first season and the two subsequent cropping seasons, while minimal temporal differences were observed between seasons two and three. This was indicated by the shift to the left of the cumulative frequency curve to the left after the first season, and the near overlap of the cumulative frequency curves for the second and third seasons (Fig. 5.2c). Similar response patterns to application of secondary and micronutrients were observed across all three seasons (Fig. 5.2d). In all the seasons, close to 70% of sites were responsive to secondary and micronutrients applications, though strong reaction ($RY_{MN} < 0.5$) were only observed in a small proportion of sites across all three seasons (Fig. 5.2d). While strong between field differences in reaction to secondary and micronutrients were observed, temporal differences in responses were very weak as shown by the near overlap of the cumulative frequency curves for the three cropping seasons (Fig. 5.2d). These patterns suggest localized and persistent secondary and micronutrients limitations.

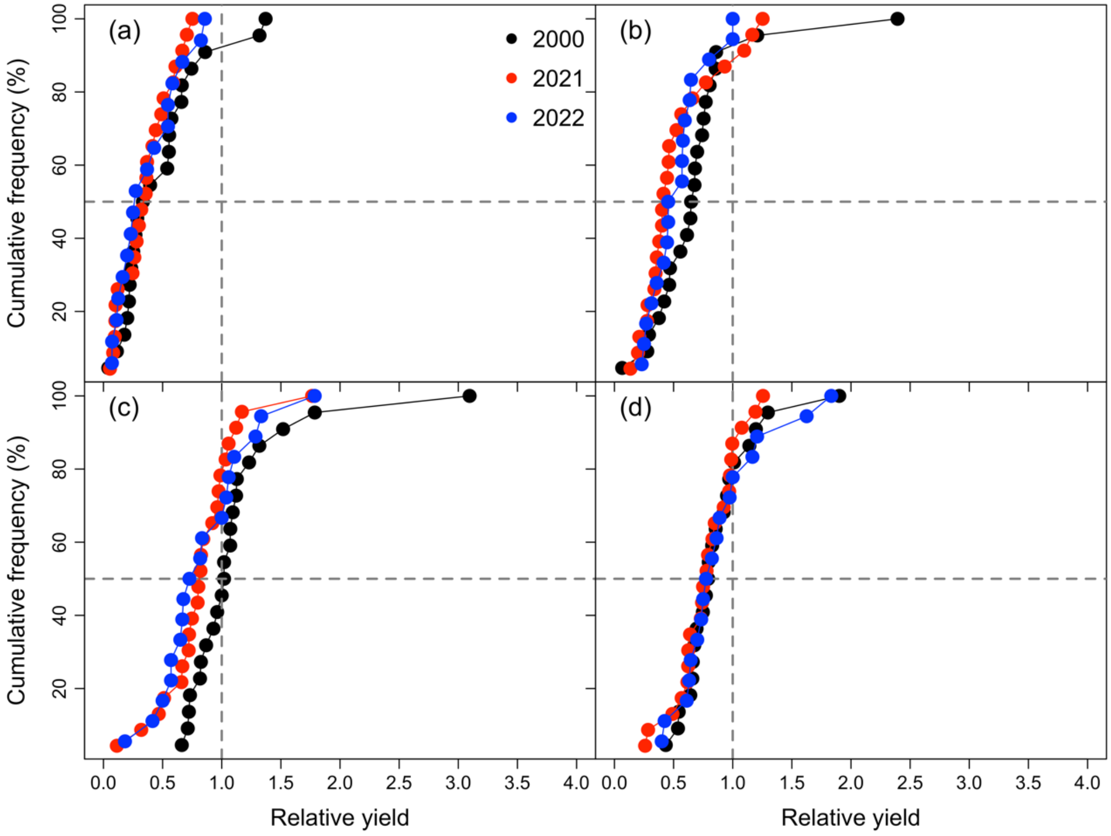

Figure 5.1: Cumulative frequency (%) of relative maize grain yield in three consecutive cropping seasons across on-farm (n=23) NOTs in the northern Ghana region for: (a) RY_{PK} (minus N); (b) RY_{NK} (minus P); (c) RY_{NP} (minus K); and, (d) RY_{MN} (minus S, Mg, Zn & B). The 2020, 2021, and 2022 in the legend refer to the 2020, 2021, and 2022 cropping seasons respectively. Dotted horizontal lines indicate the 50% cumulative frequency mark, while the vertical dotted lines indicate an RY of 1 which indicates no response to the applied nutrient.

5.4.7: Relationship between soil data, and field quality on yield responses to nutrient applications

Recursive partitioning using CTREE analysis showed that there was no partitioning of yield responses to nutrient applications based on any of the soil variables included at a level of significance ($p<0.05$) (not shown) for any of the yield response variables evaluated. This indicated that none of the soil parameters evaluated had a significant influence on yield responses recorded. Subsequently, these relationships were not evaluated further.

Boundary lines fit over scatterplots of the relationship between control yield classes, yield in NPK treatment plots and in plots with N, P or K omitted, or secondary and micronutrients added illustrated the relationship between field quality and responses to nutrient applications (Fig. 5.3). Maximum attainable yield with NPK application was about 4.5 t ha^{-1} and was already attained at control yields <0.5 t ha^{-1} (Fig. 5.3a), suggesting low fertility but strongly responsive fields. Surprisingly, attainable yields with NPK appeared to decline with increasing field quality (Fig. 5.3a). The effect of omitting N on attainable yield was largest at low control yields, with a yield loss of about 3 t ha^{-1} at lower control yields. Attainable yields with N omitted increased marginally with increasing field quality, but reached a maximum of about 2 t ha^{-1} at control yields. At higher control yields, the effect of N omission on attainable yields with NPK declined substantially, though this was more related with declining NPK attainable yields with increasing field quality, rather than increases in attainable yields with N omitted (Fig. 5.3a). However, at no point did the gap between attainable yields with PK and those with NPK close, indicating persistent N limitations across all field quality classes. Similar to N, effects of P omission on attainable yields with NPK were largest at low control yields, with yield losses of about 1.5 t ha^{-1} observed (Fig. 5.3b). However, contrary to patterns observed for N, attainable yields with P omitted decreased as control yields increased in line with the patterns observed for NPK (Fig. 5.3b). Despite these patterns, the yield loss associated with omitting P relative to attainable yields with NPK was consistently >= 1 t ha^{-1} across all control yield levels, indicating P limitations across all field quality categories (Fig. 5.3b). Maximum yields with K omitted were about 3.7 t ha^{-1}, and were recorded at low control yields, with moderately lower yields observed at higher control yields (Fig. 5.3c). The largest yield loss following K omission was also observed at low control yields, with a decline in yield losses related to K omission observed at higher control yields, resulting in closure of the gap between attainable yields with K omitted and those with NPK at control yields of about 1.8 t ha^{-1} (Fig. 5.3c). This closure was however more related to declining attainable yields with NPK at higher control yields, rather than due to higher yields with K omission at higher control yields (Fig. 5.3c). Maximum attainable yields following application of NPK plus secondary, and micronutrients was only slightly larger than that with NPK at 4.6 t ha^{-1} (Fig. 5.3d). However, in contrast to attainable yields for NPK which declined with increasing control yields, attainable yields with NPK plus secondary, and micronutrients remained close to this maximum value at increasing control yields (Fig. 5.3d). Subsequently, the positive effect of application of secondary and micronutrients was more pronounced at higher control yields, resulting in a maximum yield gain of about 1.5 t ha^{-1} at control yield levels of about 2.2 t ha^{-1} (Fig. 5.3d).

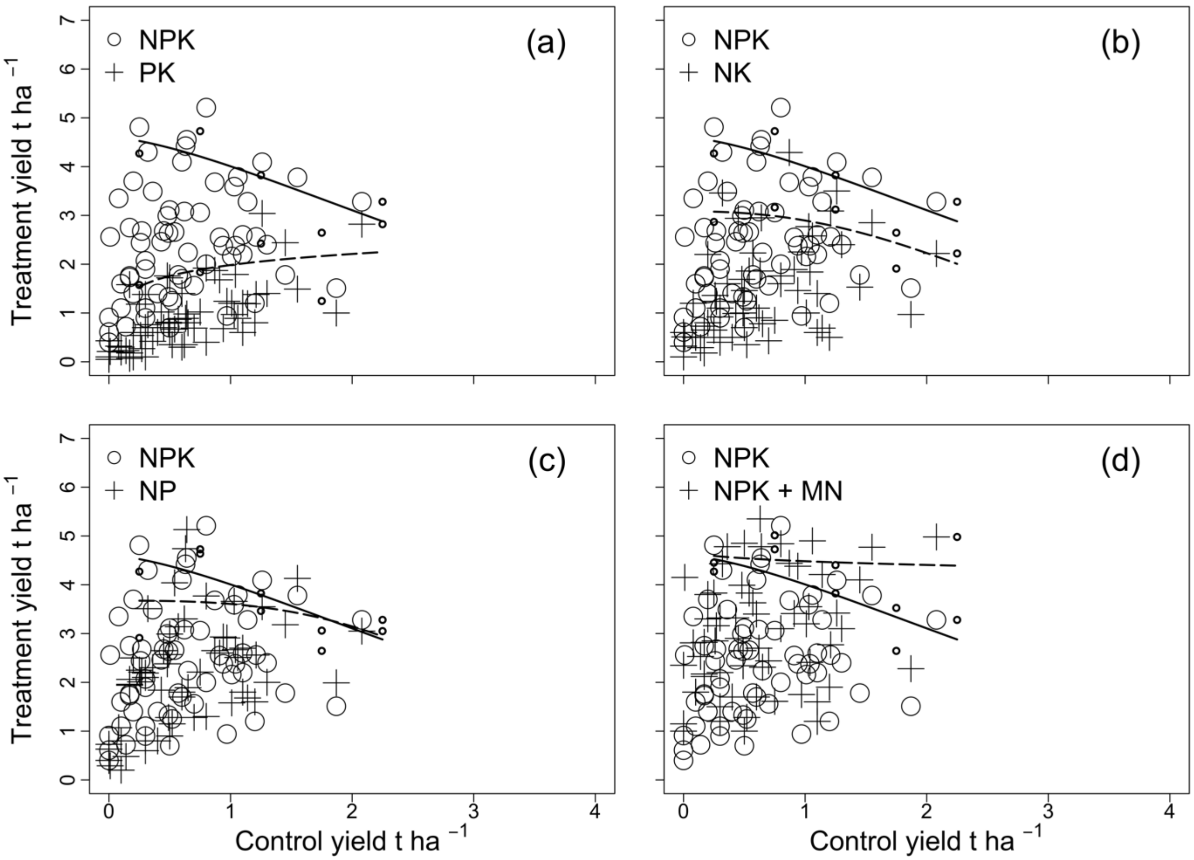

Figure 5.3: Effect of different applications of nutrients on yields attained at different levels of control yields for (a) PK applications; (b) NK applications; (c) NP applications; and (d) NPK + Secondary and micronutrient applications. Continuous boundary lines indicate attainable yields with combined NPK application at various levels of control yields, while dotted boundary lines represent maximum yields under varied nutrient applications at different levels of the control yields

5.5: Discussion

5.5.1: Low soil fertility and variable rainfall conditions limit maize productivity

Findings from our study indicated that soils in the study area were generally low in fertility. The outcome validates Ghana's agro-ecological zones' low intrinsic fertility status in the Guinea and Sudan savannah, as reported by MOFA, (2018). The soil is further stripped of its vital plant nutrients to varied degrees by practices like bushfires (Bagamsah, 2005), overgrazing (Kombiok et al., 2012), intensive cropping (AGRA, 2014), and bad agricultural methods (Boakye-Danquah et al., 2014). It is possible that this has to do with the nutrient-poor clay soils by nature. In this case, crop needs are satisfied by soil reserves until crop demands are met, at which point plant development and yield are reduced. The soil's fertility is mostly dependent on organic matter with which frequent tillage accelerates the loss of which mostly happens from continual cropping with burning or stubble removal. However, with extremely low yields, maize production is still mostly inadequate. This was evident in the research result of control treatment grain yield (table 5.3), which was mostly caused by recent climate change and diminishing soil fertility (Yegbemey et al., 2014). As a result, there were little applications of organic or inorganic nutrient inputs (Leitner et al., 2020). One of the key elements that directly affects crop yield and quality is soil fertility and nutrient management. Regardless of the size of field or plot, a successful maize production business depends on giving plants the proper amount of nutrients at the right time. A number of reasons have contributed to low soil productivity, including the loss of organic matter in the soil, the depletion of plant nutrients, high water infiltration, and limited soil water-holding capacity (FAO-RAF 2000). It is demonstrated that adding compost and organic manure increases the amount of organic matter in the soil (Soumare, Tack, and Verloo 2003; Adani et al. 2007), enhances water infiltration and retention (Agassi et al. 2004), and increases the amount of water that is available in the soil by 58–86% (Celik, Ortas, and Kilic 2004).

A continuous cereal-after-cereal cropping system has resulted from increased population pressure on the limited amount of land available (Anane-Sakyi et al. 2005).

Rainfall during the three growing seasons was characterized by variability in both total rainfall and distribution across the growing seasons (figure 5.1). This phenomenon has the potential to adversely affect crop production and food security in the area. The rainfall volume in 2020 season was moderate and well distribute from June to November while that of 2021 tend to be higher which bur poor distribution which resulted in flooding in most of the farms. The volume of rainfall in 2022 season was low with poor distribution compared to previous years which led to dry spelt. In relation with the volume of rainfall to the annual grain yield produced showed that year 2020 produced higher grain yield and this could be attributed to the rainfall being evenly distributed. Also it was observed that the higher volume of maize production were positively related to the annual rainfall volume recorded in those years (table 5.3). The finding here should provide the basis for which agriculture policy makers can plan for irrigation. The findings also point to the need for farmers to be encouraged to adopt water harvesting technologies in order to deal with periods of dry spells during the production season, which normally occurs during the months of June to October.

5.5.2: Balanced nutrient applications enhanced maize yields and reduced production risks

Strong impacts of soil fertility variability on maize productivity and nutrient requirements were confirmed by the observed responses in terms of space and temporal variation in maize yield in relation to NPK and secondary macro and micronutrients (SMN) combinations. Majority of farms had deficiencies in N, and each farm's reaction to applying P and K differed significantly. This can be attributed to ongoing cultivation without legumes and sparing use of manure or fertilizer N, the soil's organic matter levels are comparatively low, which contributes to the widespread N deficit (Tittonell et al., 2005). The addition of specific SMNs above and beyond the usual N, P, and K fertilizer boosts maize output overall, indicating that more than just the three basic nutrients are needed to close yield gaps in poorly responding soils (Vanlauwe et. al., 2015). Yields were generally higher with application of NPK plus SMN in the three consecutive seasons. The increased nutrient availability, improved growth, and productivity brought about by the SMN treatments may account for the higher grain production when combined with NPK (Qahar & Ahmad, Citation 2016). This outcome is consistent with findings by (Kihara et al. 2017, Njoroge et al. 2018, and Lisuma and Sem, 2016), which showed that adding secondary and micronutrients might greatly boost grain yield of maize and confirms that co-application of N P K and SMN is critical for optimum crop growth in the cropping system. Improvements in the area's soil nutrient imbalances and deficiencies may be the cause of the increase in grain yield resulting from secondary and micronutrient inclusion as compared to the P, K and the control plots. Furthermore, a lack of vital nutrients like N and P may have contributed to the decrease in grain production in the control plots that did not get fertilization.

Applying P did not have a statistically significant effect on maize yield in the first season as evidenced by large relative NK yields. This was most likely due to some P that was left over from treatments in prior seasons because P released into harvests afterward (Kifuko et al., 2007) is a result of P applied as manure or fertilizer that is not absorbed by the crop.

The weather pattern is a fundamental constraint to maize production beyond nutritional deficits for rain-fed agriculture, as confirmed by the noticeable seasonal effect on yield (Cooper et. al., 2008). The yields achieved during the second cropping seasons varied, despite the fact that a comparison of the yields at the regional level revealed no discernible changes. But the benefits of residual P were only short-lived; several farms eventually showed more pronounced P reactions. This demonstrates the poor resilience of the soil P reserves in these fields. When compared to P fertilized plots, yields from P-omitted plantings decreased significantly and progressively over the course of multiple seasons.

Co-applying NPK with secondary and micronutrients decreased production risk and raised the likelihood of reaching yields more than 3 t ha $^{-1}$. While yield variability was greater than with NPK + SMN, using NPK had the second-highest chance of producing yields >3 t ha $^{-1}$. The exclusion of N, P, or K also increased yield risk and decreased the likelihood of achieving yields more than 3 t ha $^{-1}$ (Kifuko et al., 2007). According to Vanlauwe et al. (2006), there are variations in the P fertility status of the soil due to past field management practices and the availability of farmer resource. The substantial range in maize yields observed following NK treatment and the occurrence of clusters with significant changes in the response to applied P reflect these variations. However, the benefits of residual P were only transient; as time went on, more farms showed increasingly pronounced P-related responses.

This suggests that there are limitations to the robustness of the soil P stores in these fields when comparing P-fertilized plots to those that were left without P for more than one season, the yield reduction was noticeable and decreased over time. Smallholder farmers in Northern Ghana apply little amounts of fertilizer, which is insufficient to increase the availability of P in the soil and sustain high maize yields over several growing seasons (MOFA 2019). Farmers can sustain productivity by applying P sparingly and judiciously, either seasonally or every other season depending on response clusters that have been found (Kamiri et al., 2011; Kihara and Njoroge, 2013). The law of the most limiting nutrient and crop growth, as well as the imperative necessity of balanced nutrient administration, are both exemplified by these results.

Increased nutrient utilization efficiency was achieved by balanced nutrient treatments. The chance of achieving yields >3 t ha-1 over all three cropping seasons, mean maize yields, and yield variability were all highly impacted by variations in fertilizer treatments. The combined application of N, P, and K performed better than any application that did not include N, P, or K. When NPK was combined with secondary and micronutrients, yields were typically highest. These harvests exceeded yields obtained in all three cropping seasons by a factor of at least three when nutrients were not applied.

A key element in determining nutrient usage is the plant's capacity to both absorb and use nutrients from the soil efficiently (NUE), which is also dependent on internal transport, storage, and remobilization of nutrients. One essential component controlling plant growth and development is nitrogen (N). Grain production per unit of fertilizer inputs is known as the partial factor productivity of fertilizer (Olk et al., 1999). Imbalanced nutrient applications significantly reduced the use efficiency of applied nutrients as indicated by differences in PFP between the treatments. Ismail et al., (2020) earlier reported that the addition of secondary and micronutrients increased maize yield, agronomic use efficiency, internal utilization efficiency and apparent recovery efficiency of N, P and K relative to the application of NPK only. Despite an increase in the use of fertilizer, its use efficiency is still low because of inadequate crop management techniques (Byerlee et al., 2007, Sheahan and Barrett, 2014), the prevalence of sandy soils with low fertility by nature (Bationo et al., 2012), and uneven fertilizer recommendations that fail to take into account the intricate nature of smallholder farming systems (Chikowo et al., 2014, Giller et al., 2011). Smaller uptakes of N, P or K following imbalanced applications resulted in larger accumulation of available stocks, while accumulation was less strong under balanced fertilization where uptake was large. Despite an increase in the use of fertilizer, its use efficiency is still low because of inadequate crop management techniques (Byerlee et al., 2007, Sheahan and Barrett, 2014), the prevalence of sandy soils with low fertility by nature (Bationo et al., 2023), and uneven fertilizer recommendations that fail to take into account the intricate nature of smallholder farming systems (Chikowo et al., 2014, Giller et al., 2011). The intake of soil nutrients and crop requirements must be balanced. A crop will yield its maximum potential if nutrients are supplied when needed and in sufficient amounts.

5.5.3: Variable maize yield responses to nutrient applications

The observed changes in yield responses to the applied N, P, K, and MSN combinations over time and space further supported the major effects of soil fertility variability on maize productivity and nutrient requirements. Most farms lacked sufficient amounts of N, and there were significant differences in the farms' reactions to applying P and K. There were little temporal changes in the response to N, as evidenced by the slow decline in RYPK observed for the majority of the time and the moderate change in mean RYPK over time. In smallholder farming systems located in Northern Ghana, there are notable variations in both spatial and temporal responses to N, P, K and SMN. Similar observation were made by Njoroge et al., (2017) elsewhere in Kenya.

However, in the subsequent two seasons, about 50% of fields were strongly responsive to P, indicating low P stocks in majority of fields. The spread of RYNK values during the three seasons revealed significant variations in field responses to P, indicating a considerable and ongoing variation in P restrictions between fields. The changed from the first to the second two seasons gave an indicating that P limitations rose as cropping continued without P treatments. Phosphorus frequently acts as a limiting element in ecosystems because it frequently forms persistent insoluble compounds that are unavailable for use by organisms (Le-Bayon et al., 2006). This implies that even in soils with adequate phosphorus levels, the element might not be readily assimilated by living things. Phosphate, the form of phosphorus that is useable, is not easily absorbed by plants, which further reduces its availability in the soil. According to Sulemana et al. (2021), the high temperatures in northern Ghana cause minimal return to the soil and rapid mineralization, undermining the roles of organic components and leaving the soils deficient in available P. Thus, a major issue with the soils of northern Ghana is the lack of phosphorus, a nutrient that is available to plants. Thus, large applications of P fertilizer are required to grow high-yield arable crops. Consequently, in order to provide the soil with a consistent source of P, a more resistant type of organic matter may be used. It is preferable to band phosphorus fertilizer at the roots rather than apply it in a broadcast or ring manner. This tactic aims to minimize P contact with soil in order to saturate the root sorption sites and increase solution concentrations (Havlin et al., 2006).

Approximately 50% of fields responded to K during the first cropping season. None of the fields recorded RYNP values less than 0.5, indicating that these reactions were moderate to minimal. However, there were notable variations in response to K between fields, with RYNP values more than 1.5 seen in two of them. In the next two seasons, more than 60% of the fields responded to K, with almost 10% of the total fields exhibiting a robust response (RYNP < 0.5). Nonetheless, throughout these two cropping seasons, no responses to K were seen in roughly 20% of the fields, suggesting that some of the study's fields had sufficient K reserves. As with P, there were little temporal variations between seasons two and three, but significant temporal differences were seen in the response to K between the first season and the two following cropping seasons. In all three seasons, comparable reaction patterns to the application of secondary and micronutrients were noted. Nearly 70% of sites responded to the addition of secondary and micronutrients in all three seasons, however only a small percentage of sites showed robust reactions (RYMN < 0.5) (Fig. 2d). These findings point to persistent and localized deficiencies in secondary and micronutrients.

5.5.4: Variability in field quality, related to variations in maize yield responses to nutrient applications.

The difference between actual farm yield and attainable farm yield has been defined as the yield gap (Stuart et al., 2016) which has been liked to differences in the quality of field. A different definition that is more applicable to actual agricultural circumstances is the economically feasible yield, as suggested by Fischer, (2015). The gap between attainable yields with PK and those with NPK were not close at any point, indicating persistent N limitations across all field quality classes. This suggests a significant relationship between the nutrient requirements for maize production and the variability of the soil and also asserts that N is the most yield-limiting nutrient. According to Kamara et al. (2005) and Adnan et al. (2017), there have been other studies that show a comparable significant response of maize production to N application in various parts of the Nigerian Savanna. According to Vanlauwe et al. (2011), the most restricting nutrient in the maize cropping system across a significant portion of SSA is generally known to be N insufficiency (Morris et al, 2007). This implies that in order for maize to grow as well as it can in Northern Ghana, fertilizer techniques and technologies that control the dynamics of nitrogen in the soil are essential.

The effects of P omission on attainable yields with NPK were also largest at low control yields, with appreciable yield losses observed (Fig. 3b). Achievable yields with P removed decreased with increasing control yields in line with the patterns seen for NPK, in contrast to the trends seen for N. These trends notwithstanding, the yield loss linked to P omission compared to achievable yields with NPK was consistently higher across all control yield levels, suggesting P restrictions over all field quality categories. Lower maize grain yield was observed when P was eliminated. This observation was consistent with the findings of Kogbe et al. (2003), who also discovered that the absence of P or insufficient P application reduced the grain yield of maize. According to Grant et al., (2001), plants need sufficient P from the very beginning of growth for optimal production; this may be among the causes of the current result of lower yield recorded in the study when P was omitted.

The yield response to K fertilizer was significantly lower than the response to N or P application. The largest yield loss following K omission was also observed at low control yields, with a decline in yield losses related to K omission observed at higher control yields, resulting in closure of the gap between attainable yields with K omitted and those with NPK at control yields. This is probably because the crop's inherent K levels are high enough to meet its K needs. After applying NPK along with secondary and micronutrients, the maximum yields that could be obtained were marginally higher than those obtained with NPK alone. On the other hand, achievable yields with NPK with secondary and micronutrients stayed rather close to reaching maximum yields, in contrast to feasible yields for NPK, which decreased with rising control yields. Consequently, at greater control yields, the beneficial effects of applying secondary and micronutrients were more noticeable, leading to a maximum yield gain.

One of the most efficient ways to increase nutrient uptake in crop plants and enhance crop yields and quality is to apply NPK, which includes secondary and micronutrients, as most soils cannot provide all the plant nutrients needed in sufficient amounts to ensure optimal crop development and production (Kumar et al., 2012).

3.6: Conclusion

This study has shown that in order to restore the poorly responding soils, more has to be done than just apply the recommended amounts of N, P, and K fertilizers. The study suggests that inclusion of secondary and micronutrients to maize fertilizer application could significantly increase its yield. It is recommended to use balanced nutrition that includes both basic and secondary macronutrients as well as micronutrients to close the nutrient-related yield gaps in maize. Although there are currently no studies on the inclusion of secondary and micronutrients in fertilizer formulation for decision-making in the region, the findings of this study provide a basis for their addition. Fertilizer recommendations that are customized to the needs of individual farmers, crops, soil fertility, and climate can boost productivity while lowering environmental hazards associated with fertilizer use and production risks due to climate change. More specifically, varied farm types, varying soil and climate conditions and crop systems most susceptible to altering patterns of rainfall all call for the use of such tailored suggestions. The result of this study is site-specific nutrient recommendations that will address the observed variability. All fields responded to a mixed NPK fertilizer and the addition of secondary and micronutrients; the reaction was strongly correlated with yields in the P, K, and control plots.

CHAPTER SIX

MAIZE YIELD RESPONSES TO VARIED RATES OF S, ZN AND B INCLUSION IN NPK

Abstract

Current fertilizer recommendations in majority of maize production systems in sub-Saharan Africa provide for the application of the primary macronutrients namely nitrogen (N), phosphorus (P) and potassium (K) only. Deficiencies of secondary and micronutrients (SMNs) have however been identified as are a major cause of low maize yields in poorly responsive soils. We assessed the effect of co-application of N, P and K with secondary (sulphur), and micronutrients (zinc and boron) on maize yields. Field experiments were conducted on-station based on a split-plot design that included omission of secondary or micronutrients. Investigations were carried out in the 2021 and 2022 cropping seasons in Nyankpala and Damongo areas of Northern Ghana. The results of this investigation demonstrated that the addition of secondary and micronutrients, as opposed to NPK alone, significantly increased maize yields in both years. In Nyankpala, yields of 4.5 and 5.0 tons ha^{-1} were achieved with inclusion of S, Zn and B combined in both years while in Damongo, yields of 3.26 and 2.58 t ha^{-1} were achieved. For NPK-only treatment, average yields of 2.30 and 2.53 were achieved in Nyankpala for both years while 1.28 and 1.48 were achieved in Damongo. Secondary and micronutrients have a significant impact on maize grain output even though plants only require modest amounts of them compared to NPK. In order to guarantee increased maize productivity and profitability in Northern Ghana, fertilizer recommendations should not only include NPK fertilizers but also take into account all limiting secondary and micronutrients in a comprehensive and balanced fertilizer recommendation.

6.1: Introduction

Crop nutrients are essential for the development and growth of plants (Datnoff et al., 2007). Maize require a range of nutrients to grow and develop properly, with some being required in larger quantities than others. The primary macronutrients that plants need in lager quantity, are nitrogen (N), phosphorus (P), and potassium (K). Secondary and micronutrients are also important plant nutrients for maize production. However, usually require in smaller quantities compared to primary macronutrients. In the Guinea Savannah agro-ecological zone of Ghana, low soil fertility and inadequate nutrient management have been key challenges restricting yields of several crops, particularly maize (IFDC, 2012). Compared to water-limited potential, current crop yields are generally very low. (Jayne et al., 2010). The majority of Ghana's soils are deficient in many plant nutrients, but the situation is worse in the north, which falls under the Sudan and Guinea savannah agro-ecological zones (Debpuur et al., 2021). The soils in this region are sandy loams with high sand concentrations and pH values between 4.9 and 5.9, which indicate moderately to strongly acidic soils. Soils with low levels of soil organic carbon (SOC) and soil available P are indicated by organic carbon (OC) values less than 1% and soil available P contents less than 10 mg kg-1, respectively. Additionally, the CEC content of the soils is quite low; most locations have CEC values less than 6 me/100g. The values of the three main exchangeable cations that were measured—K, Mg, and Ca—also suggested that the exchangeable K, Mg, and Ca levels were low, which is a common feature of sandy, acidic soils. Overall, the soil data suggested that the soils had low fertility and are not given much inputs of either organic or inorganic nutrients.

Crop production in this region is characterized by continuous cropping in smallholder farming systems with minimal application of external nutrients, resulting in little replenishment of nutrients taken up by crops (Agovino et al., 2019). Subsequently, most soils are deficient of most nutrients required for attaining and sustaining desired crop yields (Kugbe and Issahaku, 2015), with nutrient management practices in these smallholder systems identified as unsustainable (MoFA 2019 ; 2015).

Despite expected widespread nutrient deficiencies, maize nutrition research in northern Ghana has largely focused on maize yield responses to the primary macronutrients nitrogen (N), phosphorus (P) and potassium (K) (IFDC, 2012). Although the application of primary macronutrients has helped to boost maize yields in northern Ghana, addressing secondary and micronutrient limitations is expected to further increase yields (Sutar et al., 2018). There is however limited information on the key secondary and micronutrients that limit maize yields, and the expected maize yield responses to addition of secondary and micronutrients in northern Ghana. This study therefore sought to document and quantify maize yield responses to secondary and micronutrient applications. The specific objective of this study was to determine the effect of the inclusion of sulfur (S), zinc (Zn), and boron (B) on maize yields at varying levels of NPK fertilizer application.

i. To determine the potential responses of secondary and micro nutrients to the contribution of maize productivity.
ii. To determine the optimum rate of sulphur, zinc and Boron application in maize production.

6.2.0 Bridging yield gaps through secondary and micronutrients

Secondary macronutrients and micronutrients are critical for crop productivity, although they are rarely investigated in Sub-Saharan Africa (Chilimba and Chirwa, 2000), with the main attention focused on primary macronutrients (Chilimba and Chirwa 2000; Voortman 2012; Vanlauwe et al., 2015). There is growing evidence that secondary and micronutrients are becoming increasingly limiting factors for crop productivity, especially in systems where continuous cropping occurs without adequate nutrient replenishment (Vanlauwe et al. 2015; Van Asten et al. 2004). Deficiencies of these nutrients have been linked to yield stagnation in other places. (Abbas et al., 2007).

6.2.1: Primary macro nutrients

Nitrogen (N) is one of the main elements that maize needs for the best possible development and output which is necessary to achieve high and quality grain yield. The accumulation of nitrogen in the stems and leaves of maize plants facilitates photosynthesis. This encourages yield increase, which is correlated with the number of seeds per cob, particularly during blooming. Enhancing the availability of nitrogen also benefits grain filling. (Nuttall, 2012), phosphorus (P), which is required for good root growth and development. Crop tolerance to biotic and abiotic stressors is promoted by adequate K supply and efficient K use, which also impact crop yield and quality. Soil fertility and previous field management are the primary determinants of the amount of fertilizers needed for good yield. Applying 120:60:40 kg/ha of NPK in a balanced manner is required in northern Ghana (FAO 2005). However, the rates of nitrogen, phosphorus, and potassium (NPK) depletion range from 40 to 60 kg per ha/year (FAO 2005).

6.2.2: Secondary macronutrients

Key secondary macronutrients for maize production include calcium (Ca), magnesium (Mg), and (S) are necessary plant nutrients (Oldham, 2019). Secondary macronutrients are different from primary macronutrients in that they are required in smaller amounts by plants ranging from 25-50kg/ha according to Yara fertilizer nutrition summary. Cropping practices that have been in place for a long time have removed measurable amounts of these nutrients from the soil. As a result, secondary macronutrient deficits are becoming more prevalent in intensive maize production systems, particularly in soils that are exclusively fertilized with primary macronutrients (Vanlauwe et al. 2015).

6.2.3: Importance of sulphur to maize production

Sulphur is second only to nitrogen, phosphorus, and potassium in terms of importance, the secondary macronutrient sulphur (S) is one of the most important for plant growth Marschner, H., (1995). Sulphur is necessary for a variety of processes in plants, such as photosynthesis, chlorophyll synthesis, nitrogen fixation, and protein synthesis (Beegle, 2013). Low sulphur levels can cause a deficiency, which might manifest as pale green color, slower plant growth, and delayed maize maturity (Beegle, D. 2013). Sulphur is a crucial component for maintaining the health of both human and animals as well as increasing maize production. The majority of the S in soil is bound by organic matter and cannot be utilized by plants until it is mineralized by soil bacteria into soluble sulphate (SO4-2). Sulphate is easily leached from the soil by irrigation or rainfall since it is mobile there. It is more likely that sandy soils with little organic matter and clay particles will lack sulphur.

The key factor influencing nitrogen availability in plants is sulphur, therefore as sulphur consumption rises, so does nitrogen availability and absorption. According to (Bhagya Laxmi et al., 2010), treatment of 60 kg S ha^{-1} resulted in the greatest cob length and grain weight of 100 for maize. The maximum cob length, weight, and 100 grain weight were obtained with the application of 20 kg S ha^{-1}. According to (Gahlout et al. 2010), applying 45 kg S per hectare resulted in much more grains per cob and grains per 100 grams than at earlier levels. Bharati and Poongothai (2008) also came out to a conclusion that applying 45 kg S ha-1 produced better grain weight. According to Khan et al. (2006), application of 60 kg S ha-1 resulted in greater weight of 100 grains than 40 kilogram S ha $^{-1}$.

4.2.4: Effect on N uptake by Maize

Reduction through absorption reactions of nitrate and sulphate are required for the production of amino acids containing sulphur, hence the absorption and assimilation of nitrogen and sulphur are intimately related (Brunold, 1993). The plant's S state has a significant impact on N metabolism, according to Irfan (2015). According to Fismes et al. (2000), S deficit can make nitrogen usage less effective. Sulfur concentrations rose gradually, increasing the absorption of nitrogen by maize from 208.9 - 244.2 kg ha-1 7. According to (Mehta et al., 2005), grain and stover absorbed the most nitrogen when there was 60 kg of S per hectare. S concentrations that rose over time improved maize's ability to absorb all nitrogen, increasing it from 64.72 to 88.69 kg ha-1. According to (Sakal et al., 2000), grain and stover in the treatment receiving 60 kg S ha^{-1} absorbed more nitrogen than earlier levels. According to Niaz et al., (2014), application of nitrogen @ 200 kg N ha^{-1} resulted in the plant absorbing the most nitrogen of 173.86 kg ha^{-1} compared to 125,150 and 175 kg N ha^{-1}.

6.2.5: Critical threshold for S deficiency in the tissue of maize plant

A sensitive indicator of the status of Sulphur in plants is the amount of sulphate found in plant tissue. Some of the extractants used for this purpose are water, ethanol, trichloroacetic acid, hydrochloric acid, formic acid, hypophosphorus acid, sodium hydroxide, acetone, and acetic acid. Sutar et al. (2017) have done comprehensive review on this subject. The total S concentration of the leaves is another indicator of the amount of S that is sufficient or insufficient in the plant tissue. According to Sugar (2017), the plant contains 0.1% to 5% S and if the levels fall outside of that range, deficiencies result; if sulfur levels rise over that range, plants become poisonous. According to extensive data from the United States published by Kamprath et al. (1981) significant response to S fertilization occurred in maize, especially when the level in the tissue is les or over. According to Kang et al. (1976), the critical level of sulphur in maize ear leaves was 0.14%. In the maize ear leaf, Diagger and Fox (1971) found that the critical level of S was 0.24%. In the maize plant tissue that was 60 days old, the critical concentration of S was determined by the geographical technique of Cate and Nelson, (1965) to be 1120 mg kg-^{1} (0.112%) on a dry weight basis. 650 mg kg^{-1} was described as the critical limit by Sakal et al., (1993)

6.2.6: Sulphur deficiency symptoms

The signs of S deficiency are sometimes mistaken for a nitrogen deficit. Both deficiencies might show up as plants that are stunted and have leaves that are generally yellowing Johnston, A. et al., (2019). Younger leaves show the earliest signs of a shortage since S is immobile in plants.

Figure 6. 1: Sulfur deficiency in maize (source: IPNI image collection)

In contrast, nitrogen shortage symptoms first occur on the older leaves. Sulphur deficits have become increasingly widespread with continuous use of high analysis fertilizers with little or no S and reduced deposition of atmospheric S with efforts to reduce acid rain.

6.2.7: Sources of sulphur

Significant amounts of S can be supplied by rainfall and irrigation water. S emissions from industry and the quantity of S delivered to the soil by precipitation have both decreased as a result of efforts to reduce air pollution (Weil, R.R. 2000). Manure and fertilizers can be applied to give sulphur as well. Ammonium and calcium sulphates, which are moderately to highly soluble in water, make up the majority of the S sources in fertilizers. On sandy soils with little organic matter, maize can respond to additional Sulphur (Rehm, G.W. 2005). There is often no reaction when extra S is added to fine-medium textured soils with an organic matter level of more than 2% (Megan et al., 2008). Sulphur may be present in starter or pre-plant fertilizers. Anything that adds large amounts of organic residues to a soil may increase S content of the soil. On the other hand, anything that causes soil organic matter to decompose more rapidly or to be lost through erosion may deplete S content Rehm, G.W. (2005). The best way to monitor S in the crop is by plant analysis because soil testing is not particularly dependable.

4.2.8: Micronutrients

Plant Micronutrients are vital nutrients that the plant requires in lesser quantities than macronutrients (Mengel et al., 2001). Iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), boron (B), molybdenum (Mo), and chlorine (Cl) are all such micronutrients (Mengel et al., 2001). Many of the activities required for growth rely on these nutrients. It can be difficult to detect a vitamin shortage in maize (https://www.yara.co.uk/). To diagnose a micronutrient shortage, soil tests and plant tissue analyses are frequently required (Holmes, 1980). Micronutrients are necessary for plant growth, despite the fact that they are only required in minute amounts. Critical plant functions can be hampered by a lack of micronutrients, resulting in plant deformities, restricted growth, and poorer production potential. Each micronutrient can play a role in a variety of plant growth processes (Johnston et al., 2004). While an amounts of secondary macronutrients required ranged between 25-50 kg ha^{-1} for maize production, a range of 9-29 g ha $^{-1}$ is required for micronutrients (www.yara.co.uk).

Zinc (Zn) is an essential component of many enzymes and proteins, and it aids in the creation of growth hormones, engaged in different physiological activities such as protein and carbohydrate synthesis, as well as stomata management and lowering the stresses of less water by creating ionic equilibrium in plants' systems (Baybordi, 2006, Yadavi et al., 2014). Similarly, Boron (B) treatment boosts plant growth and stress tolerance, as well as grain output (Hussain et al., 2012). Both Zn and B are essential for basic plant processes such as photosynthesis, protein synthesis, and chlorophyll synthesis (Cakmak, 2008). These nutrients (Zn and B) are also important in root growth, protein and carbohydrate synthesis, floral setting (Moeinian et al., 2011), and kernel abortion (Moeinian et al., 2011; Wahid et al., 2011).

When Zn deficiency is severe, basal plant portions may exhibit a reddish to necrotic brown discoloration along the leaf margins and the stems. Reduced internode development results in a stunted look. In order to assure cereal output and Zn content in the grain, Zn fertilizers must be applied to poor Zn soils (Cakmak, 2008A severe zinc deficiency and adequate supply are crucial for the growth and flowering of maize. The youngest leaves may grow abnormally, with growing tips finally becoming stunted and dead, as one sign of a boron shortage according to Johnston, A. and Dowbenko, R. (2004)

In order to find lasting solutions to the issue of crops with inadequate zinc and boron levels, it is crucial to have a fundamental understanding of the dynamics of Zn, and B in soils, water, and plants. In order to boost Zn and B uptake and usage efficiency in crops, it is necessary to locate the key areas having Zn and B deficiency in soils and food crops and treat them with Zn and B supplements, primarily fertilizers. According to Alloway, (2008), Zn can contaminate food chains, water, and soil. Zn insufficiency in humans is linked to diet quality and made worse by Zn-deficient soils (Alloway, 2009). Sandalloid, calcareous, saline, and marsh soils are soil types that are vulnerable to zinc deficiency because they are compacted, rich in organic matter, and contain high levels of nitrogen and phosphate. (Alloway, 2008). Zn is also present in surface and groundwater, and it enters the environment through a variety of channels, including urban runoff, industrial and municipal waste, mine drainage, and, primarily, the erosion of soil fragments that contain Zn according to U.S. Environmental Protection Agency (EPA, 1980). The most common form of boron found in soil is boric acid (BA) (H 3 BO 3), which is highly soluble and readily leached by rainfall (Bolaños et al., 2004), particularly in soils with low levels of organic matter (Yermiyahu et al., 2001).

6.2.9: Concentration range of major elements in mature plant leaf tissue and grain

A plant's nutritional makeup varies according to age and developmental stage in addition to within its individual plant components. Varietal variations also impact the amount of nutrients present in different regions of the plant. Based on a comparison between the nutrient concentration found in a specific plant part obtained at a given time and known target values or concentration ranges, a plant analysis interpretation is established. One interpretation strategy according to Jones and Eck (1973) is based on "critical values," where "critical value" refers to the concentration below which a deficiency is most likely to manifest. Sufficiency ranges, or the optimal element concentration range above which toxicity or imbalances occur and below which deficiencies develop, provide a more practical framework for interpretation.

Table 6.1: Concentration range of major elements

Major elements	% deficient	% Sufficient	% excess/toxic
N	>2.50	2.5-4.5	>6.00
P	>0.15	0.20-0.75	>1.00
K	>1.00	1.50-5.50	>6.00
S	>0.20	0.25-1.00	>3.00
Micronutrients	Ppm	Ppm	ppm
Zn	>10-20	27-100	>100-400
B	>5-30	10-20	>50-200

Source: R. B. Lockman, 1984.

6.3: Materials and Methods

6.3.1: Experimental sites

The experiment was conducted in two on-station research locations namely Nyankpala and Damongo in the Northern and Savanna regions of Ghana respectively. Nyankpala is a town in Tolon district, which is about 16 kilometers south-west of Tamale, the capital of the Northern Region. Nyankpala lies at an altitude of about 170 meters above sea level with coordinates of 9.3965° N, 0.9892° W. The area is characterized by a mild, semi-arid tropical climate with a mono-modal annual rainfall of 800-1200mm, which falls largely between May/June and October, though patterns are highly variable.

Damongo, on the other hand, is the capital of the Savannah Region, on coordinates of 9.0913 ^{o} N 1.827 ^{o} W, an elevation of 217 m, and is located 125 kilometres west of Tamale. It has a mono-modal rainfall pattern, with average annual rainfall of about 1144 mm. The rainy season commences in late April and ends in late October, though patterns are highly variable. The month of August/September is the wettest

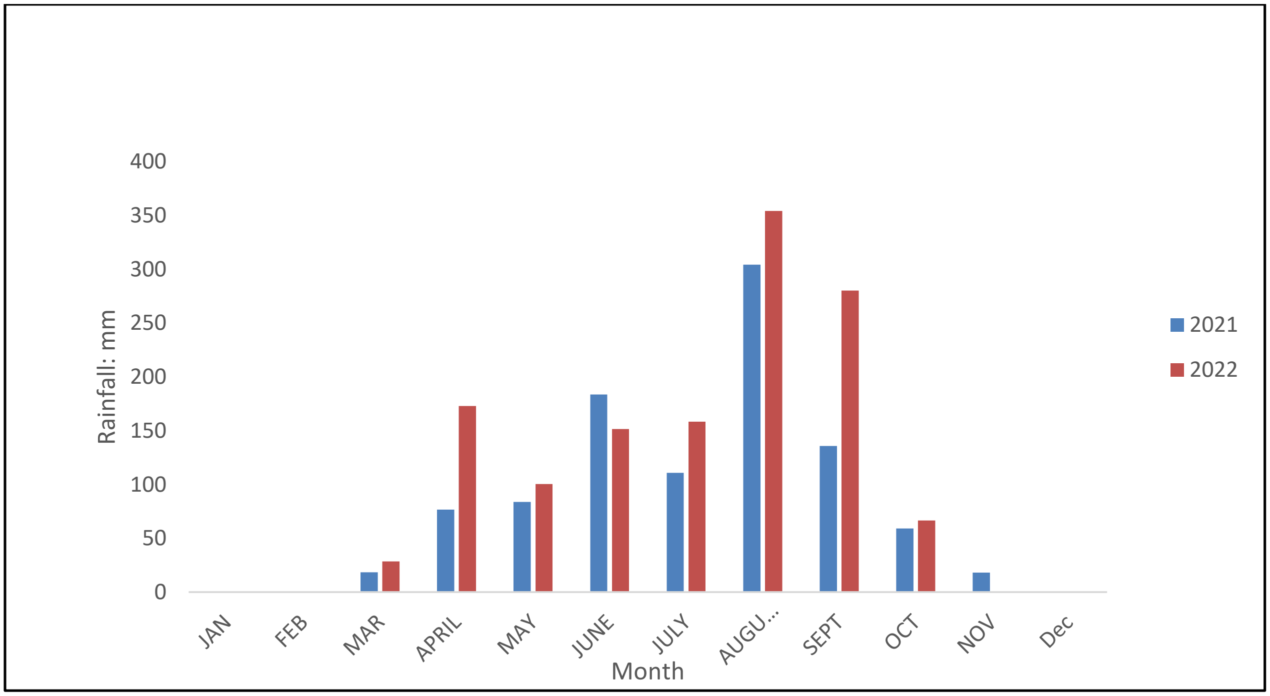

Figure 6. 2: Rainfall data at Nyankpala 2021/2022 season. Source: SARI weather station

6.3.2: Experimental Design and Treatments

The field experiment was laid in a split plot design with three replications (table 4.2**)**. The main plot factor treatments were two NPK rates: 60, 40, 40 kg ha $^{-1}$ and 90, 60, 60 kg ha $^{-1}$ which were denoted as MR (minimum rate) and HR (high rate). The sub plot factor treatments were ten combinations of secondary and micronutrients (sulphur, and zinc and boron). A control treatment with no nutrients applied was also included.

The main plot size was 26 m x 11m with an alley of 1.5 m between each main plot which gave an area of 305 m^2, while the sub plots size was 5 m x 4.5 m within the main plot with an alley of 1m which gave an area of 22.5 m^2 planted with six rows of maize.

The planting distance of the maize was 75 cm between rows and 40 cm within rows with two plants per stand which gave a plant population of 150 per plot and 66,666 per hectare, respectively.

Table 6. 1: Nutrient composition in the treatments

Treatment	Size of nutrient rate	Rate (kg nutrient ha $^{-1}$)
Main plot treatments		
NPK (MR)	mr*	60- 40- 40
NPK (HR)	hr**	90- 60- 60
Sub plot treatments (SMN)		
T1. SB_{mr}	mr	$S_{10} + B_{0.5}$
T2. SB_{hr}	hr	$S_{20} + B_{1.}$
T3. ZnB_{mr}	mr	$Zn_{1} + B_{0.5}$
T4. ZnB_{hr}	hr	$Zn_{2} + B_{1}$
T5. SZn^{mr}	mr	$S_{10} + Zn_{1}$
T6. SZn_{hr}	hr	$S_{20} + Zn_{2}$
T7. $SZnB_{mr}$	mr	$S_{10} + Zn_{1} + B_{0.5}$
T8. $SZnB_{hr}$	hr	$S_{20} + Zn_{2} + B_{1}$
T9. S only	hr	S_{20}
T10. NoMN	None	NPK only

***mr is minimum rate, **hr is high rate**

6.3.2.1: Land preparation and sowing

The process of preparing the field for sowing involved ploughing and harrowing the pre-plant land. The proper plot size was then used for field laying and pegging. Finatly, the maize was planted using a 75 cm by 40 cm spacing.

6.3.2.2: Planting Materials

Source of seed maize was CSIR-SARI office in Nyankpala. The variety was Sanzal-sima an OPV and a medium duration with a potential yield of 4.5 t ha $^{-1}$. The grain is flinty in texture, white in color, and with a normal grain type. It is the most commonly used maize variety in northern Ghana which was released by CSIR–SARI in 2012

6.3.2.3: Weed management

Both pre and post emergence herbicide (Atrazine and Glyphosate) were used for effective initial weed control. It was done just after planting or not later than two days after planting with the availability of adequate soil moisture. Subsequent weed management was done by manual hand hoeing.

6.3.2.4: Fertilizer Application

Basal fertilizer application was done by the use of dibblers to dibble a hole 5 cm away at the base of the plant and then fertilizer was placed by the use of bottle dollop cups to ensure even distribution. The holes were then closed after placement. Fertilizer application for the treatments were based on the recommended rate of 90-60-60 and 60-40-40 for the higher and medium rates respectively. Straight fertilizers, urea, MOP and TSP were used for the formulation of the basal application two weeks after planting (WAP). At six WAP topdressing was carried out with urea. The secondary and the micro elements were imposed at the basal application time by weighing the respective rates of the elements and mixed it with the macro elements.

6.3.2.5: Insect pest management on maize Plants

Ema Star 112 (EC.) with an active ingredient of Emamectin benzoate was used against many insect pests such as fall armyworm (FAW) at a rate of 0.25-0.5 L ha^{-1}. This was repeated when necessary after regular scouting biweekly for FAW.

6.3.2.6: Collection of soil samples and analysis

Five representative soil samples were taken from each replication in the experimental field using an auger, at a depth of 0–20 cm. The soil samples were taken in a zigzag form across each replication (Smith and Atkinson 1975). Samples were then bulked together and prepared for analysis for initial soil fertility status at the start of the experiment. Following air drying and crushing, the soil samples were run through a 2-mm screen. Stones, gravel, and pieces of non-decomposed vegetation were thrown away. The samples were thereafter kept for chemical and physical investigation in polythene bags. The following parameters and their corresponding methods of soil analysis were performed in the Soil Science laboratory of SARI, Nyankpala:

1. Soil pH – By the use of potentiometer to determine the degree of acidity or alkalinity in soils
2. Organic Carbon (OC) - Walkley-Black chromic acid wet oxidation method
3. Nitrogen (N) -The Kjeldahl method which involves, digestion of the organic material to convert nitrogen into HNO_3. Distillation of the released Ammonia into an absorbing surface or medium.
4. Phosphorous (P) - Bray-1 Method was used by evaluating the intensity of the blue hue produced using the Murphy-Riley method, the amount of phosphorus removed is ascertained. A Brinkman PC 900 probe colorimeter set to 880 nm is used to measure the color.
5. Potassium (K) - Determination of K was done by using the flame photometer method which involved first by calibration using standard solutions of K before the sample was run. The percentage of K was thus calculated as: %K = (Reading from flame photometer (ppm) X dilution factor)/10000, Where dilution factor is weight of sample taken into the final volume =100mls
6. Sulphur - Lead Acetate Test Paper by lightly spray or place a drop of hydrogen peroxide (3% v/v) on the test paper. Record any colour change. The test is positive for sulfur if the paper turns dark brown or black after exposure to the fumes from the sample and then turns white after exposure to hydrogen peroxide.

7. Magnesium (Mg) – This was determined by direct titration method (Titrimetric) by which the cations can be detected directly with the EDTA compound. The EDTA compound is an abbreviated check of the chemical compound called ethylenediamine tetraacetic acid.
8. Zinc was determined using the Atomic absorption spectrometry (AAS) 25ml aliquot of the solution is taken and used for the determination. The AAS was first calibrated with standard solutions of Zn and a calibration curve drawn. Samples were then aspirated in the machine and the resultant concentration determined in ppm. Concentration of Zn = ppm value of machine reading X 100Where 100 is the weight of sample ash to volume ratio
9. ECEC - The ECEC was determined by summation method by extracting bases and aluminium with ammonium acetate and potassium chloride, respectively.

6.3.2.6: Determination of grain and stover yields

At physiological maturity, harvesting was conducted within a net plot of 3m by 5m ($15m^2$) including four centre rows from the six-row main plot, one row being omitted on each side of the center row to reduce edge effects. Cutting every plant in the net plot at a height of roughly 5 cm above the ground allowed for harvesting, and the total number of plants was recorded. Next, the cobs were taken out of the stover. Using a digital scale that was accurate to two decimal places, the total number of cobs was noted and the weight of the cobs and stover was calculated on the spot. Five cobs and five stover were randomly chosen as samples and their fresh weights were ascertained. Five cobs were used as a subsample; their grains and cores were separated, and their fresh weights were ascertained individually. The chosen stovers were then divided into 5 cm pieces and well mixed prior to the collection of a 300 g subsample. After being packaged in bags with clear labels, the three sub-sample plant parts—grain, corbs, and stover—were air-dried to a consistent weight. Samples that had been air dried were weighed again, and dry weights for stover yield (t ha^{-1}) and dry matter grain were recorded.

6.3.2.7: Determination of Plant Harvest Index (PHI)

The portion of the biological yield that translates into an economic yield is known as the harvest index (HI). In order to calculate the biological yield, the economic yield and stover of the four center rows were harvested together but the roots were left out. Then, the harvest index was calculated as follows: $\left(\frac{EY}{BY}\right) x\ 100$

Where EY is economic yield and BY is biological yield

6.3.2.8: Assessment of overall nutrient absorption

In order to assess the total nutrient intake in the above ground biomass, grain and stover biomass were collected at harvest and labelled for additional processing. The yield (t ha-1) for air-dry stover was computed using the weights and the mass fraction of air-dry stover in fresh material after this subsample was air-dried to a fixed weight. Next, at the Soil Research Laboratory in Kumasi, the nutrient contents in grain and stover were determined. For this purpose, representative subsamples of the stover and grain that had been air-dried were crushed to pass a 1 mm screen following a 48-hour oven drying process at 60 °C. The total grain and stover nitrogen (N) contents were ascertained using the Kjeldahl method following digestion with sulphuric acid (Miller and Horneck,1997), while the other macro and micronutrients were measured using an inductively coupled plasma emission spectrometer following ashing at 500 °C and digestion in concentrated hydrochloric acid (Isaac and Johnson, 1997). Based on the nutrient concentrations and dry matter yields of each, nutrient absorption in grain and stover was calculated. The total amount of nutrients absorbed for each nutrient was then calculated by adding the nutrients consumed by the stover and grain in each treatment.

6.3.2.9: Determination of Volumetric Water Content (VWC)

The VWC of the soil was measured using a Campbell Hydro sense II. It is a lightweight, portable instrument for measuring soil moisture with ease. At five separate points within each plot, a 20 cm probe was inserted, and the average was taken.

Volumetric water content is a metric used to express the moisture level in soil. It is the proportion of soil to water volume. Mineral particles (such as sand, clay, or other particles), water, and air are the three primary components of soil. The remaining mineral particles and air and water make up arround 50% of the soil's volume on average, and they also make up 50% of the pore space. Therefore, water content varies between 0 and 50 percent.

Figure 6. 3: Hydrosense moisture meter

6.3.2.10: Measurement of moisture with HydroSense II

The main panel of the HydroSense II can show two separate types of data. Volumetric water content (VWC) in percent and time (in sec) are the two main data sets. Every time a measurement is successful, water content is displayed. Water Deficit is represented by the second data set. Because it gives an estimate of the soil water content in relation to the previously chosen "wet" and "dry" reference levels and the amount of rain needed (in mm), this is useful for irrigation planning. Water Deficit can be enabled via the configuration menus if desired. By default, only Water Content data is displayed on the main screen.

6.3.2.11: Determination of plant light interception

Photosynthetically Active Radiation (PAR) was measured using a canopy analyzer (AccuPAR model LP-80 PAR/LAI ceptometer) (PAR). The section of the spectrum that plants employ for photosynthesis is the 400–700 nanometer (nm) waveband of energy. The amount of light falling on the crop plant is automatically recorded by this device, and it can translate these data into the leaf area index (LAI) for the plant canopy. The area of leaves per unit area of soil surface is known as LAI. It is a useful tool for determining the canopy density and biomass. The AccPAR comes with an external PAR sensor that enables simultaneous above and below canopy PAR measurements.

Figure 6. 4: LP-80 PAR/LAI ceptometer

At four different positions on each plot, the one-meter bar of the ceptometer was positioned bellow the plants to take measurements across the rows. The bar bellow the plant biomass measures sunlight that the plants did not absorb, whereas the external PAR sensor measures direct sunlight. The amount of PAR absorbed by the plants is shown by the difference between the two numbers. A commonly used metric to describe the structure of plant canopies is the leaf area index (LAI).

A large number of mass and energy exchanges between the biosphere and atmosphere take place at the leaf surface, LAI is especially helpful for understanding canopy function.

6.3.2.12: Measuring plant chlorophyll content using a SPAD meter

SPAD 502 plus chlorophyll meter which instantly measures the chlorophyll content of a plant was used. Four leaves each from the top, middle, and bottom of five randomly chosen plants' SPAD values were obtained from each plot, and the mean was calculated.

Figure 6. 5: Measuring chlorophyll content using a SPAD meter.

The chlorophyll content of plant leaves can be quickly and easily measured using the SPAD-502 Plus without causing any harm to the leaf. One of the measures of plant health is the amount of chlorophyll, which can be used to determine when and how much additional fertilizer to apply in order to produce higher-yielding, higher-quality crops with less environmental impact. The SPAD observation obtained from it is highly and positively correlated with leaf Chlorophyll and N contents.

6.3.2.13: Analysis of data

The statistical analysis application software (Statistix 2010) was used to examine the data that had been gathered. To ascertain whether treatments differed from one another, the split-plot analysis of variance approach was employed. Using the Least Significant Difference (LSD), all treatments were contrasted and Honest Significant Difference (HSD) at 5% probability level. The all-pairwise multiple comparisons procedure, available for the One-Way AOV and all the Analysis of Variance procedures were used to compare the means of the different levels of the main effects and interactions. Dunnett's test for comparing all treatment means with the mean of a control and mean of the best were also used.

6.4: Results

6.4.1: Initial soil characteristics

The result in table 6.3 shows the properties of soil prior to amendment. The particle sizes varied with sand dominating among the fractions giving sandy silt textural class. The pH of both Nyankpala and Damongo sites were acidic with Nyankpala being strongly acidic. The pH fell below the ideal for crop production in terms of agronomy. Total nitrogen was very low, below 0.02% while available phosphorus was moderate. With the exception of K, all the nutrients values were within lower limits and below the ideal for crop production (Table 6.3). Organic matter and organic carbon values were low. Calcium and magnesium dominated the exchange complex of soil. Cation exchange capacity recorded was very low value.

Table 6.3: Initial chemical and physical soil characteristics of the two site

CLASSES	% CLAY	% SILT	% SAND	TEXTURE	Cmol$^+$/kg ECEC	Cmol$^+$/kg	Cmol$^+$/kg Ca	Mg/kg K	Mg/kg P	% N	% OC	pH : H$_2$O (1:2.5)	Community Depth (Cm)	ID No. Northern Soils 2022	LAB No.
SANDY SILT	8.12	21	70.88		7.631	1.6	2.2	48	5.86	0.012	0.195	4.11	0-20	Nyankpala	112/22
SANDY SILT	10.12	23	66.88		8.846	1.4	2.8	56	6.47	0.018	0.234	5.15	0-20	Damongo	113/22

6.4.2: The effect of S, Zn and B inclusion on maize greenery

The result of the chlorophyll content measured as SPAD reading showed no significant differences (P>0.05) between high and medium rate of NPK as main factor treatments (Tables 6.4 and 6.5). However, SMN at various growth stages showed varied range of significant differences with higher value recorded by S, Zn and B combination (SZnBh) treatment. Record of greenery proved that treatment (SZnBh) was significant different as compared to treatment of non SMN with higher NKP rate (hr) at various growth stages (P<0.05)) (Tables 6.4, 6.5)

Table 6. 2: SPAD reading: Season 1

Treatments	Nyankpala 2021 SPAD				Damongo 2021 SPAD			
	4WAP	6WAP	8WAP	10WAP	4WAP	6WAP	8WAP	10WAP
Main factor								
NPK MR	34.2^{a}	42.4^{a}	46.5^{a}	37.0^{a}	41.7^{b}	43.6^{a}	45.0^{a}	36.9^{a}
NPK HR	36.8^{a}	44.1^{a}	49.2^{a}	39.0^{a}	43.6^{a}	40.9^{a}	45.7^{a}	38.9^{a}
HSD	9.6	7.7	3.7	9.3	1.8	6.7	0.9	9.3
Sub factor								
SBmr	35.6^{abc}	42.4^{cd}	47.2^{bcd}	37.6^{bcd}	42.2^{ab}	41.5^{bc}	43.0^{d}	37.6^{bcd}
SBhr	34.6^{bc}	41.9^{cd}	51.3^{ab}	36.7^{bcd}	45.6^{a}	40.8^{bc}	43.5^{cd}	36.7^{bcd}
ZnBmr	34.6^{bc}	40.1^{cd}	45.9^{cd}	36.7^{bcd}	40.9^{b}	39.8^{c}	43.1^{d}	36.7^{bcd}
ZnBhr	35.2^{abc}	41.3^{cd}	46.4^{cd}	37.3^{bcd}	41.4^{ab}	40.5^{c}	46.1^{bcd}	37.3^{bcd}
SZnmr	35.2^{abc}	41.6^{cd}	46.1^{cd}	36.2^{cd}	41.1^{b}	41.1^{bc}	46.1^{bcd}	36.2^{cd}
SZnhr	33.6^{bc}	44.8^{bc}	52.1^{a}	37.3^{bcd}	43.8^{ab}	43.5^{abc}	47.4^{abc}	37.3^{bcd}
SZnBmr	36.3^{abc}	47.9^{ab}	47.7^{bcd}	39.0^{abc}	42.7^{ab}	45.8^{ab}	49.0^{ab}	39.0^{abc}
SZnBhr	39.9^{a}	50.5^{a}	48.4^{abc}	42.9^{a}	43.4^{ab}	47.5^{a}	50.2^{a}	42.9^{a}
S only	38.3^{ab}	43.5^{bcd}	49.6^{abc}	41.2^{ab}	44.6^{ab}	43.6^{abc}	47.6^{ab}	41.3^{ab}
NoSMN	32.3^{c}	38.7^{d}	43.7^{d}	34.4^{d}	40.6^{b}	38.7^{c}	37.8^{e}	34.4^{d}
MF*SF(n.s)	0.49	0.95	0.11	0.21	0.34	0.99	0.18	0.34
HSD	5.2	4.9	4.3	4.7	4.5	5.2	3.9	4.7

A different superscript indicates a significant difference at P (<0.05) between values in the same columns. For every column, the term "HSD" stands for "honest significant difference between means."

Values in MainF*SubF =** Highly significant at $p < 0.05$, * = significant at $p \leq 0.05$, ns = Not significant $p > 0.05$

Table 6. 3: SPAD reading: Season 2

Treatments	Nyankpala 2022 SPAD 4WAP	6WAP	8WAP	10WAP	Damonga 2022 SPAD 4WAP	6WAP	8WAP	10WAP
Main factor								
NPK MR	37.8^{a}	47.3^{a}	39.2^{a}	38.69^{a}	36.0^{a}	44.9^{a}	45.0^{a}	37.82^{a}
NPK HR	40.3^{a}	49.6^{a}	42.4^{a}	40.60^{a}	38.6^{a}	46.9^{a}	47.6^{a}	39.75^{a}
HSD	9.6	6.64	11.7	9.18	9.6	7.0	4.0	9.22
Sub factor								
SBmr	39.1^{abc}	46.5^{bcd}	41.2^{ab}	39.3^{bcd}	37.4^{abc}	44.4^{cd}	45.6^{bcd}	38.44^{bcd}
SBhr	38.1^{bc}	47.4^{bcd}	39.1^{bc}	38.4^{bcd}	36.3^{bc}	44.7^{cd}	49.7^{ab}	37.58^{bcd}
ZnBmr	38.1^{bc}	45.6^{cd}	39.7^{abc}	38.4^{bcd}	36.4^{bc}	42.9^{cd}	44.3^{cd}	37.52^{bcd}
ZnBhr	38.7^{abc}	46.8^{bcd}	41.3^{ab}	38.9^{bcd}	37.0^{abc}	44.1^{cd}	44.8^{cd}	38.14^{bcd}
SZnmr	38.7^{abc}	47.1^{bcd}	39.80^{abc}	37.9^{cd}	36.9^{abc}	44.4^{cd}	44.5^{cd}	37.01^{cd}
SZnhr	37.1^{bc}	50.8^{abc}	43.07^{ab}	39.2^{bcd}	35.3^{bc}	47.8^{bc}	51.2^{a}	38.25^{bcd}
SZnBmr	39.8^{abc}	51.7^{ab}	41.20^{ab}	40.7^{abc}	38.0^{abc}	49.9^{ab}	46.1^{bcd}	39.86^{abc}
SZnBhr	43.4^{a}	56.0^{a}	43.73^{a}	44.6^{a}	41.6^{a}	53.2^{a}	46.8^{bc}	43.78^{a}
S only	41.8^{ab}	49.0^{bc}	41.65^{ab}	42.9^{ab}	40.1^{ab}	46.3^{bc}	48.0^{abc}	42.10^{ab}
NoSMN	35.8^{c}	43.6^{d}	36.87^{c}	36.1^{d}	34.0^{c}	41.1^{d}	42.1^{d}	35.20^{d}
MF*SF(n.s)	0.49	0.99	0.15	0.19	0.48	0.98	0.11	0.20
HSD	5.23	5.25	4.29	4.61	5.2	5.0	4.1	4.6

When values in the same columns differ significantly at P (<0.05), it is indicated by a distinct superscript. The word "HSD" for each column refers to the "honest significant difference between means."

Values in MainF*SubF =** Highly significant at $p < 0.05$, * = significant at $p \leq 0.05$, ns = Not significant $p > 0.05$

6.4.3: The effect of S, Zn and B inclusion on maize LAI

The medium and high rate of NPK did not show any significant difference in leaf area index (P>0.05) in the two seasons and at the two sites (Table 6.6, 6.7). However, there were two groups in the SMN in which the LAI showed significant difference (P<0.05) at 4 and 6 WAP (P<0.05). At the sub factor level, there was significant differences among the treatments (P<0.05) with the

S, Zn and B (SZnBhr) combination showed higher LAI in Nyankpala. Similar result was recorded in 10 WAP where this combination (SZnBhr) recorded higher LAI in both sites and seasons (P<0.05) (Table 6.6, 6.7). The result at Damongo site also recorded similar result with the treatment SZnBhr showing higher LAI in all the various WAP (P<0.05) accept 4WAP.

Table 6. 4: Effect of treatments on Leaf Area Index (LAI) in Season 1.

Treatments	Nyankpala 2021				Damongo 2021			
	LAI				LAI			
	4WAP	6WAP	8WAP	10WAP	4WAP	6WAP	8WAP	10WAP
Main factor								
NPK MR	1.7^{a}	2.6^{a}	3.3^{a}	4.2^{a}	1.1a	1.9a	2.7^{a}	3.5^{a}
NPK HR	1.9^{a}	3.0^{a}	3.9^{a}	4.9^{a}	1.4^{a}	2.3a	3.2^{a}	4.2^{a}
HSD	0.7	1.2	1.5	2.0	0.9	1.1	1.3	2.0
Sub factor								
SBmr	1.6^{b}	2.7^{b}	3.6^{bc}	4.6^{abc}	1.2^{a}	2.1^{bc}	2.9^{bc}	3.9^{abc}
SBhr	1.8^{b}	2.9^{ab}	3.8^{abc}	4.8^{abc}	1.3^{a}	1.9^{bc}	2.9^{bc}	4.1^{abc}
ZnBmr	1.4^{b}	2.4^{b}	3.0^{c}	3.8^{c}	1.1^{a}	1.8^{c}	2.5^{c}	3.1^{c}
ZnBhr	1.9^{ab}	3.1^{ab}	3.9^{ab}	4.9^{ab}	1.3^{a}	2.3^{ab}	3.3^{ab}	4.2^{ab}
SZnmr	1.8^{ab}	2.7^{b}	3.4^{bc}	4.3^{bc}	1.3^{a}	1.9^{bc}	2.8^{bc}	3.6^{bc}
SZnhr	1.8^{ab}	2.8^{ab}	3.5^{bc}	4.4^{bc}	1.3^{a}	2.1^{bc}	2.9^{bc}	3.6^{bc}
SZnBmr	2.0^{ab}	2.8^{ab}	3.6^{bc}	4.7^{bc}	1.4^{a}	2.0^{bc}	3.0^{bc}	3.9^{bc}
SZnBhr	2.3^{a}	3.4^{a}	4.5^{a}	5.7^{a}	1.5^{a}	2.8^{a}	3.8^{a}	5.0^{a}
S only	1.6^{b}	2.6^{b}	3.3^{bc}	4.2^{bc}	1.2^{a}	1.8^{bc}	2.6^{bc}	3.5^{bc}
NoSMN	1.7^{b}	2.7^{b}	3.4^{bc}	4.2^{bc}	1.1^{a}	1.9^{bc}	2.87^{bc}	3.5^{bc}
MF*SF(n.s)	0.52	0.67	0.44	0.34	0.90	0.08	0.54	0.34
HSD	0.5	0.67	0.8	1.1	0.5	0.5	0.8	1.1

Values in the same columns followed by a different superscript are significantly different at P (<0.05) HSD refers to honest significant difference between means and applies for each column.

Values in MainF*SubF =** Highly significant at $p < 0.05$, * = significant at $p \leq 0.05$, ns = Not significant $p > 0.05$

Table 6. 5: Effect of treatments on Leaf Area Index (LAI) in Season 2.

Treatments	Nyankpala 2022 LAI				Damongo 2022 LAI			
	4WAP	6WAP	8WAP	10WAP	4WAP	6WAP	8WAP	10WAP
Main factor								
NPK MR	2.4^a	3.6^a	4.1^a	4.6^a	2.1^a	3.1^a	3.71^a	4.4^a
NPK HR	2.6^a	3.9^a	4.7^a	5.4^a	2.3^a	3.5^a	4.27^a	5.1^a
HSD	0.7	1.1	1.3	2.0	0.7	1.1	1.40	2.0
Sub factor								
SBmr	2.3^b	3.7^{bc}	4.4^{bc}	5.0^{bc}	2.0^b	3.2^{ab}	4.01^{bc}	4.8^{bc}
SBhr	2.5^b	3.7^{bc}	4.4^{bc}	5.2abc	2.1^b	3.3^{abc}	4.08^{abc}	5.0^{abc}
ZnBmr	2.2^b	3.3^c	3.9^c	4.3c	1.8^b	2.9^c	3.43^c	4.1^c
ZnBhr	2.6^{ab}	4.1^{ab}	4.7^{ab}	5.4ab	2.3^{ab}	3.6^{ab}	4.33^{ab}	5.2^{ab}
SZnmr	2.5^{ab}	3.6^{bc}	4.2^{bc}	4.8bc	2.2^{ab}	3.1^{bc}	3.82^{bc}	4.5^{bc}
SZnhr	2.6^{ab}	3.8^{bc}	4.3^{bc}	4.9bc	2.2^{ab}	3.6^{ab}	3.86^{bc}	4.6^{bc}
SZnBmr	2.7^{ab}	3.8^{bc}	4.4^{bc}	5.1bc	2.3^{ab}	3.3^{abc}	4.00^{bc}	4.8^{bc}
SZnBhr	3.1^a	4.4^a	5.3^a	6.2a	2.7^a	3.9^a	4.88^a	5.9^a
S only	2.3^b	3.5^{bc}	4.1^{bc}	4.7bc	1.9^b	3.1^{bc}	3.69^{bc}	4.5^{bc}
NoSMN	2.4^b	3.6^{bc}	4.2^{bc}	4.7bc	2.0^b	3.1^{bc}	3.82^{bc}	4.5^{bc}
MF*SF(n.s)	0.52	0.82	0.63	0.11	0.52	0.75	0.53	0.37
HSD	0.5	0.7	0.8	1.1	0.5	0.7	0.8	1.1

Values in the same columns followed by a different superscript are significantly different at P (<0.05) HSD refers to honest significant difference between means and applies for each column.

Values in MainF*SubF =** Highly significant at $p < 0.05$, * = significant at $p \leq 0.05$, ns = Not significant $p > 0.05$

6.4.4: The effect of inclusion of S, Zn and B in maize grain yield, stover and HI

At Nyankpala, the grain yield differences of the high rate of NPK, 90-60-60 kg ha $^{-1}$ was not significant (P>0.05) to the medium rate of NPK, 60-40-40 kg ha $^{-1}$ in both years (table 6.8). The result in the 2021 cropping season at Damngo also showed no significant (P>0.05). However, in the 2022 season the high rate produced significantly higher grain yield than the medium (P<0.05) (table 6.8). A large variability in maize grain yield response was observed within the sub factor treatments. Grain yield obtained was significantly different (P<0.05). Non addition of SMN to

NPK produced lesser grain yield. The combined application of S, Zn and B at high rate (SZnBhr) was spectacular in grain yield at both sites. Stover yield was statistically similar in the main plot factor in both sites but different in the sub plot factor in which the treatments yields significantly different among the treatments ($P<0.05$). Though the H.I proved that treatments with S, Zn and B combination recorded higher, this was not different to some of the treatments (Table 6.8). Treatment combinations with S and Zn without B equally recorded significant H.I ($P<0.05$)

Table 6.8: Effects of treatments on mean grain yield, stover yield, and Harvest Index (HI) of maize.

Treatments	Grain yield tons ha $^{-1}$				Stover yield tons ha $^{-1}$				
	Nyankpala		Damongo		Nyankpala		Damongo		Nyankpala
	2021	2022	2021	2022	2021	2022	2021	2022	2021
<u>Main factor</u>									
NPK MR	3.0^{a}	3.8^{a}	2.5^{a}	1.9^{b}	4.2^{a}	4.0^{a}	2.9^{a}	3.0^{a}	37.8^{a}
NPK HR	3.5^{a}	4.1^{a}	2.3^{a}	2.4^{a}	4.7^{a}	4.5^{a}	3.2^{a}	3.6^{a}	38.6^{a}
LSD	1.7	1.9	2.4	0.4	1.8	2.5	2.3	1.2	6.5
<u>Sub factor</u>									
SBmr	3.1^{bc}	3.4^{cde}	2.5^{ab}	2.0^{abc}	4.5^{ab}	4.4^{a}	3.2^{abc}	2.8^{bc}	36.6^{cde}
SBhr	3.3^{bc}	3.8^{bcd}	2.2^{ab}	1.8^{bc}	4.4^{ab}	4.6^{a}	2.5^{bc}	3.8^{a}	38.6^{bcd}
ZnBmr	2.7^{cd}	3.4^{de}	2.4^{ab}	2.0^{abc}	4.4^{ab}	3.8^{ab}	3.4^{ab}	3.1^{abc}	35.0^{e}
ZnBhr	3.4^{bc}	3.8^{bcd}	2.4^{ab}	2.2^{ab}	4.8^{ab}	4.2^{a}	3.0^{abc}	3.4^{abc}	37.4^{bcde}
SZnmr	3.1^{bc}	4.2^{abcd}	2.6^{a}	2.0^{abc}	4.3^{ab}	4.5^{a}	3.2^{abc}	3.4^{abc}	37.4^{bcde}
SZnhr	3.5^{b}	4.6^{ab}	2.7^{a}	2.5^{ab}	4.4^{ab}	4.5^{a}	2.8^{abc}	3.7^{ab}	40.1^{abc}
SZnBmr	3.3^{bc}	4.5^{abc}	2.2^{ab}	2.6^{a}	3.9^{ab}	4.6^{a}	3.6^{a}	3.5^{ab}	40.7^{ab}
SZnBhr	4.5^{a}	5.0^{a}	3.3^{a}	2.6^{a}	4.8^{ab}	4.7^{a}	3.5^{a}	3.7^{ab}	43.4^{a}
S only	3.5^{b}	4.1^{abcd}	2.1^{ab}	2.1^{abc}	5.1^{a}	4.3^{a}	3.2^{abc}	3.1^{abc}	37.0^{cde}
NoSMN	2.3^{d}	2.53^{e}	1.3^{b}	1.5^{c}	3.7^{b}	3.1^{ab}	2.3^{c}	2.6^{c}	35.5^{de}
MF*SF(n.s)	0.73	0.47	0.96	0.05	0.51	0.14	0.78	0.51	0.44
HSD	0.8	1.1	1.3	0.7	1.4	1.0	1.0	0.89	3.5

Values in the same columns followed by a different superscript are significantly different at P (<0.05) HSD refers to honest significant difference between means and applies for each column. Values in MainF*SubF =** Highly significant at $p < 0.05$, * = significant at $p \leq 0.05$, n.s = Not significant $p > 0.05$

6.4.5: Grain and tissue nutrient concentration (%)

Across all nutrient management strategies, there were a wide range of differences among the treatments in the total nutrient concentration (grain and tissue) at both sites. The main plot factors, NPK only did not show any significant differences ($P>0.05$). However, the subplot factor treatments showed significant differences among treatments ($P<0.05$). Treatment groups that have S, Zn and B combined had the highest concentration of N, P, K, S and Zn (Tables 6.8, 6.9). At the sub factor level, there was differences among the treatments ($P<0.05$) with the S, Zn and B (SZnBhr) combination showed higher grain and tissue concentration in Nyankpala. Similar result was recorded at the Damongo site with the treatment SZnBhr showing higher concentration of both grain and tissue.

Table 6. 9: Grain and tissue nutrient concentration (%) – Nyankpala

	Grain					Plant tissue				
Treatment	N %	P %	K %	S %	Zn ppm	N %	P %	K %	S %	Zn ppm
<u>Main factor</u>										
NPK MR	1.0^{a}	0.5^{a}	1.1^{a}	0.1^{a}	33.4^{a}	1.3^{a}	0.4^{a}	1.7^{a}	0.1^{a}	48.5^{a}
NPK HR	1.1^{a}	0.5^{a}	1.1^{a}	0.1^{a}	42.8^{a}	1.3^{a}	0.4^{a}	1.7^{a}	0.1^{a}	41.1^{a}
LSD	0.0	1.0	0.31	0.04	31.8	0.2	0.1	0.2	0.04	29.6
<u>Sub factor</u>										
SBmr	1.0^{ab}	0.5^{ab}	1.0^{b}	0.04^{ab}	25.6^{c}	1.2^{b}	0.3^{b}	1.5^{bc}	0.1^{ab}	36.0^{b}
SBhr	1.0^{ab}	0.5^{ab}	1.2^{b}	0.03^{abc}	36.3^{abc}	1.5^{a}	0.4^{ab}	1.8^{b}	0.1^{abc}	43.3^{ab}
ZnBmr	1.0^{ab}	0.5^{ab}	1.1^{b}	0.02^{cd}	37.9^{ab}	1.2^{b}	0.4^{ab}	1.7^{b}	0.1^{cd}	44.9^{ab}
ZnBhr	1.0^{ab}	0.5^{ab}	1.0^{b}	0.03^{abc}	40.7^{a}	1.3^{ab}	0.4^{ab}	1.7^{b}	0.1^{abc}	42.7^{ab}
SZnmr	1.1^{ab}	0.5^{ab}	1.1^{b}	0.03^{bcd}	42.5^{a}	1.3^{ab}	0.4^{ab}	1.7^{b}	0.1^{bc}	49.5^{a}
SZnhr	1.2^{a}	0.6^{a}	1.4^{a}	0.03^{abc}	44.7^{a}	1.3^{ab}	0.4^{ab}	2.0^{a}	0.1^{abc}	51.7^{a}
SZnBmr	1.1^{ab}	0.5^{ab}	1.2^{b}	0.04^{a}	39.2^{a}	1.3^{ab}	0.4^{ab}	1.7^{b}	0.1^{a}	45.7^{ab}
SZnBhr	1.1^{ab}	0.5^{ab}	1.1^{b}	0.04^{ab}	41.9^{a}	1.3^{ab}	0.4^{ab}	1.7^{b}	0.1^{abc}	50.5^{a}
S only	1.1^{ab}	0.5^{ab}	1.1^{b}	0.03^{abc}	44.9^{a}	1.2^{ab}	0.4^{ab}	1.7^{b}	0.1^{abc}	46.9^{ab}
NoSMN	0.1^{b}	0.6^{a}	1.0^{b}	0.02^{d}	27.3^{bc}	1.0^{b}	0.4^{ab}	1.3^{c}	0.1	37.1^{b}
HSD	0.1	0.1	0.2	0.01	11.2	0.3	0.1	0.3	0.01	11.7

Values in the same Column followed by a different superscript are significantly different at ($P<0.05$) HSD refers to Honest significant difference between means and applies for each column

Table 6. 10: Grain and tissue nutrient concentration (%) – Damongo

	Grain					Plant tissue				
Treatment	N %	P %	K %	S %	ppm	N %	P %	K %	S %	ppm
<u>Main factor</u>										
NPK MR	1.0^{a}	0.4^{a}	1.21^{a}	0.1^{a}	31.8^{a}	1.1^{a}	0.4^{a}	1.0^{a}	0.8^{a}	27.0^{a}
NPK HR	1.0^{a}	0.4^{a}	1.16^{a}	0.1^{a}	39.9^{a}	1.2^{a}	0.4^{a}	1.0^{a}	0.8^{a}	36.0^{a}
LSD	0.0	0.1	0.31	0.0	37.0	0.3	0.1	0.1	0.0	24.6
<u>Sub factor</u>										
SBmr	1.0^{ab}	0.3^{b}	1.1^{b}	0.1^{ab}	24.8^{c}	1.2^{abc}	0.3^{b}	0.9^{b}	0.8^{ab}	26.6^{bc}
SBhr	0.9^{b}	0.4^{ab}	1.2^{b}	0.1^{abc}	32.2^{bc}	0.9^{bc}	0.4^{ab}	0.9^{ab}	0.8^{abc}	27.4^{bc}
ZnBmr	1.0^{ab}	0.4^{ab}	1.1^{b}	0.1^{cd}	35.4	1.2^{abc}	0.4^{ab}	1.0^{ab}	0.8^{cd}	30.7^{abc}
ZnBhr	1.0^{ab}	0.4^{ab}	1.1^{b}	0.1^{abc}	38.2^{ab}	1.3^{ab}	0.4^{ab}	0.9^{ab}	0.8^{abc}	28.5^{abc}
SZnmr	1.1^{ab}	0.4^{ab}	1.2^{b}	0.1^{bcd}	40.0^{b}	1.5^{a}	0.4^{ab}	1.0^{ab}	0.8^{abcd}	35.2^{abc}
SZnhr	1.1^{ab}	0.4^{ab}	1.5^{a}	0.1^{abc}	44.4^{a}	1.1^{abc}	0.5^{a}	1.0^{ab}	0.8^{abc}	39.5^{a}
SZnBmr	1.1^{ab}	0.4^{ab}	1.2^{b}	0.1^{a}	37.5^{ab}	1.4^{ab}	0.4^{ab}	1.0^{ab}	0.8^{a}	31.4^{abc}
SZnBhr	1.1^{ab}	0.4^{ab}	1.1^{b}	0.1^{ab}	39.4^{ab}	1.1^{abc}	0.4^{a}	1.0^{ab}	0.8^{ab}	36.0^{ab}
S only	1.0^{ab}	0.4^{ab}	1.2^{b}	0.1^{abc}	35.7^{abc}	1.1^{abc}	0.4^{ab}	1.0^{ab}	0.8^{abc}	36.0^{ab}
NoMN	1.0^{b}	0.4^{ab}	1.1^{b}	0.04^{d}	30.7^{bc}	0.8^{c}	0.4^{ab}	0.9^{b}	0.7^{d}	24.0^{c}
HSD	0.1	0.1	0.2	0.1	11.0	0.5	0.1	0.1	0.0	11.6

Values in the same Colum followed by a different superscript are significantly different at ($P<0.05$) HSD refers to Honest significant difference between means and applies for each Colum

6.5: Discussion

Due to the impact on photosynthesis, leaf chlorophyll is a crucial factor in crop growth. The improved leaf chlorophyll content in the treatments of plants that received NPK inclusive of S, Zn and B treatment combination and may have contributed to the rise in leaf chlorophyll hence the high SPAD reading. According to Daphade et al. (2019), B and Zn, as micronutrients, increase the availability of primary and secondary nutrients to facilitate crop uptake. This demonstrates that the addition of micronutrients to NPK fertilizer increased photosynthetic activity because of the high leaf chlorophyll, which increased stover weight and grain yield (tables 6.8,). The findings indicated that even at increased application rates, the availability of NPK alone, may not be enough to boost photosynthetic capacity in northern Ghana's nutrient-poor soils for maize cultivation unless SMN is included. Generally no significant difference was recorded between the main factors (NPK MR and NPK HR) (table 6.8,) which suggests that inclusion of secondary and micronutrients can help to reduce the rate of NPK application. The result is similar to that of Li et al. (2020) which also stated that nutrients, S in particular, can significantly influence the chlorophyll reading. Brentrup (2005) also stated that S is an important nutrient for chlorophyll formation and photosynthesis conversely, application of secondary nutrients such as S may give uniform green coloration to crops but may not result in increased crop yield unless the soil is deficient in S.

One of the key factors influencing net primary production, nutrient and water use, and carbon balance is LAI. There are a number of effects of canopy LAI on the understory populations, particularly in the soil. At the productive stage, S, Zn and B sub plot treatment combinations showed significant higher LAI to the control. Plant increases up to a crucial LAI value as light interception rises along with LAI. This might be caused by variations in leaf counts and an increase in leaf size as the duration lengthens. The outcome is comparable to research by Soomto et al.

(2011) in maize, where 90 DAS resulted in increased LAI. With the addition of Zn and B, Bature (2018) also noted a substantial difference in leaf number that increased LAI.

During the growth and development of the maize plant, morphological and physiological processes result in grain yield, which is the most important economic output. Mean maize grain yields following secondary and micronutrients inclusion to NPK application revealed that NPK application on the deficient soils had a significant yield response at the two sites (Table 6.8). Generally, the medium and high rates did not show significant differences in grain yield but the inclusion of secondary and micronutrients brought differences especially the high rates of the S, Zn and B combined. Fertilizer practices and technologies that manage secondary and micronutrients dynamics in the soil are highly required for optimal performance of maize in the northern Ghana. Increased nutrient availability, improved growth, and increased productivity were the results of the improved grain yield with S and the micronutrients Zn and B added to the NPK. Additionally, the decrease in grain yield (Table 6.8) shown in the treatments which did not receive SMN amply demonstrate the benefits of adding secondary and micronutrients to NPK intake. This outcome is consistent with other studies (Kihara et al., 2017; Njoroge et al., 2018; Lisuma et al., 2016), all of which showed that grain production could be greatly boosted via the addition of secondary and micronutrients. Plants need sulphur to synthesize important metabolic substances like proteins, amino acids, sulpho-lipids, and glutathione—all essential for healthy crop growth (Qahar and Ahmad, 2016). Similar to sulfur, boron boosts a plant's protein content and is essential for cell wall production, elongation, and metabolism of nucleic acids, all of which contribute to a plant's rapid growth (Tahir et al., 2012). Additionally, zinc and boron cooperate with hormones and enzymes to facilitate the efficient use of water in the crop and the metabolism of carbohydrates and proteins (Ceyhan et al., 2008; Gupta and Solanki, 2013; Rudani et al., 2018). A more efficient use of water is necessary for agricultural growth in the current rainfed system, which is periodically beset by drought. According to Irfan et al. (2019), adding boron improves crop output even in P-deficient soils due to the phosphorous absorption by B that results in synergy. According to Rizwan, et al. (2019), zinc plays a function in disease resistance, the enhancement of photosynthesis, and carbohydrate storage. The combined effects of zinc, boron, and sulfur may have led to the observed enhanced high yields in fertilizer formulations containing all three minerals. The high rate of NPK formulation (90-60-60) did not give the greatest grain yield when compared to secondary and micronutrient inclusion. Grain yield increased by an average of 24% and 26% in Nyankpala and Damongo, respectively, over the two seasons when high rates of S, Zn, and B (SZnBhr) were added to high rates of NPK. According to Njoroge (2018) adding secondary and micronutrients could significantly boost maize productivity above certain levels of NP and K fertilization.

The treatments had a variety of effects on the stover yield in both years at Nyankpala and Damongo (Table 6.8). The treatments that are secondary and micronutrients inclusive significantly showed higher stover than the control. The dry matter output is often comparable to the dry grain yield. Appropriate reductions of N, P, and K application rates may reduce the per unit area carbon footprint of maize production without reducing yield with the inclusion S, Zn and B. According to research by S. Buah et al. (2020), although the goal of this application was to increase the N rate, the S in the AS might have been important in obtaining a greater yield. The harvest index also revealed a similar pattern with the secondary and micronutrient inclusion treatments at high rate of the three combined recording higher harvest index.

4.6: Conclusion

In northern Ghana, maize crop growth and grain output were increased by adding sulphur in addition to the minerals zinc and boron, as a supplement at 20, 2 and 1 kgha^{-1} respectively. By combining these nutrients with primary NPK fertilizers rather than applying primary NPK fertilizers alone, yield improvements of up to 26% have been observed. Enhanced resistance to illnesses and the environment, improved absorption of P and N, and increased resistance to water stress that promote crop growth are all factors that contribute to the higher yields brought on by the inclusion of S, Zn and B. Therefore, for the cultivation of maize in Northern Ghana, sulphur, boron, and zinc should be taken into consideration while formulating chemical fertilizers.

CHAPTER SEVEN

ENHANCING INDIGENOUS CROPPING SYSTEMS UNDER CLIMATE CHANGE: A CASE STUDY OF MAIZE (ZEA MAYS L.) AND GROUNDNUT (ARACHIS HYPOGEA) IN NORTHERN GHANA

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Topic: Enhancing Indigenous Cropping Systems under Climate Change: A Case Study of Maize (Zea mays L.) and Groundnut (Arachis hypogea) in Northern Ghana

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Abstract

Due to the continuous cropping of maize and groundnuts on the same land for livelihood, the production yields have declined significantly below potential levels. The objective of this study was to evaluate the cropping systems of the crops to assess the ecological and socioeconomic limitations that smallholder farmers confront in northern Ghana. Five cropping systems (*viz.* sole continuous maize (SCM), sole continuous groundnut (SCG), maize-groundnut intercrop (MGI), groundnut/maize rotation (GMR) and maize/groundnut rotation (MGR)), each with or without fertilizer were established under RCBD at Nyankpala during the 2021 and 2022 cropping seasons. For the fertilized rotation treatments, the maize crop received 60-N, 40-P_2O_5, and 40-K_2O, kg/ha, while the groundnut crop received 20-N, 40-P_2O_5, and 40-K_2O, kg/ha using NPK 11, 22, 21 with trace elements S, Zn and B. The cropping systems were characterised on grain yields, resource utilization, economic returns, and response to macro, secondary and micronutrients applications. The results showed that intercrop and rotation treatments gave significant yields. The land equivalent ratios (LER) for the intercrops were 1.2 and 1.09 respectively, in the two seasons. Maize grain yield under the rotation increased from 2.5 to 3.8 t/ha while groundnut pod yield increased from 0.6 to 0.9 t/ha. Continuous cropping of groundnut did not show significant fertilizer effects on pod yields.

7.1 Introduction

Despite increasing national food security globally, household food insecurity continue to be a challenge, with an estimated 821 million people currently experiencing both food insecurity and malnutrition (Abegaz, 2018; Gashu et al., 2019; Xie et al., 2019). In Northern Ghana where agriculture is the major livelihood source, food insecurity remains a challenge. However several factors pose significant risk to farms leading to yield reduction when they are not correctly monitored and well managed. These factors can be grouped into three categories which are technological, biological and environmental. In Northern Ghana, food insecurity is primarily related to low crop yields (Mabhaudhi et al., 2018b) as a result of low and decreasing fertility of the soil (Ukeje, 2010, Rippke et al., 2016, Badu-Apraku and Fakorede, 2017, etc.), high incidence of pest and diseases (Mpandeli et al., 2018; O'Leary et al., 2018; Nhamo et al., 2019; Sserunkuuma et al. 2001 and Doss et al., 2001). Low adoption of improved varieties and improved agronomic practices, low use of yield-enhancing inputs like fertilizers and agrochemicals, lack of access to credit, and insufficient credit facilities are all contributing factors to Northern Ghana's declining maize productivity gap (Asante et al., 2014; Bempomaa and Acquah, 2014; Addai and Owusu, 2014). In addition, growing climate variability makes it more difficult to increase crop yield and provide food security in rural areas (Ellis-Jones et al., 2012). Improvements in crop yields are therefore a prerequisite for increased food and nutrition security in this region (NEPAD), 2014). There is general agreement that rural agricultural systems need to become more resource-efficient for optimized yields and productivity (Isaacs et al., 2016; Matthews and McCartney, 2018). The use of improved technologies, such high yielding improved crop varieties, improved nutrient management practices, food preservation and post-harvest processing, advanced irrigation systems and intercropping systems has been shown to enhance the efficiency of agricultural systems

(Hammer et al., 2014; Ran et al., 2017; Mabhaudhi et al., 2019a). These innovations enable farmers to optimize resource utilization, reduce waste, and improve crop yields. A farmer can have exact information about their fields using technologies like GPS, remote sensing, and Geographic Information Systems (GIS). With the aid of this information, they may use herbicides, water, and fertilizers more effectively, increasing crop yields while minimizing their negative environmental effects. 4Cereal-legume cropping systems offer opportunities for improved resource use efficiency and can sustainably enhance crop productivity. Crop rotation is used by most farmers because of this. A cereal crop (like maize) grown after a legume crop (like groundnut) benefits from the legume's biological nitrogen fixation. Rotating crops also reduces the accumulation of pests and soil diseases. Crop rotation increases soil fertility and the availability of nutrients. Crop diversification decreases the risk of nutrient depletion by allowing the growth of numerous plants with various nutritional requirements. As a result, there is less need for and cost for synthetic fertilizers. Since different crops require different amounts of nutrients, crop rotation enables the uptake of different nutrients from year to year depending on the crop. Crop rotation promotes more microflora variety since each plant has certain microbiological preferences for the soil's living organisms.

In terms of enhancing food diversity and nutrient yield per unit of water and area used, cereals plus legumes are preferable to monocropping. Intercropping refers to growing two or more crop species in close proximity at the same time (Willey, 1990; Hauggaard-Nielsen et al., 2008). Intercropping's most common purpose is to increase production on a given piece of land by utilizing resources that would otherwise go unused by a single crop. Many scholars have recommended diversifying crop systems by expanding the number of planted species in the same or surrounding locations as a solution to many modern agriculture concerns. The benefits of intercropping include increased yield (Ofori and Stern, 1987), improved nitrogen cycling (Cong et al., 2015), increased soil organic matter (Yu et al., 2015), and the prevention of insect infestations, weeds, and diseases (Boudreau, 2013; Zhang et al., 2019). Intercrops frequently require fewer chemical inputs than solitary crops (e.g., N fertilizer, insecticides, and herbicides) (Martin-Guay et al., 2018; Xu et al., 2020). Mixed cropping therefore offers a chance to enhance farming in a sustainable way (Li et al., 2020a). Intercropping has a number of advantages, including a higher yield per unit of land. Webster and Wilson (1996) came to the conclusion that there was no benefit to replacing the practice of mixed cropping for the small-scale tropical farmer. In the majority of mixed cropping trials conducted in the tropics, more than one acre of pure stand was needed to produce the yield of one acre of mixed crop. For smallholders in Northern Ghana, intercropping offers a significant risk reduction. The farmer can still harvest the crops that are still growing in the field even if one crop is totally destroyed by pests, disease or drought. Given the unpredictability of the rainy season and the varying water requirements of each crop, planting multiple crops in the same field increases the farmer's chances of some crops surviving. Even though intercropping may be beneficial for yield overall, the performance of each crop in an intercrop system is affected by the interactions between different crops and the availability of resources (Martin-Guay et al., 2018).

In this study, we propose that it is advantageous to intercrop maize (Zea mays L.) and groundnut (Arachis hypoogea), as the groundnut smaller canopy provides little competition to the cereal crop (Saxena et al., 2018). Legumes that fix nitrogen which is captured from the atmosphere include groundnut. It is unclear how crop interactions and the fluctuation and change of the climate affect water and production. Smallholder farmers in Northern Ghana, especially women, use maize-groundnut intercropping at regular basis due to limited agricultural grounds. An agronomic survey of 240 farm households in East Gonja, Nanumba North, Nanumba South, and Kpandai districts found that around 60% to 70% of women farmers adopt maize-groundnut intercropping. Planting density, insufficient soil nutrients, inadequate and incorrect fertilizer application, absence of improved seed, and diseases and pests all influenced maize and groundnut mean yields, which were 1.7 and 1.2 tons per hectare, respectively. Traditionally, in Northern Ghana, groundnut is intercropped with millet, sorghum, and maize by small scale farmers. Early to late June is when the rains become fully established, at which point the crop is sown in broader spacing or alternate rows. Prior research has focused on improving intercropping system performance by simultaneous groundnut and cereal planting, as well as adjustments to row spacing and plant population.

7.1.1 Study objectives

1. Evaluate the effects of varied maize-groundnut cropping systems on crop yields and productivity.
2. Evaluate the efficiency of varied maize- groundnut cropping systems.
3. Evaluate the contribution of fertilizer application in on yields and resource use efficiency in varied maize-groundnut cropping systems.

7.1.2 Research hypotheses

1. Intercropping maize and groundnut enhances crop productivity and resource use efficiency.
2. Fertilizer application enhances the yield, economic and resource use benefits associated with maize-groundnut cropping systems.

7.2.1 Cropping system of maize and groundnut

The word "cropping system" refers to the crops, cropping sequence and management strategies applied over a number of years to a specific agricultural land. It covers every facet of managing an agricultural system in terms of time and space. Cropping systems have historically been created to optimize output, however modern agriculture is increasingly focused on encouraging environmental sustainability in cropping systems (Blanco et. al., 2010)

7.2.2 Factors to consider in the choice of cropping system

Any cropping system must start with crop choice. A farmer must examine a crop's profitability, ability to adapt to changing environmental circumstances, resilience to disease, and need for certain technologies during growth or harvesting before deciding whether to plant it. Additionally, they must consider the farm's local environmental variables and how the crop will work with the other components of their production system.

7.2.3 Impacts of maize-groundnut intercropping system on smallholder agriculture

Intercropping system involves the simultaneous cultivation of two or more crops on the same piece of land (Seran et. al., 2010). This is a typical practice in developing nations, and it is primarily used by small and marginal farmers. (Abdulai et. al., 2018).

Intercropping is usually practice on small scale farms with few resources and has been proven to increase yields with more consistency in a range of crop combinations. Additionally, intercropping systems are noted for using fewer inputs, such as fertilizers and plant protection chemicals, and producing food that is safe, healthy, and of a high caliber while adhering to environmentally friendly practices.

Figure 7. 1: Maize groundnut intercropping: farmer practice vrs improved practices

In order to achieve production sustainability in agriculture, crop diversification through systems like mixed cropping, intercropping, and agroforestry is also encouraged. This results in variations in diet and net return, higher levels of production stability, proper utilization of limited human labor resources under minimal technological intervention, and a variety of other factors (Abdulai et. al., 2018).

The system of intercropping groundnut and maize is advantageous in a variety of ways. The choice of crops, as well as their maturity, density, and timing of planting, are key factors in the effectiveness of the maize-groundnut intercropping system. The benefits of managing weeds, pests, and diseases, the fixation of biological nitrogen by legumes and transfer of N to associated maize, insurance against crop failure for small farmers, and control of erosion by covering a large area of ground are all pronounced benefits of the maize-legume combination of intercropping system. Even though the maize-legume intercropping system has drawbacks, such as a limited amount of farm mechanization, a greater reliance on human labor, and a potential for lower maize output, the system suggests additional benefits for smallholder farmers in Northern Ghana.

7.2.4 Effect of Groundnut intercropping on the succeeding crop

The direct release of fixed nitrogen from groundnut has a stimulatory impact on maize plants. Zakia Ahmad et al., (2008) stated that the release of some allelochemicals from legume plants, which stimulate the development and yield components of the related maize plant, may also confirm that nodules of legumes only become active at the flowering stages, releasing nitrogen that has been directly absorbed from the soil and incorporated in the formation of ears per plant. Nambiar et al., (1983) in their findings also stated that when nitrogen was applied to the maize, both the nodule weight per plant and the rate of fixation per unit of nodule weight decreased.

Intercropping groundnut and maize led to higher land equivalent ratios (LER) and higher economic returns. The yields from the intercrops were discovered to be directly correlated with their population densities, providing evidence that the intercrop's general plant population can be biased to favour one crop over another depending on the farmer's priorities or the profitability of specific crops (Langat et al., 2006).

As a matter of principle, new promising maize and groundnut varieties should only be distributed to farmers if they can successfully meet the requirements of the current intercropping systems, which have been successfully established over decades of scientific research. The decrease in intercropped groundnut's leaf area indices most likely caused by the shade provided by the maize plants, which inhibited photosynthesis. Because there was less dry matter available to support the growth and production of new leaves, the intercropped groundnut's leaf area index (LAI) was lower than that of its solitary counterpart (Dalley et al., 2004).

The construction of leaves and the growth of larger LAI, which in turn supported more photosynthesis, depended heavily on sunlight availability, which is essential for the production of photosynthate (Dalley et al., 2004). According to Rwamugira and Massawe's (1990) intercropping study findings, maize grown in a peanut intercrop responded to fertilizer up to 60 kg N ha^{-1} while maize grown in a single intercrop responded up to 120 kg N ha^{-1}. In a study on the nitrogen intake of groundnut and maize, it was shown that, at low nitrogen levels, the nitrogen content of the intercropped maize was higher than that of solitary maize, indicating some transfer of fixed nitrogen from the groundnut to the maize. According to Rao et al. (1979), the relative yield benefit of intercropping over solitary cropping was 44% at the highest nitrogen level. This implies that intercropping might be more favourable in low fertility settings, this has significant practical consequences.

7.3.1 Effects of intercropping on light interception

Light interception (LI) and light utilization efficiency (LUE) are characteristics of cropping systems' ability to catch and utilize resources efficiently, especially in groundnut-maize intercrops. When planting groundnut alongside tall cereals like maize, light is essential. In field crops, the connection between total photosynthetically active radiations (PAR) intercepted and biomass accumulation is frequently linear. The light use efficiency is the slope of this connection (Russell et al., 1989). According to Willey (1990), increased productivity might come from either better solar radiation absorption, better light usage efficiency, or a combination of the two.

Growing two species together in the same field can sometimes result in an increase in light interception, either due to a longer period of soil covered or a more comprehensive soil cover as documented by Keating and Karberry, (1993). According to Fukai and Trenbath (1993), since there is no competition between the component crops in intercropping systems with crops that have different growth seasons, resource usage efficiency is not likely to be significantly impacted. In intercrop systems, the amounts of incoming PAR that are absorbed by component crop canopies mostly rely on the Index of leaf area and structure of the canopy (Bastiaans et al., 2000). Despite the fact that these concepts are well known, Willey (1990) noted that it might be difficult to estimate the amount of light that individual crops in intercrops are capturing. Numerous investigations have noted the negative impact of shadowing on cowpea in connection with cereal. According to Wahua et al. (1981), cowpea grows and produces more when it receives more light.

7.3.4 Effects of intercropping on soil fertility maintenance

Keeping the soil fertile is frequently one of the difficulties in farming. One method for preserving soil fertility and crop productivity is intercropping. Groundnut and maize intercropping have an impact on soil fertility maintenance through nitrogen fixation and differential plant uptake, according to Hochman et al. (2013). Decomposing roots and dropped leaves after the intercrop are harvested supply nitrogen and other nutrients for the following crop. The intercrop's lasting impact on the following crop is greatest when the leftovers are left in the field after harvest before being ploughed under. However, because a significant amount of nitrogen is withdrawn when grain is harvested, according to Giller (2001), soil depletion can still occur if manure or fertilizers are not used to replenish the nutrients that plants have used. The intercropping strategy increases the quantity of humus in the soil in addition to giving the linked crops nitrogen and other nutrients. This improves soil structure and lessens the necessity of tilling the land while also lowering water loss, soil erosion, and nutrient leaching.

7.3.5: Intercropping Effects on Weed Infestation

In northern Ghana, one of the main causes of low yield has been discovered to be inefficient weed control. A weed refers to any plant that grows where it is not required. Weeds have a negative impact on plants. They compete with plants for space, nutrients, water, sunlight, and other minerals stored in the soil. Some weeds sponsor the development of pests and diseases on the farm, which reduces the profit of the farmer by lowering the quality and quantity of the produce. In addition, a dense growth of weeds on the farm land makes harvesting very difficult. Maize and groundnut are very sensitive to weed competition during the first three to six weeks after germination.

If weeds are not controlled properly during this period, it will negatively affect the growth of the plant and decrease its yield drastically. Beyond this period, well planted, and healthy growing crop would choke surrounding weeds sufficiently.

In farming systems, controlling weeds is one of the most important aspects of food production. Although a properly chosen herbicide may play a significant role in weed management, the necessity for non-chemical weed control in agro-ecosystems has increased due to growing weed resistance to herbicides, high costs, and particularly harmful impacts on the environment and human life (Augustine, 2003; Spliid et al., 2004).

Intercropping is viewed as an alternative to the usage of pesticides because it slows or stops the growth of weeds, according to (Liebman and Davis, 2000) as well. As also stated by Kuchinda et al. (2003) and Olasantan et al. (1994), intercropping can reduce weed incidence on maize, but this effect is dependent on a number of variables, including the type of maize cultivar, the local climate, the sowing window, the species that are intercropped, the kind of weed, and fertilizer rates. Because they compete for resources more effectively than monocropping systems or because they have an allelopathic effect on weeds, intercropping systems may be more favourable.

As an alternative, intercropping systems may also employ resources that aren't consumed by weeds or may transform those resources more effectively than monocropping would into the crop's usable components (Liebman and Dyck, 1993).

7.3.6 Intercropping Effect on Economic Returns

Intercropping legumes with maize have been shown to increase grain production per unit of land (Abdulai et al., 2018). In cropping systems, intercropping groundnut with maize may boost yield and meet Northern Ghana's need for both crops. A similar study was done on groundnut, and it was reported that treatments involving intercropping increased yield. But there have also been reports of shorter grains like maize shading down low-growing legumes (Dalla 1974; Chang and Shibles 1985).

Poor growth, inadequate emergence of intercropped legumes, and low fertility have all been recorded in smallholder systems, and these factors prevent farmers' fields from contributing as much nitrogen and organic matter as they could (Kumenda et al. 1993). However, because the majority of the above-ground dry matter and almost all of the nitrogen are removed from the field in the grain, the more productive (high harvest index) grain legumes add relatively little organic matter and N to the soil (Giller et al., 1994).

7.4: Materials and Methods

7.4.1 Study Site

The experiment was carried out at on-station in the Savanna Agricultural Research Institute research fields at Nyankpala during the 2021 and 2020 cropping seasons. Nyankpala is situated within the Northern savannah Agro-ecological zone of Ghana, and lies 16 kilometers west of Tamale, the capital city of Northern region. The area is characterized by a mild, semi-arid tropical climate and receives 800-1200 mm of rainfall annually, the majority of which falls between May/June and October. The fluctuation of rainfall is 15% to 20% and often negatively impacts on agriculture production in the region. A minimum of 26 oC is experienced in December and January during the harmattan, while a maximum of 39 oC is reached in March. The yearly mean temperature of the atmosphere is 32 oC during the rainy season. In the wet season, relative humidity can reach 100%, while in the harmattan period, it can drop as low as 10%. It likewise fluctuates from 65% to 85%.

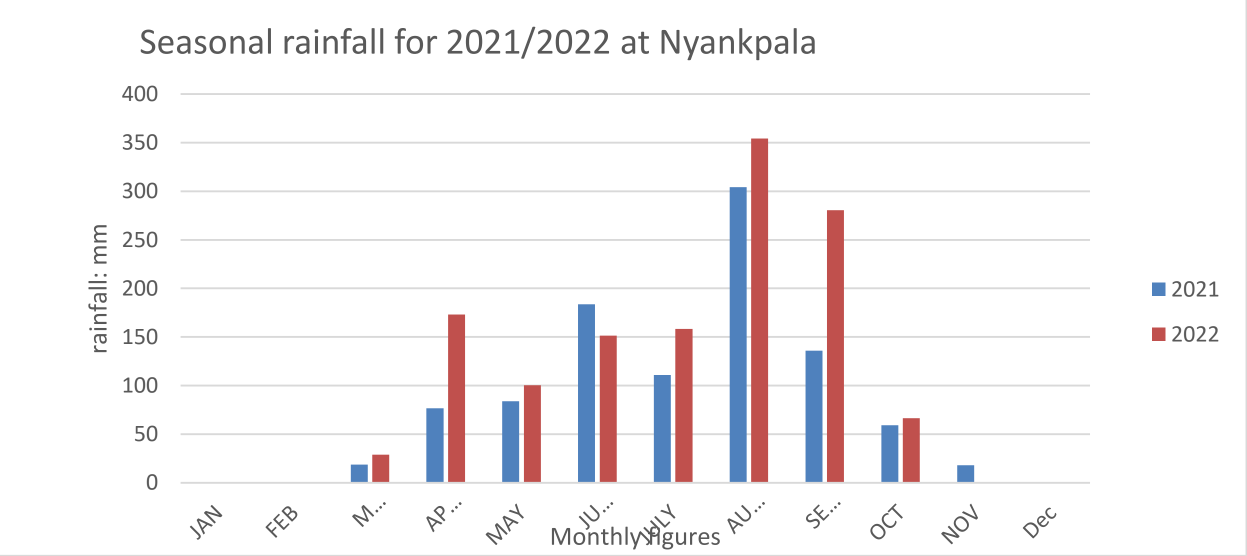

Figure 7. 2: Monthly rainfall at Nyankpala during Experimental Period
Source: SARI meteorological station

Table 7. 1: Initial soil sample result of the experimental site

Community/ Depth(cm)		pH H_20 (1:2.5)	% O.C	% N	mg/kg P	mg/kg K	Cmol$^+$/ Kg ECEC
Nyankpala	0-20	4.11	0.195	0.012	5.86	48	7.631

7.4.2 Experimental Design

The experiment design was based on a randomized complete block design (RCBD) with cropping systems (continuous mono cropping, rotation, and intercropping) as the main factors. A total of 10 treatments were established (Table 5.2 & 5.3), with each treatment replicated thrice. For all cropping systems and crops, treatments were established on experimental plots measuring 10m by 5m, with a between plots spacing of 1m, with a spacing of 1.5m maintained between experimental blocks.

Table 7. 2: Treatment layout - Season one (2021)

Treatment	Description	Maize fertilization0	Groundnut fertilization	NPK rate
T1	SCM	None	-	0
T2	SCG	_	None	0
T3	MGI	None	None	0
T4	GMR	None	None	0
T5	MGR	None	None	0
T6	SCM	Yes	-	60:40:40
T7	SCG	-	Yes	20:40:40
T8	MGI	Yes	Yes	60:40:40
T9	GMR	Yes	Yes	20:40:40/60:40:40
T10	MGR	Yes	-	60:40:40/20:40:40

Table 7. 3: Treatment layout - season two (2022)

Treatment	Description	Maize fertilization	Groundnut fertilization	NPK rate
T1	SCM	None	-	0
T2	SCG	_	None	0
T3	MGI	None	None	0
T4	GMR	None	None	0
T5	MGR	None	None	0
T6	SCM	Yes	-	60:40:40
T7	SCG	-	Yes	20:40:40
T8	MGI	Yes	Yes	60:40:40
T9	MGR	Yes	-	60:40:40/20:40:40
T10	GMR	-	Yes	20:40:40/60:40:40

7.4.3: Cropping systems of maize and groundnut

The maize and groundnut varieties used for the establishment of the experiment were Sanzal Sima (drought tolerant maize) and SARInut2 (Early maturing groundnut variety). For all cropping systems, maize and groundnut were sown at a spacing of 75 cm (inter-row) and 40 and 20 cm (intra-row) respectively. For maize, two seeds were sowed per planting hill, while groundnut was one seed per hill. The plant densities (plants ha^{-1}) were 16,667 and 66,667 for intercropped and sole cropped maize respectively, and 33,333 and 66,667 for intercropped and sole groundnut respectively.

To attain the targeted nutrient application rates, basal and top-dressing fertilizers were applied at the rates indicated in the table 4 below.

Figure 7. 3: cropping systems

Table 7. 4: Treatment level basal and top-dress nutrient application rates

Treat	Treatment description	NPK rate	Basal nutrient ap		
			N	P_2O_5	K_2O
T1	SCM	0	0	0	0
T2	SCG	0	0	0	0
T3	MGI	0	0	0	0
T4	GMR	0	0	0	0
T5	MGR	0	0	0	0
T6	SCM	60:40:40	20	40	40
T7	SCG	20:40:40	20	40	40
T8	MGI	60:40:40	20	40	40
T9	GMR	20:40:40	20	40	40
T10	MGR	60:40:40	20	40	40

For the fertilized rotation treatments, the maize crop received 60 N, 40 P_2O_5, and 40 K_2O, while the groundnut crop received 20 N, 40 P_2O_5, and 40 K_2O.

Basal fertilizer application timing was guided by the respective treatment associated with each experimental plot as previously presented. For treatments where, basal fertilizer application was required, equal amounts of basal fertilizer were applied in each planting hill prior to sowing of seeds, and gently covered with soil. Dollop cups were calibrated and used to ensure exact amount of fertilizer per planting hill.

Top dressing carried out 6 WAP when manual weeding of all experimental plots were done. Top dressing rates were based on the specific quantities required for each experimental plot as presented in the above table. Urea was used for the topdressing by dibbling small holes close to the base of each planting hill, applied and buried. For the intercrops, top-dressing of N was applied only to the maize crop. For the groundnut-maize rotation the succeeding maize crop was top-dressed with N at a rate of 40 kg/ha.

7.5: Assessment of resource utilization

7.5.1 Volumetric Water Content (VWC)

Volumetric water is the proportion of soil volume to water volume. Measurement of VWC makes it possible to estimate the requirement for watering before a crop exhibits symptoms of stress. Knowing the soil moisture condition enables highly efficient irrigation, supplying the water as and when required, and preventing the unnecessary consumption of water when irrigation is not necessary. It also makes it possible to determine when and how to carry out some activities such as fertilizer application. Three primary components make up soil: air, water, and mineral particles such as clay, sand, or loan. Typically, 50% of the volume of soil is made up of mineral particles and 50% is made up of air and water that occupy the pore space. Water content so varies from 0 to 50%. The soil's VWC was measured using Campbell Hydro sense II. It's a small, handheld tool that makes measuring soil moisture simple. In each plot, a 20-cm rugged probe was inserted into the ground at five locations and the average of the readings determined.

7.5.2: Light Interception (PAR) and LAI

Photosynthetically Active Radiation (PAR) was measured using a canopy analyzer (AccuPAR model LP-80 PAR/LAI ceptometer). The section of the spectrum that plants employ for photosynthesis is the 400–700 nanometer (nm) waveband of energy. The amount of light falling on the crop plant is automatically recorded by this device, and it can translate these data into the plant canopy's leaf area index (LAI). LAI is the ratio of the area of leaves to the area of the soil surface. It is a useful tool for determining the biomass and density of the canopy. To provide simultaneous above and below canopy PAR readings, an external PAR sensor is included with the AccPAR. Measurements were taken throughout the rows using the ceptometer's one-meter bar, which was placed below the plants at four different locations on each plot. Whereas the bar below the plant canopy monitors energy that is not caught by the plants, the external PAR sensor reads radiation that is coming directly at the sensor. The PAR that the plants then absorb is the difference between the two readings.

7.5.3: Determination of Chlorophyll through Soil Plant Analysis Development (SPAD)

SPAD 502 plus chlorophyll meter which instantly measures the chlorophyll content of plant was used to determine the chlorophyll content of both maize and groundnut. SPAD-502 meter is a hand-held device that is used for rapid, accurate and non-destructive measurement of leaf chlorophyll concentrations. Measurements with the SPAD-502 meter produce relative SPAD meter values that are proportional to the amount of chlorophyll present in the leaf. The SPAD values of four leaves from the top, the middle and lower parts of five plants were randomly chosen from each plot and the mean calculated to determine the chlorophyll content. Chlorophyll is the green pigment that allows plants to photosynthesize. This process use sunlight to convert carbon dioxide and water into the building blocks of plants. The SPAD value of all the leaves of the five randomly selected plants determined was then related to the chlorophyll content of the plant.

7.6 Land Equivalent Ratio (LER)

The competition function known as LER was determined in order to analyze the effects of crop competition and compare intercrop performance to that of the sole crop. For making wise decisions, it provides an accurate assessment of the biological effectiveness of the intercropping scenario. In order to calculate the LER of the maize impacted by the groundnut intercropping systems, Mead and Willey (1980) defined the intercrop grain yield as a ratio of the solitary maize grain production.

Thus,

LER = La+Lb = Ya/Sa + Yb/Sb

Where;

La and Lb are the partial LER or crop species a and b

Ya and Yb are the individual crop yields in the intercrops.

Sa and Sb are their sole crop yields.

The total LER was the addition of the partial LERs of the two component crops.

7.8: Calculating the financial benefits of treatments

Economic benefits related to different cropping systems established were assessed using partial budgeting. One way to arrange experimental data and details about various methods that have been tried is through partial budgeting (Kombiok, 2004).

All variable input costs were taken into account, as well as the seasonal average operational costs that apply to all treatments during the cropping season in the research area. The amount farmers paid for clearing land, planting, buying supplies like seed, hiring labor to weed, harvest, and transport farm products to their homes were all considered variable costs. Next, the difference between the gross income and the total cost of production for each treatment was computed to determine its worth, or net return per hectare. The mean of the annual net returns over the study period was used to compute average net returns. There were no levies on capital expenses like land, capital interest, farm equipment depreciation, or other overhead. After dividing the net benefit by the operating cost, the benefit ratio of each treatment was determined. Farmers would consider the farming system treatment that produced the highest net returns to be profitable.

Thus;

Net benefit = Gross returns – total variable cost of production

Benefit cost= Net benefit/Total variable cost

7.9: Yield data

Both grain and pod yields of the intercrops (maize and groundnuts) were determined from a net plot of 5m x 4m (20m^2) from four middle rows. The yield per plot was then multiplied by 10,000 (m2/ha) and divided by the plot's area (m^2/plot) in order to convert yield from a plot to a hectare basis. To avoid biased yield estimation, the following measurements were made prior to that: plant count, number of ears or pods, number of grains per ear or pod, and grain moisture %. After that, this was translated into kilograms per hectare.

7.8: Data Analysis

Data collected from the on-station experiment was subjected to statistical analysis package (Statistix, 2015). The RCBD analysis of variance approach was used to see if there were any treatment differences. All treatments were compared using (0.05 alpha) level. However, Microsoft Excel Program was used for data input before transferring for analysis.

7.9: Results

7.10 Grain yield, pod yield and LER of maize and groundnut

Grain yield of maize treatments with the application of fertilizer was significant higher ($P<0.05$) compared to treatments without fertilizer in both years (table 5.5). Yield of maize rotational treatment of year two was significantly higher among the treatments in both years ($P<0.05$). However, year two recorded general yield increase as compared to year one. In terms of groundnut pod yield, there was no significant yield increase ($P>0.05$) among treatment applied with fertilizer and treatments without fertilizer applied in its corresponding sole and intercrop treatments. Treatments with fertilizer applied in both years gave higher LER of 1.2 and 1.09 respectively (table 5.5) while intercrop treatment without fertilizer in both years recorded LER of 0.8 and 0.95 respectively.

Table 5. 5: Effects of cropping systems on grain/pod yield and LER of maize and groundnut

Treatment	Grain/pod yield kg ha $^{-1}$ 2021			Grain/pod yield kg ha $^{-1}$ 2022		
	maize	Groundnut	LER	Maize	Groundnut	LER
T1 SCM-NF	1179.30	-	-	1585.60	-	-
T2 SCG-NF	-	769.23		-	922.00	-
T3 MGI-NF	443.00	324.07	0.8	878.90	380.00	0.95
T4 GMR-NF	-	686.11	-	1696.6	-	-
T5 MGR-NF	1142.20	-	-	-	1012.30	-
T6 SCM-F	2171.90	-	-	2987.90	-	-
T7 SCG-F	-	660.74	-	.	755.70	-
T8 MGI-F	1450.40	348.52	1.2	1934.6	332.50	1.09
T9 GMR-F/MG	-	596.30	-	3839.30	-	-
T10 MGR-F/GM	2453.30	-	-	-	909.30	-
Grand mean	1473.30	562.23		2153.7	722.31	
Lsd (0.05)	1022.40	223.23		1925.90	163.14	
P.Value	0.013	0.01		0.001	0.000	
CV	38.14	21.82		47.49	12.42	

7.11.2: SPAD value of maize affected by maize groundnut cropping systems.

7.11.2.1: SPAD value of maize and groundnut

The SPAD value of fertilized treatments of both maize and groundnut were significantly higher as compared to non-fertilized treatments in both years (P<0.05). SPAD values of both crops decreases as their age increases (figures 7.8, 7.9, 7.10 and 7.11). At week 10, groundnut was within the senescence period so SPAD reading was not taken

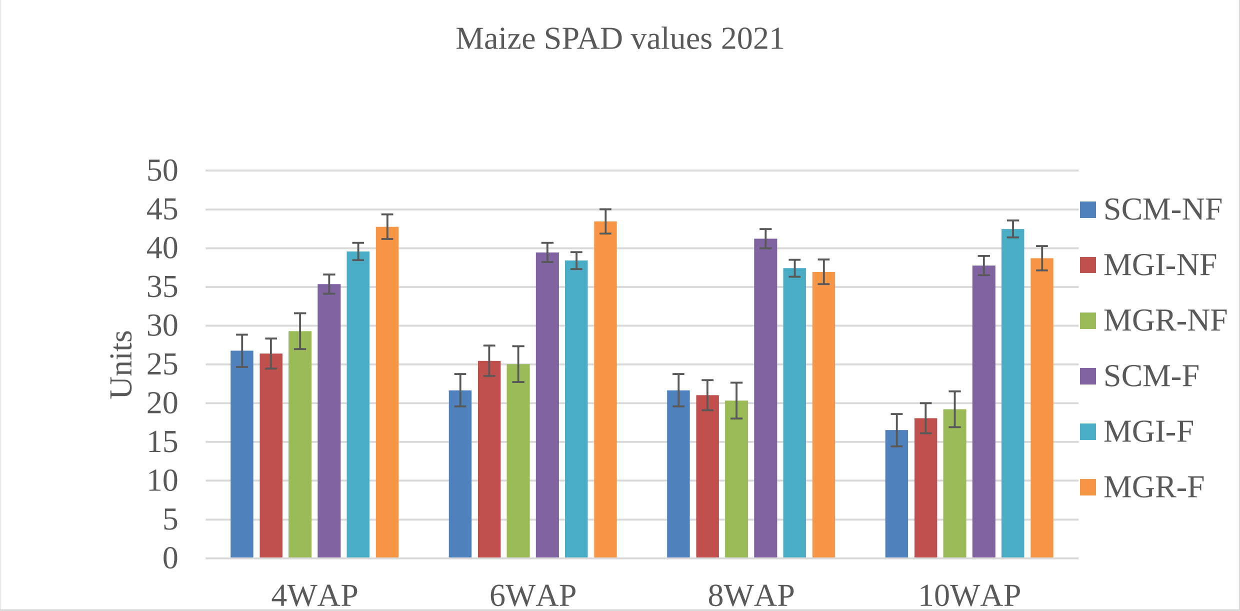

Figure 7. 4: Maize SPAD values, 2021

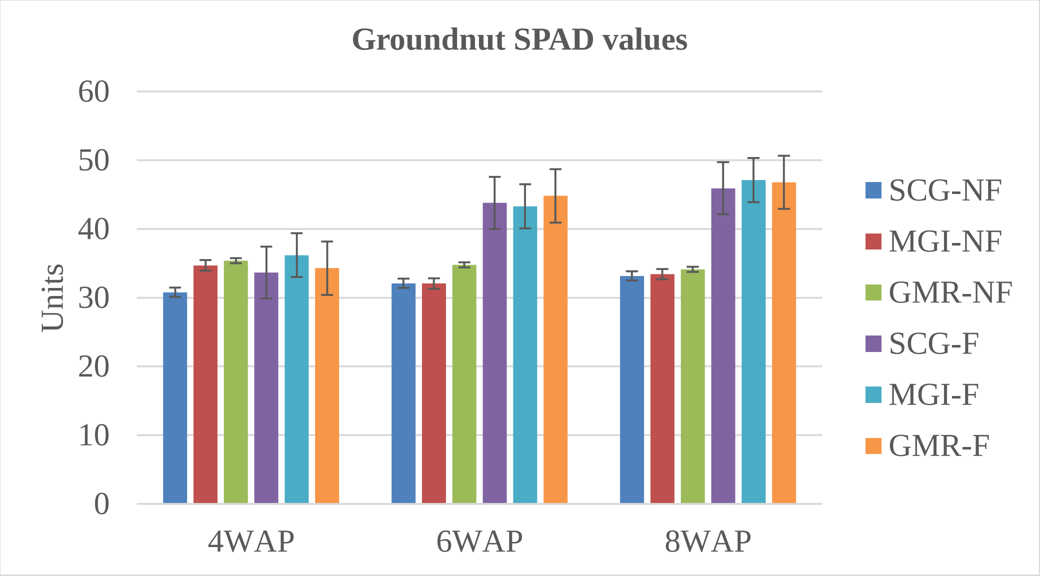

Figure 7. 5: Groundnut SPAD values, 2021

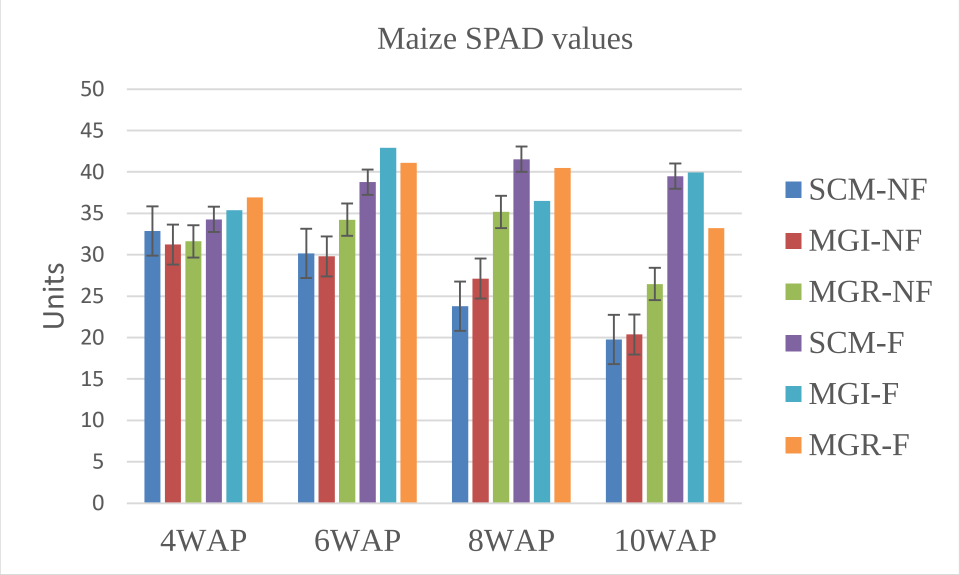

Figure 7. 6: Maize SPAD values, 2022

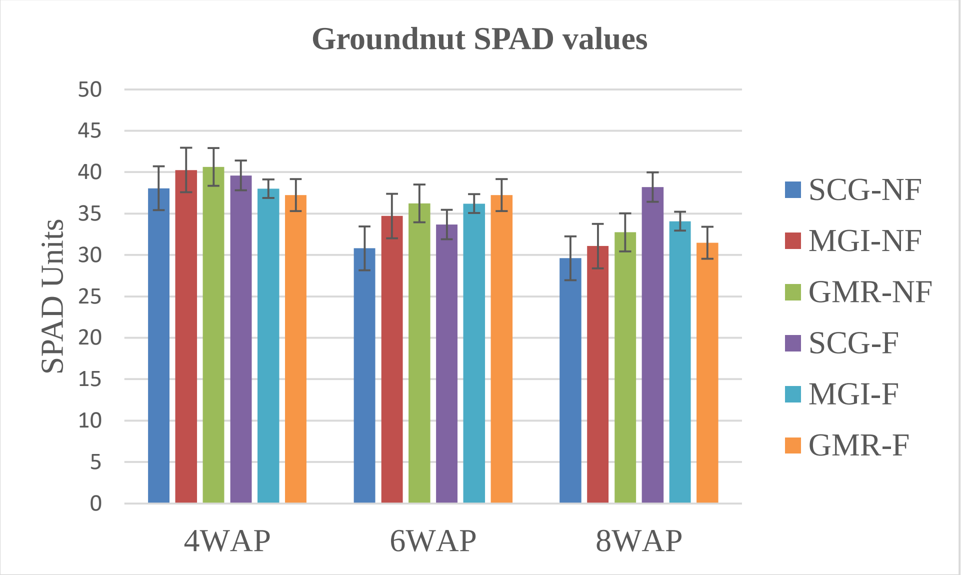

Figure 7. 7: Groundnut SPAD values, 2022

7.11.3: Photosynthetic Active Radiation (PAR) affected by cropping systems (%)

A rise in light interception was observed from 4 WAP to 8 WAP, as demonstrated by (figure 7.8). However, there were significant differences among treatments at the various stages of growth 4WAP, 6 WAP and 8 WAP with the fertilized intercropped treatment (T8 MGI-F) recorded higher light interception (P<0.05)

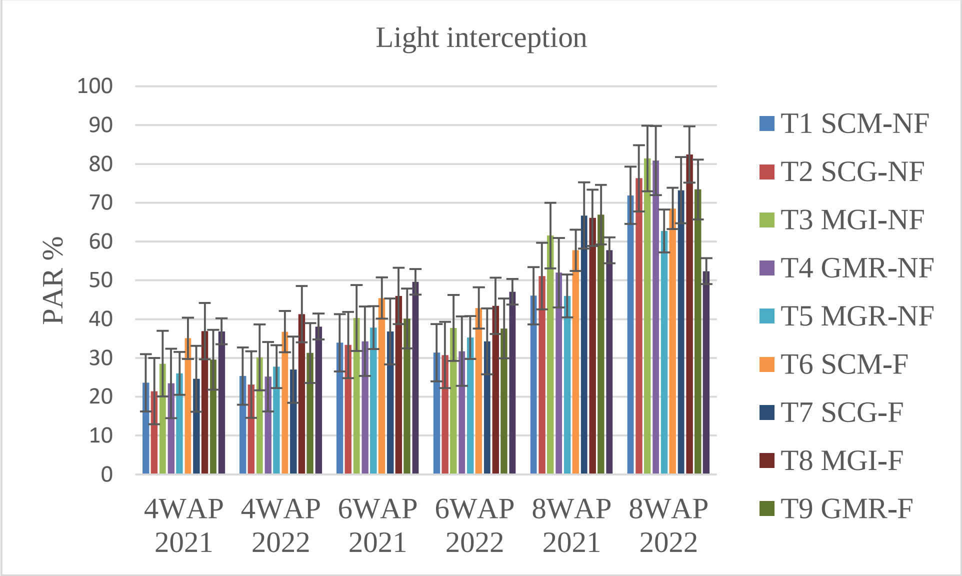

Figure 7.8: Light interception

7.11.4: LAI of maize groundnut affected by cropping systems

Intercropped treatments significantly recorded higher LAI as compared to sole cropping system treatments ($P<0.05$). LAI increased at development stages (WAP) and decreased as the plant got to the maturity stage.

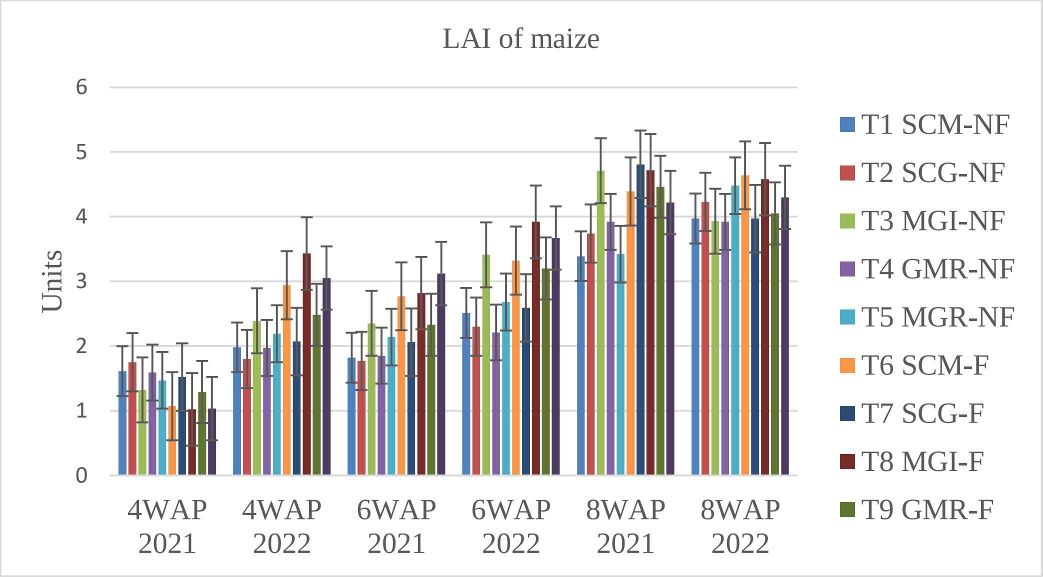

Figure 7.9: LAI

7.11.5: Cropping systems impact on soils volumetric water content (%)

Intercropped plots (treatments) had significant higher values of VWC ($P<0.05$) among the various week intervals than the sole crops of maize and groundnut. However, treatment with fertilizer applied had significantly higher value among all treatments.

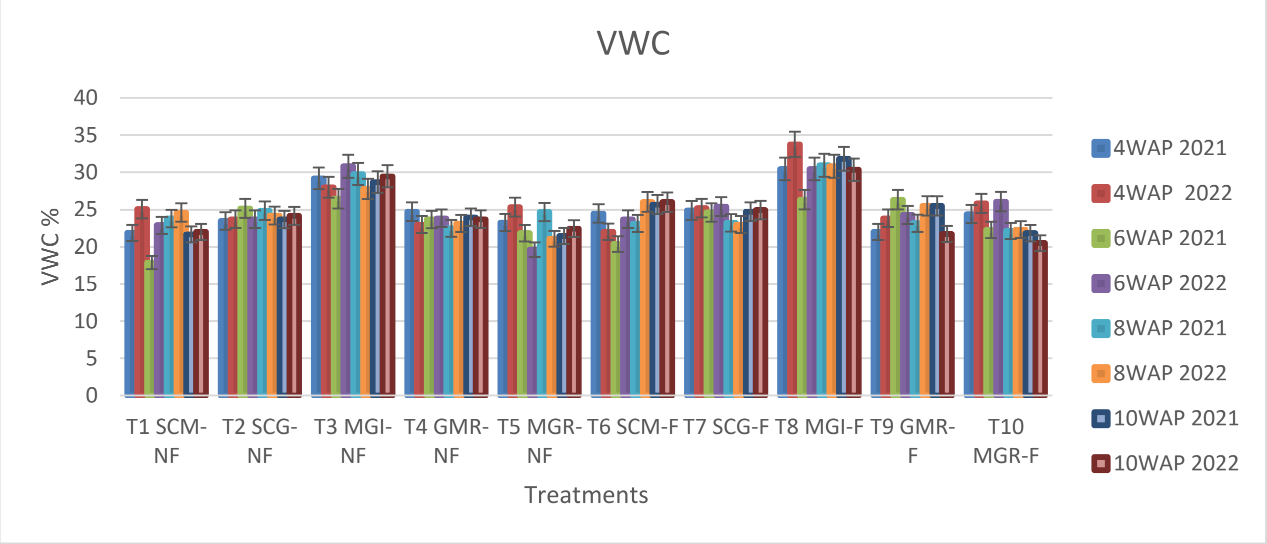

Figure 5.10: VWC

7.12: Variable cost and net benefit of maize and groundnut as affected by the intercropping systems

Table 7.6: Variable cost and net benefit of maize and groundnut: Season one

Treatment	Maize Grain yield Kg ha^{-1}	Groundnut Pod yield Kg ha^{-1}	Gross return of maize (GHC) *(100kg/bag= GHC200.00)	Gross return Of groundnut (GHC) **(40kg/bag = GHC300.00	Total Gross returns (GHC)	Total Variable cost of production (GHC)	Net returns (GHC)	Benefit Cost Ratio (BCR)
T1 SCM-NF	1179.30	-	2,358.60	-	2,358.60	1,420.00	938.60	0.66
T2 SCG-NF	-	769.23	-	5,769.23	5,769.23	1,420.00	4,340.23	3.06
T3 MGI-NF	443.00	324.07	886.00	2,430.53	3,316.53	1,460.00	1,856.53	1.27
T4 GMR-NF	-	686.11	-	5,145.83	5,145.83	1,420.00	3,725.83	2.62
T5 MGR-NF	1142.20	-	2284.40	-	2,284.40	1,420.00	864.40	0.61
T6 SCM-F	2171.90	-	4343.80	-	4,343.80	2,550.00	1,793.80	0.70
T7 SCG-F	-	660.74	-	4,955.55	4,955.55	1,970.00	2,985.55	1.52
T8 MGI-F	1450.40	348.52	2900.80	2,613.90	5,514.70	2,220.00	3,294.70	1.48
T9 GMR-F	-	596.30	-	4472.25	4,472.25	1,970.00	2,502.25	1.27
T10 MGR-F	2453.30	-	4906.60	-	4,906.60	2,550.00	2,356.60	0.92

Total Gross return = Gross returns of maize + groundnut

Total variable cost of production = Land preparation+ inputs + cost of labour for farm operations

Net returns = Total Gross returns – Total variable cost of production

Benefit cost ratio = Net returns / Total variable cost of production.

Table 7.7: Variable cost and net benefit of maize and groundnut: Season Two

Treatment	Maize Grain yield Kg ha^{-1}	Groundnut Pod yield Kg ha^{-1}	Gross return of maize (GHC) *(100kg/bag= GHC450.00)	Gross return Of groundnut (GHC) *(40kg/bag= GHC400.00)	Total Gross returns (GHC)	Total Variable cost of production (GHC)	Net returns (GHC)	Benefit Cost Ratio (BCR)
T1 SCM-NF	1585.60	-	7,135.20	-	7135.20	1860.00	5275.20	2.84
T2 SCG-NF	-	922	-	9,220.00	9220.00	1850.00	7370.00	3.98
T3 MGI-NF	878.90	380	3,955.05	3,800.00	7755.05	1855.00	5900.05	3.18
T4 MGR-NF	1669.60	-	7,513.20	-	7513.20	1860.00	5653.20	3.04
T5 GMR-NF	-	1012.30	-	10,120.00	10120.00	1850.00	8270.00	4.47
T6 SCM-F	2987.9	-	1,3441.55	-	13441.55	3210.00	10231.55	3.19
T7 SCG-F	-	755.70	-	7,557.00	7557.00	2525.00	5032.00	1.99
T8 MGI-F	1934.60	322.50	8,705.70	3,225.00	11930.70	2868.00	9062.70	3.16
T9 MGR-F	3839.30	-	17,276.85	-	17276.85	3210.00	14066.85	4.38
T10 GMR-F	-	909.30	-	9,093.00	9093.00	2525.00	6568.00.	2.60

Total Gross return = Gross returns of maize + groundnut

Total variable cost of production = Land preparation+ inputs + cost of labour for farm operations

Net returns = Total Gross returns – Total variable cost of production

Benefit cost ratio = Net returns / Total variable cost of production.

7.13: Discussion

A thorough understanding of physical and chemical properties of the soil within the site is very important. The analyses (Table 7.1) indicated that the experimental site is sandy silt in texture and strongly acidic in soil reaction (pH <5.5) with a very low organic carbon content (<1%) and total nitrogen (<0.1%). The pH felt short of the optimum for agronomic purposes of crop production and needed some liming to bring the pH upwards. The available P and exchangeable cations (except for K) were smaller than 10 mg/kg and 5 Cmol^{+}/kg respectively and hence the effective cation exchange capacity of the soil (Landon, 1991). All of the figures recorded (except for K) were considered lower limits and below the optimum for crop production without external input

Generally, the most important factors affecting crop yield are water availability, soil fertility, sunlight and management practices (Kombiok, 2004)). The result of grain yield of maize treatments with the application of fertilizer recorded significant higher yield (Table 7.5) compared to treatments without fertilizer in both years and this may be attributed to the external nutrient supplied since all other factors were similar. Maize grain yield in the rotational treatments of year two was also significantly higher among the treatments in both years (Table 7.5). The Results showed a common assumption that a groundnut crop improves N availability and enhances yield in a subsequent year. The effect on the yield is therefore influence mostly by moisture, nutrient and sunlight. However, year two recorded general yield increase as compared to year one but similar and this may be related to the early onset and even distribution of rains in year two (figure 7.2). In terms of groundnut pod yield, there was no significant yield increase (Table 7.5) among treatment applied with fertilizer and treatments without fertilizer applied in its corresponding sole and intercrop treatments. Though there was an increase in pod yield of groundnut in year two, this was not significant different from sole or intercrop. Intercropping significantly reduced the yields of individual crops. Similar findings were reported by Kombiok (2004) and Drisah (2006), who noted a notable decrease of individual grain yields of maize and groundnut intercropped. These are obvious since the plants stands are less. Many research investigations conducted on maize groundnut combinations demonstrated that, economically, the yields of the component crops offset the losses, even if the component crops often have lower yields when compared to their solitary or pure stands. Even though the grain and pod yields of both groundnut and maize in the intercrop plots decreased similarly, treatments with fertilizer applied in both years produced Land Equivalent Ratios (LER) of 1.2 and 1.09 (table 7.5), which is above unity and amply demonstrated the benefit of intercropping. Intercrop treatment without fertilizer in both years recorded LER of 0.8 and 0.95 respectively which is a disadvantage to the farmer. Yu et al., 2015 and Martin-Guay et al., 2018 in their research findings showed an average land equivalent ratio (LER) of around 1.22 ± 0.02 and 1.30 ± 0.01 or 1.29 ± 0.02 in intercrops with maize. Although they only included a small number of studies on maize groundnut intercropping, these earlier studies were global meta-analyses that took a wide range of species combinations into account. According to Francis (1986), the fractions of yields relative to their solitary and LER, an indicator of intercropping productivity, are equivalent. A yield advantage (LER>1), a yield disadvantage (LER<1), or an intermediate result (LER=1) are the three possible results for LER for intercropping. With this result, it means land resource use efficiency was better guaranteed by intercropping maize and groundnut with the application of fertilizer. Maize and groundnut intercropping has the potential to boost crop yields, lower risk, and improve soil fertility because of interspecific complementarity. Ghosh, 2004 also stated that it is possible to increase system production and resource use effectiveness by intercropping cereal and legumes. In this study, we found that intercropping greatly increased land use efficiency. Odhiambo et al., 2011 and Feike et al., 2012 stated that the main reason for farmers practicing intercropping is that it can increase land productivity and profitability. Selecting the right crops for intercropping can make good use of resources, thereby increasing the yield per unit area of farmland. The average LER in this investigation was consistent with meta-analyses based on combinations of multiple species. The broad consensus that intercropping cereals and legumes offers an advantage in land usage is supported by this. Due to the overall increase in the prices of products and services in Ghana, as well as the rise in agricultural inputs and farm operations, high variable cost of production was generally seen during the research period (tables 5.6 and 5.7). Plots with intercropped maize and groundnuts had greater production costs than single-crop plots. Due to the fixed costs of inputs and land preparation, solitary cropping has a low cost of production. The greatest total net returns were from sole groundnut treatment without fertilizer in year one and maize groundnut rotation treatment in year two. This might be explained by the fact that the two treatments produced a larger yield (tables 5.6 and 5.7). The higher groundnut yield of sole cropping in year one could be attributed to the availability of required nutrients for groundnut production since the land was fallowed two years before it was put into production. The higher yield with higher return recorded with maize in year two with maize groundnut rotation treatment was attributed to the contribution of nutrients of the remains of the groundnut cropped in the previous year. Drisah (2006) and Kombiok (2004) observed similar results when they alternated treatments of cowpea and groundnut with maize.

Benefit Cost Ratio (BCR) both years look quite good. However, year two recorded higher BCR as compared to year one (tables 7.6 and 7.7). This could be as a result of low yield recorded in year one. Also market price of both crops in year two was higher compared to year one. Again treatment with maize groundnut rotation in year two recorded the highest BCR and proved the significance of crop rotation.

Crops' light interception and light use efficiency (LUE), which depend on canopy characteristics like leaf distribution and photosynthetic capacity, directly affect the accumulation of dry matter and the generation of yield. Results of sun light interception by the treatments presented in (figure 7.8) showed that there was an increase in light interception from 4WAP to 8WAP. However, there were significant differences among treatments at the various stages of growth 4WAP, 6 WAP and 8 WAP with the intercropped treatment (figure 7.8) recorded higher light interception ($P<0.05$). Given interspecific complementarity, intercropping of maize and groundnuts as cereal legume is a good strategy to increase system production and resource use efficiency. The higher percentage of intercepted light and better utilization of the intercepted light in mixed crops can be used to explain their higher productivity when compared to sole groundnuts and maize, respectively which is also reported by (Searle et al., 1981; Li et al., 2001; Ghosh, 2004; Li et al., 2009). Numerous studies reported that yield advantage in intercropping was mainly due to greater light interception and use efficiency. It has been demonstrated that combining tall and short species, as in maize-groundnut intercropping systems, increases light absorption due to the increased soil cover (Zhang et al., 2020). Furthermore, because C4 species have higher saturation points than C3 species, intercropping of shorter C3 species and taller C4 species might increase the LUE.

Intercropped treatments with fertilizer inclusion recorded higher significantly LAI as compared to sole cropping system treatments (figure 7.9). These results are quite consistent with expectations, given that fertilizer was applied close to maize. This also reported by (Alhassan, 2000) when he intercropped sorghum with groundnut. After 8 WAP, the LAI values of all treatments decreased, most likely as a result of less dry matter being divided at this point between fruit development and leaf production, which were the main physiological processes requiring the accumulation and storage of dry matter at this stage. Similar findings were reported by Kombiok (2004) and Alhassan (2000), who proposed the onset of senescence.

The result of maize and groundnut chlorophyll content presented in (figure). The SPAD value of fertilized treatments of both maize and groundnut were significantly higher as compared to non-fertilized treatments (figure 7.4, 7.5, 7.6, 7.7). SPAD values of both crops decreases as their age increases. According to Dwyer et al., central leaves in maize plants have greater N concentrations prior to anthesis, which thereafter begin to decline up to two weeks after anthesis. However, groundnut SPAD values was higher as compared to maize values in both years and this could be attributed to groundnut ability to capture Nitrogen from the atmosphere.

Volumetric moisture content (VWC) varied significantly between different week intervals according to the findings (figure 5.10). In general, intercropped plots had significantly higher VWC during the various week intervals than the sole crops of maize and groundnut. This can be attributed to the biomass ability to conserve moisture. The outcome is similar to the report of Ajayi, (2015). The maize-groundnut intercrop improved soil and water conservation due to the additional surface soil protection it provided, and with appropriate intercrop selection, the competition for water under intercropping may be lessened. It was also clear that the VWC among the intercropped treatments was higher than that of the sole crops, indicating that groundnut in the intercropped treatments was capable of acting as live-mulch to shield the soil from direct sunlight, so slowing down the loss of moisture from the soil. Additionally, it was found that maize absorbed moisture more readily than groundnut. These findings are consistent with those of Crookston and Kent (1976), who found that the rate and amount of water uptake are influenced by the roots' capacity for absorption.

There have been reports of beneficial interactions between maize and legumes (groundnut) in strip intercropping and rotation by (Liu et al., 2018; Liu et al., 2017) including high land use efficiency, improved soil fertility, decreased disease and insect incidence, and assurance of steady output. The increased usage of natural resources, notably light, is an ecological benefit of cereal-groundnut intercropping. Optimizing maize row distance and gap width in maize-groundnut strip intercropping resulted in a significant increase in the photosynthetic active radiation (PAR) at the top of the groundnut canopy as well as the photosynthetic rate and radiation-use efficiency (RUE) of maize leaves close to the ear.

7.14: Conclusions

Crop rotation and intercropping with fertilizer application are emphasized in the study as beneficial soil management and conservation approaches. Maize and groundnut intercropping and rotation has the ability to raise productivity and income in vulnerable agricultural systems, retain soil nutrients, improve food security, and provide as a feasible starting point for ecological intensification. It is essential for developing countries to conserve land in addition to assisting smallholder agriculture in meeting their demands for protein and food. The dominant crop species, maize, makes the largest contribution to the high LER of maize/peanut intercropping. Despite the potential competition for water and plant resources from the soil, it still serves as the best management techniques for crop production to a small scale farmer.

CHAPTER EIGHT

8.0: GENERAL DISCUSSION

8.1: OVERVIEW

Food security is linked directly to factors like poverty, joblessness, illiteracy, rising food prices, climate and environmental conditions, and insufficient market access. 90% of families in northern Ghana depend on agriculture for their income, and severely constrained food production has led to persistent poverty, food insecurity, and malnutrition. Prices vary around the nation as a result of varying food availability, which has an impact on affordability. Food insecurity in Northern Ghana persists largely due to low crop yield and output. If current crop productivity levels continue, future increases in food demand are expected to put the inhabitants of Ghana's northern region and the nation at large at even greater risk to their ability to access food. If the Northern region of Ghana and Ghana as a whole are to become more food secure, with less reliance on significant imports, and extension of farming into forest areas and marginal lands, crop yield intensification of currently used farmlands is desperately needed. The solution to nutrient deficits that reduce agricultural output is to use fertilizer more frequently. However, there are significant regional and farm-level variability in crop production responses to fertilizer use in most of the smallholder agriculture practices in Northern Ghana. Therefore, investments in fertilizer use have not kept pace with increases in maize and groundnut productivity, and important crops yields remain low. If significant increases in crop production are to be achieved, a better knowledge of agricultural yield performance trends to fertilizer treatments and cropping systems are needed. This thesis, therefore, sought to offer ways for enhanced prediction of the anticipated agricultural production response using Northern Ghana as a case study, and groundnut and maize as the test crops.

Chapter four was to enable us understand the socio-economic setting and characteristics of farms and farming households involved in maize and groundnut production in northern Ghana. Assess current crop and nutrient management practices, and productivity in maize and groundnut cropping systems, explore factors associated with productivity in maize-groundnut cropping systems. The findings showed that the region's ability to produce maize is constrained by a variety of factors. However, insufficient soil fertility, the lack of and high cost of seeds of better varieties, weed and insect pest, lack and high cost of fertilizer are the major obstacles to maize production in the study sites (figure 4.4). According to these findings, if farmers have access to better soil and variety technologies, they will be able to better manage the stated constraints and boost production.

Chapter five emphasized on maize nutrient omission with the aim of assessing the degree to which maize yield responses vary in size and in time and space to balanced and imbalanced nutrient applications, evaluate effects of balanced and imbalanced nutrient applications on yield and yield quality and also to evaluate effects of balanced and imbalanced nutrient applications on soil nutrient balances. The significant effects of soil fertility variability on maize productivity and nutrient requirements were confirmed by the observed variations in reactions of maize yield across time and space to applied NPK and SMN combinations. Most farms lacked sufficient amounts of N, and there were significant differences in the farms' reactions to applying P, K and SMN (table 5.3). The slow drop in RYPK served for the majority of clusters, and the little shift in the average RYPK in time demonstrated the limited temporal differences in response to N. The different response groups' observed integration in RYPK in time also indicated a decrease in spatial disparities in response to N. As suggested by Tittonell et al. (2005), the prevalent N deficit can be related to the comparatively minimal levels of organic matter in the soil resulting from lack of legumes in the ongoing agricultural process and very little manure or fertilizer N applied.

The N status of farms in this region can be improved by farmers applying fertilizer N in combination with natural resources Vanlauwe et al. (2011) and rotating cereal crops with legumes Tully et al. (2015). We anticipate minor gains in nitrogen usage efficiency when taking into consideration variations in the regional and temporal reactions to N amongst farms in the different experimental districts, considering the limited spatial-temporal variances in responsiveness to N that have been observed.

Chapter six was to quantify the contribution of secondary and micronutrients (S, Zn and B) fertilization in enhancing yield and yield quality of maize with the objectives to identify the main secondary or micronutrient limiting maize yields in northern Ghana and assess the potential for profitability of varied combinations under heterogeneous smallholder farming conditions. The greater grain yield brought about by the addition of S and the micronutrients Zn and B to the NPK was due to increased improved growth, greater production, and nutrient supply. Additionally, the drop in grain yield that was observed in the control plots (table 6.4) abundantly illustrated the advantages of supplementing NPK consumption with secondary and micronutrients. The most significant economic outcome of the morphological and physiological events that occur during the growth and development of the maize plant, for the resource-limited farmer in Northern Ghana, is grain yield. Regardless of the nutrient formulation, the rate of primary nutrient distribution has to be a substantial impact in determining production because NPK, secondary, and micronutrient administration rates all grew steadily with grain yield. The average maize grain yields after adding secondary and micronutrients to NPK application showed that NPK application had a robust yield response on impoverished soils (Table 6.5). The incorporation of secondary and micronutrients can help to reduce the rate of NPK application because there were often no significant variations between the primary factors (NPK MR and NPK HR). This shows that for maize to function at its best in Northern

Ghana, fertilizer methods and technologies that control the dynamics of secondary and micronutrients in the soil are essential. S and the micronutrients, Zn and B were added to the NPK, which boosted grain yield and increased nutrient availability, growth, and productivity. Furthermore, the decrease in grain production (table 6.8) observed in the control plots convincingly illustrated the advantages of supplementing NPK intake with secondary and micronutrients. This result shown that the addition of secondary and micronutrients could significantly increase grain output. For healthy crop growth, plants need sulphur to generate essential metabolic substances such sulpho-lipids, proteins, amino acids, and glutathione. For the crops to develop under the current rain-fed system, which is periodically characterized by drought, increased water use efficiency is crucial.

Chapter seven analyses co-fertilization of maize and groundnuts as a feasible option for increasing crop productivity in maize and groundnut cropping systems. It also examines the yield, economic, and resource use advantages of improved fertilizer management in maize and groundnut cropping systems with the potential goal of quantifying the yield advantages of co-fertilization of maize and groundnuts. The findings supported a widely held belief that a groundnut crop increases N availability and raises yield in the following year. Therefore, moisture, nutrients, and sunlight have the greatest impact on the yield. The three outcomes for LER for intercropping are a yield advantage (LER>1), a yield disadvantage (LER1), or an intermediate result (LER=1). With this outcome, it can be concluded that fertilizer use efficiency was improved by intercropping maize and groundnuts. Due to their interspecific complementarity, maize and groundnut Intercropping can lower risk, boost soil fertility, and increase crop yields. The yield per unit area of farmland can be increased by intercropping the correct crops, which can make efficient use of resources. The contribution of nutrients from the remnants of the groundnut cropped in the previous year was attributed to the higher yield with higher return recorded with maize in year two with maize groundnut rotation treatment, and this proved the significance of maize groundnut rotation to a small-scale farmer

8.2: General conclusion

In conclusion, this study underscores the importance of addressing the challenges of low soil fertility, yield variability, and nutrient depletion in maize and groundnut production. The findings demonstrate that the strategic use of secondary and micronutrients, such as S, Zn, and B, in combination with NPK fertilizer, can significantly enhance grain yield. Furthermore, the adoption of integrated cropping systems, including intercropping and rotation, can lead to improved productivity, resource efficiency, and overall sustainability. Ultimately, the results suggest that farmers can improve their livelihoods and contribute to food security by adopting these practices, highlighting the potential for sustainable agricultural intensification in maize and groundnut production systems

8.3 Recommendations

The following research and policy driven recommendations are made.

1. The study recommends the inclusion of secondary and micronutrients with NPK fertilizer to enhance maize productivity. Specifically, the application of sulfur at a rate of 20 kilograms per hectare, zinc at a rate of 2 kilograms per hectare, and boron at a rate of 1 kilogram per hectare as supplementary nutrients is expected to significantly increase maize yields.
2. Crop rotation of maize with groundnut is a beneficial soil management and conservation approach that could retain soil nutrient, ability to raise productivity and improve food security
3. Fertilizer recommendations that are customized to the needs of individual farmers, soil fertility and climate can boost productivity and lower environmental hazards.

4. The integration of maize and groundnut intercropping with fertilizer application is expected to boost productivity, offering a more sustainable alternative to the prevailing farmer practice of no nutrient application.
5. Further research is also recommended on different secondary and micronutrients and varied application rates.

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APPENDICES

Appendix 4.1: Type III Analysis of Variance with Satterthwaite's method for maize grain yield

	SS	MS	DF	DenDF	F value	Pr(>F)
Variety	0.9725	0.9725	1	207.07	2.1906	0.1404
PlantTime	0.7156	0.3578	2	208.26	0.8060	0.4480
FertUse	0.1420	0.1420	1	205.79	0.3199	0.5723
FertFreq	0.5617	0.2808	2	206.88	0.6325	0.5323
WeedFreq	0.9623	0.3208	3	208.38	0.7225	0.5396
CropPract	19.2663	19.2663	1	210.15	43.3965	3.527e-10 ***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' '1

Linear mixed model fit by maximum likelihood t-tests use Satterthwaite's method ['lmerModLmerTest']

Formula: Yield_tha ~ Variety + PlantTime + Fert Use + Fert Freq + Weed Freq + Crop Pract + (1 community)

Appendix 4.2: Fixed effect

```
                          Estimate     Std. Error    Df           t value   Pr(>|t|)
(Intercept)               1.014198     0.349492      45.182607    2.902     0.00571 **
Variety Improved          -0.244380    0.165113      207.073934   -1.480    0.14037
Plant Time at (rains)     -0.120152    0.172280      209.241641   -0.697    0.48631
Plant Time (after rains)  0.036956     0.212235      208.635116   0.174     0.86193
Fert Use (Yes)            0.124592     0.220282      205.792556   0.566     0.57228
Fert freq (once)          0.147056     0.227610      206.555416   0.646     0.51894
Fert freq (twice)         -0.043508    0.250545      206.018676   -0.174    0.86231
Weed freq (once)          -0.001437    0.195418      209.133937   -0.007    0.99414
Weed freq (twice)         -0.168974    0.176707      210.294859   -0.956    0.34005
Weed freq (thrice)        -0.069752    0.283758      207.965391   -0.246    0.80607
Crop pract (Monocrop)     0.771955     0.117183      210.152092   6.588     3.53e-10
***

---

Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’1
```

Appendix 4.3: Correlation of Fixed Effects

```
                          (Interc) VTimp  PTr PTAr FY Fo Ftw Fth WdFon WdFtw WdFth
Varty improved            0.020
 Plant Time at (rains)    -0.498  -0.074
Plant Time (after rains)  -0.413  -0.089  0.752
Fert Use (Yes)            0.058   0.050 -0.052 -0.065
Fert freq (once)          -0.039  -0.062  0.040  0.012  -0.781
Fert freq (twice)         -0.054  -0.147  0.066  0.065 -0.795  0.720
Weed freq (once)          -0.425  -0.114  0.130  0.131   -0.074 -0.068  0.004
Weed freq (twice)         -0.469   -0.059  0.099  0.149  -0.140  0.025  0.035  0.754
```

```
Weed freq (thrice)       -0.318  0.000   0.062   0.071  -0.161 0.085  0.101  0.485  0.577

Crop pract (Monocro)-0.240  0.020  0.039  -0.072  0.020 -0.130 -0.117 0.119 0.085 0.124


[1] Cropping Practice effect

Type III Analysis of Variance Table with Satterthwaite's method

         Sum Sq Mean Sq NumDF DenDF F value    Pr(>F)

CropPract   24.5  24.5  1 211.1  52.452 8.114e-12 ***

Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' '1

[1]

Linear mixed model fit by maximum likelihood. T-tests use Satterthwaite's method
['lmerModLmerTest']

Formula: Yield_tha ~ CropPract + (1 | community)
```

Appendix 5.1: Type III Analysis of Variance with Satterthwaite's method, NOTs (2020)

```
                  SS        MS       DF DDF   F value    Pr(>F)

Treatment 125.48   25.096    5   105    48.703   < 2.2e-16 ***

---

Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' '1

Linear mixed model fit by REML. t-tests use Satterthwaite's method
['lmerModLmerTest']

Formula: Gryldtha ~ 1 + Treatment + (1 | SiteCODE)
```

Appendix 5.2: Fixed effects

```
                    Estimate       Std. Error      df t        value           Pr(>|t|)

(Intercept)           0.9064        0.1933         74.2916     4.689       1.22e-05 ***

TreatmentPK         0.3395        0.2164         105.0000    1.569       0.12

TreatmentNK          0.9864        0.2164         105.0000    4.557      1.41e-05 ***

TreatmentNP         2.1155        0.2164          105.0000     9.774      < 2e-16 ***
```

```
TreatmentNPK      2.0259     0.2164       105.0000      9.360      1.67e-15 ***
TreatmentNPK+MN 2.6482   0.2164       105.0000      12.235      < 2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’1
```

Appendix 5.3: Correlation of Fixed Effects

```
                      Intr     TrtmPK  TrtmNK  TrtmNP  TrtNPK
TreatmentPK      -0.560
TreatmentNK     -0.560     0.500
TreatmentNP     -0.560      0.500   0.500
TreatmntNPK    -0.560     0.500     0.500   0.500
TrtmnNPK+MN -0.560   0.500    0.500     0.500     0.500
Predicted Means`
Treatment
Control     PK         NK      NP     NPK   NPK+MN
 0.9064     1.2459   1.8927  3.0218  2.9323   3.5545
```

Appendix 5.4: Type III Analysis of Variance with Satterthwaite's method, NOTs (2021)

```
                 SS        MS       DF   DDF   F value    Pr(>F)
Treatment 118.19    23.638     5    110    59.218    < 2.2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
[1]
Linear mixed model fit by REML. t-tests use Satterthwaite's method
['lmerModLmerTest']
Formula: Gryldtha ~ 1 + Treatment + (1 | SiteCODE)
  Fixed effects:
                             Estimate   Std. Error      df        t value    Pr(>|t|)
```

```
(Intercept)          0.4439    0.1818    62.0520   2.442     0.0175 *
TreatmentPK          0.3922    0.1863   110.0000   2.105     0.0376 *
TreatmentNK          0.7861    0.1863   110.0000   4.219 5.  06e-05 ***
TreatmentNP          1.4326    0.1863   110.0000   7.689     6.70e-12 ***
TreatmentNPK         2.0100    0.1863   110.0000   10.789     < 2e-16 ***
TreatmentNPK+MN   2.6717    0.1863   110.0000   14.340     < 2e-16 ***


Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’
```

Appendix 5.5: Correlation of Fixed Effects

```
                    (Intr)  TrtmPK  TrtmNK  TrtmNP  TrtNPK
TreatmentPK         -0.512
TreatmentNK         -0.512   0.500
TreatmentNP         -0.512   0.500   0.500
TreatmntNPK         -0.512   0.500   0.500   0.500
TrtmnNPK+MN  -0.512   0.500   0.500   0.500   0.500
$`Predicted Means`
Treatment
Control   PK     NK     NP     NPK  NPK+MN
 0.4439  0.8361  1.2300  1.8765  2.4539  3.1157
```

Appendix 3.6: Type III Analysis of Variance with Satterthwaite's method, NOTs (2021)

```
                 SS       MS       DF        DDF     F value    Pr(>F)
Treatment      33.386    6.6773   5 97.969  24.182   8.925      e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
Linear mixed model fit by REML. t-tests use Satterthwaite's method
['lmerModLmerTest']
Formula: Gryldtha ~ 1 + Treatment + (1 | SiteCODE)
```

Appendix 5.7: Fixed effects

```
                Estimate   Std. Error    df       t value Pr(>|t|)
(Intercept)      0.4756     0.1651     54.6204   2.882    0.00565 **
TreatmentPK      0.0700     0.1662     97.8524   0.421    0.67449
TreatmentNK      0.3482     0.1646     98.0742   2.116    0.03692 *
TreatmentNP      0.7625     0.1646     98.0742   4.633    1.11e-05 ***
```

```
TreatmentNPK      1.1148     0.1646 98.0742   6.774 9.35e-10 ***
TreatmentNPK+MN   1.4006     0.1646 98.0742   8.510 2.04e-13 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Appendix 5.8: Correlation of Fixed Effects:

```
                  Intr   TrtmPK  TrtmNK TrtmNP TrtNPK
TreatmentPK       -0.503
TreatmentNK       -0.513   0.505
TreatmentNP      -0.513    0.505   0.515
TreatmntNPK      -0.513    0.505   0.515  0.515
TrtmnNPK+MN  -0.513    0.505  0.515  0.515  0.515
Predicted Means`
Treatment
Control     PK     NK     NP     NPK     NPK+MN
 0.4756   0.5456  0.8238  1.2381  1.5905  1.8762
```

Appendix 5.9: Partial Factor Productivity, K

```
Type III Analysis of Variance Table with Satterthwaite's method
              SS        MS       DF   DDF   F value    Pr(>F)
Treatment 19588    6529.5     3    63       41.531     6.224e-15 ***

Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
Linear mixed model fit by REML. t-tests use Satterthwaite's method
['lmerModLmerTest']
Formula: PFPK ~ 1 + Treatment + (1 | SiteCODE)
```

Appendix 5.9: Fixed effects:

```
                       Estimate   Std. Error    df       t value     Pr(>|t|)

(Intercept)            20.765      3.455        56.649   6.011     1.41e-07 ***

TreatmentNK           10.780      3.781 63.000   2.852             0.00588 **

TreatmentNPK         28.106      3.781 63.000   7.434             3.48e-10 ***

TreatmentNPK+MN   38.477      3.781 63.000  10.178            6.27e-15 ***


Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Appendix 5.10: Correlation of Fixed Effects

```
                  Intr     TrtmNK  TrtNPK

TreatmentNK      -0.547

TreatmntNPK      -0.547   0.500

TrtmnNPK+MN   -0.547   0.500     0.500

Predicted Means`

Treatment

 PK       NK        NPK       NPK+MN

20.7652  31.5455  48.8712  59.2424
```

Appendix 5.11: Partial Factor Productivity N

```
Type III Analysis of Variance Table with Satterthwaite's method

                SS         MS       DF  DDF  F value    Pr(>F)

Treatment  2213.8   737.94     3    63      25.108     8.343e-11 ***

Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Linear mixed model fit by REML. t-tests use Satterthwaite's method
['lmerModLmerTest']

Formula: PFPN ~ 1 + Treatment + (1 | SiteCODE)
```

Appendix 5.12: Fixed effects:

```
                     Estimate  Std. Error   df       t value   Pr(>|t|)
(Intercept)           15.773     1.798       41.307   8.770     5.59e-11 ***
TreatmentNP            9.409     1.635       63.000   5.756     2.75e-07 ***
TreatmentNPK           8.663     1.635       63.000   5.300     1.58e-06 ***
TreatmentNPK+MN   13.848     1.635       63.000   8.472     5.35e-12 ***

Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Appendix 5.13: Correlation of Fixed Effects:

```
                     (Intr) TrtmNP TrtNPK
TreatmentNP        -0.454
TreatmntNPK        -0.454   0.500
TrtmnNPK+MN  -0.454   0.500  0.500
Predicted Means`
Treatment
    NK       NP          NPK        NPK+MN
 15.7727   25.1818   24.4356    29.6212
```

Appendix 3.14: Partial Factor Productivity, P

```
Type III Analysis of Variance Table with Satterthwaite's method
                     SS        MS         DF   DDF   F value    Pr(>F)
Treatment   18343    6114.4     3     63    40.305       1.156e-14 ***
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
Linear mixed model fit by REML. t-tests use Satterthwaite's method
['lmerModLmerTest']
Formula: PFPP ~ 1 + Treatment + (1 | SiteCODE)
```

Appendix 3.15: Fixed effects:

```
                      Estimate  Std. Error   df       t value  Pr(>|t|)
(Intercept)            20.765     3.444     55.056   6.029     1.44e-07 ***
TreatmentNP             29.598    3.714     63.000   7.970      4.02e-11 ***
TreatmentNPK           28.106     3.714     63.000   7.568      2.03e-10 ***
TreatmentNPK+MN   38.477      3.714     63.000   10.361     3.08e-15 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Appendix 3.16: Correlation of Fixed Effects:

```
                  Intr    TrtmNP  TrtNPK
TreatmentNP      -0.539
TreatmntNPK      -0.539   0.500
TrtmnNPK+MN  -0.539  0.500  0.500
Predicted Means`
Treatment
PK           NP       NPK       NPK+MN
20.7 652   50.3636 48.8712   59.2424
```

Appendix 6.1: Analysis of Variance table for Grain yield t ha^{-1} - 2021

Source	**DF**	**SS**	**MS**	**F**	**P**
Rep	2	11.9403	5.97013		
MainF	1	4.4608	4.46083	1.91	0.3008
Error Rep*MainF	2	4.6629	2.33145		
SubF	9	17.7460	1.97177	4.73	0.0003
MainF*SubF	9	2.5273	0.28081	0.67	0.7266
Error Rep*MainF*SubF	36	14.9969	0.41658		
Total	59	56.3341			

** = Highly significant at $p < 0.05$, * = significant at $p \leq 0.05$, NS = Not significant $p > 0.05$

Appendix 6.2: Analysis of Variance Table for Grain yield t ha^{-1} - 2022

Source	**DF**	**SS**	**MS**	**F**	**P**
Rep	2	15.0230	7.51150		
MainF	1	1.4758	1.47580	0.52	0.5451
Error Rep*MainF	2	5.6552	2.82761		
SubF	9	27.8188	3.09098	3.33	0.0047
MainF*SubF	9	8.1942	0.91047	0.98	0.4728
Error Rep*MainF*SubF	36	33.4520	0.92922		
Total	59	91.6192			

** = Highly significant at $p < 0.05$, * = significant at $p \leq 0.05$, NS = Not significant $p > 0.05$

Appendix 6.3: Comparisons of grain yield of SMN sub factor with NPK main factor treatments: 2021

Two-sided Dunnett's Multiple Comparisons with grain yield t ha $^{-1}$

MN=NoMN: Simultaneous 95% confidence intervals of treatment mean

		Lower		Upper
SubF	**Mean**	**Bound**	**Difference**	**Bound**
NoMN	2.2950			
S	3.4683	0.1201	**1.1733***	2.2266
SBhr	3.2733	-0.0749	0.9783	2.0316
SBmr	3.0883	-0.2599	0.7933	1.8466
SZnBhr	4.4817	1.1334	**2.1867***	3.2399
SZnBmr	3.2783	-0.0699	0.9833	2.0366
SZnhr	3.5400	0.1918	**1.2450***	2.2982
SZnmr	3.0733	-0.2749	0.7783	1.8316
ZnBhr	3.4033	0.0551	**1.1083***	2.1616
ZnBmr	2.6883	-0.6599	0.3933	1.4466

Alpha 0.05 Standard Error for Comparison 0.3726
Critical D Value 2.826 Critical Value for Comparison 1.0532
Error term used: Rep*MainF*SubF, 36 DF

Appendix 6.4: Comparisons of grain yield of SMN sub factor with NPK main factor treatments: 2022

Two-sided Dunnett's Multiple Comparisons with grain yield t ha
Control: SubF=NoMN

Simultaneous 95% confidence intervals of treatment mean - control mean

		Lower		**Upper**
SubF	**Mean**	**Bound**	**Difference**	**Bound**
NoMN	2.5333			
S	4.1350	0.0286	1.6017*	3.1747
SBhr	3.7783	-0.3280	1.2450	2.8180
SBmr	3.4183	-0.6880	0.8850	2.4580
SZnBhr	4.9983	0.8920	2.4650*	4.0380
SZnBmr	4.5317	0.4253	1.9983*	3.5714
SZnhr	4.5750	0.4686	2.0417*	3.6147
SZnmr	4.2300	0.1236	1.6967*	3.2697
ZnBhr	3.8400	-0.2664	1.3067	2.8797
ZnBmr	3.3450	-0.7614	0.8117	2.3847

Alpha 0.05 Standard Error for Comparison 0.5565
Critical D Value 2.826 Critical Value for Comparison 1.5730
Error term used: Rep*MainF*SubF, 36 DF

6.5: Analysis of Variance Table for stover yield t ha^{-1} - 2021

Source	DF	SS	MS	F	P
Rep	2	22.814	11.4069		
MainF	1	4.224	4.2241	1.69	0.3232
Error Rep*MainF	2	4.999	2.4993		
SubF	9	10.061	1.1179	0.83	0.5917
MainF*SubF	9	11.325	1.2584	0.94	0.5064
Error Rep*MainF*SubF	36	48.381	1.3439		
Total	59	101.804			

** = Highly significant at $p < 0.05$, * = significant at $p \leq 0.05$, NS = Not significant $p > 0.05$

6.6: Analysis of Variance Table for stover weight t ha^{-1} - 2022

Source	DF	SS	MS	F	P
Rep	2	5.2123	2.60613		
MainF	1	4.5816	4.58161	0.88	0.4469
Error Rep*MainF	2	10.3938	5.19691		
SubF	9	12.9457	1.43842	2.18	0.0471
MainF*SubF	9	9.5887	1.06541	1.62	0.1478
Error Rep*MainF*SubF	36	23.7384	0.65940		
Total	59	66.4606			

** = Highly significant at $p < 0.05$, * = significant at $p \leq 0.05$, NS = Not significant $p > 0.05$

6.7: Analysis of Variance Table for Harvest Index - 2021

Source	**DF**	**SS**	**MS**	**F**	**P**
Rep	2	2.586	1.2928		
MainF	1	9.520	9.5202	0.27	0.6535
Error Rep*MainF	2	69.775	34.8874		
SubF	9	361.571	40.1745	4.48	0.0005
MainF*SubF	9	82.670	9.1856	1.02	0.4406
Error Rep*MainF*SubF	36	323.138	8.9760		
Total	59	849.259			

** = Highly significant at p < 0.05, * = significant at p ≤ 0.05, NS = Not significant p > 0.05

Appendix 6.8: Analysis of Variance Table for Harvest index -2022

Source	**DF**	**SS**	**MS**	**F**	**P**
Rep	2	181.30	90.6500		
MainF	1	41.67	41.6667	0.68	0.4955
Error Rep*MainF	2	122.03	61.0167		
SubF	9	352.73	39.1926	1.58	0.1577
MainF*SubF	9	293.33	32.5926	1.32	0.2628
Error Rep*MainF*SubF	36	891.33	24.7593		
Total	59	1882.40			

** = Highly significant at p < 0.05, * = significant at p ≤ 0.05, NS = Not significant p > 0.05

Appendix 6.9: Analysis of Variance Table for Leaf Area Index, 4WAP - 2021

Source	DF	SS	MS	F	P
Rep	2	8.8023	4.40113		
MainF	1	0.6573	0.65731	1.53	0.3411
Error Rep*MainF	2	0.8567	0.42835		
SubF	9	3.3215	0.36906	1.78	0.1058
MainF*SubF	9	1.7095	0.18994	0.92	0.5211
Error Rep*MainF*SubF	36	7.4503	0.20695		
Total	59	22.7976			

** = Highly significant at p < 0.05, * = significant at p ≤ 0.05, NS = Not significant p > 0.05

Appendix 6.10: Analysis of Variance Table for Leaf Area Index, 4WAP - 2022

Source	DF	SS	MS	F	P
Rep	2	8.8023	4.40113		
MainF	1	0.6573	0.65731	1.53	0.3411
Error Rep*MainF	2	0.8567	0.42835		
SubF	9	3.3215	0.36906	1.78	0.1058
MainF*SubF	9	1.7095	0.18994	0.92	0.5211
Error Rep*MainF*SubF	36	7.4503	0.20695		
Total	59	22.7976			

** = Highly significant at p < 0.05, * = significant at p ≤ 0.05, NS = Not significant p > 0.05

Appendix 6.11: Analysis of Variance Table for Leaf Area Index 6WAP - 2021

Source	**DF**	**SS**	**MS**	**F**	**P**
Rep	2	13.5006	6.75028		
MainF	1	2.6058	2.60583	2.37	0.2637
Error Rep*MainF	2	2.2008	1.10042		
SubF	9	4.1937	0.46597	1.41	0.2185
MainF*SubF	9	2.1841	0.24268	0.74	0.6730
Error Rep*MainF*SubF	36	11.8590	0.32942		
Total	59	36.5441			

** = Highly significant at p < 0.05, * = significant at p ≤ 0.05, NS = Not significant p > 0.05

Appendix 6.12: Analysis of Variance Table for Leaf Area Index, 6WAP - 2022

Source	**DF**	**SS**	**MS**	**F**	**P**
Rep	2	12.5333	6.26666		
MainF	1	2.0130	2.01300	2.27	0.2711
Error Rep*MainF	2	1.7763	0.88815		
SubF	9	5.2270	0.58077	1.77	0.1086
MainF*SubF	9	1.6584	0.18427	0.56	0.8187
Error Rep*MainF*SubF	36	11.8080	0.32800		
Total	59	35.0160			

** = Highly significant at p < 0.05, * = significant at p ≤ 0.05, NS = Not significant p > 0.05

Appendix 6.13: Analysis of Variance Table for Leaf Area Index, 8WAP - 2021

Source	**DF**	**SS**	**MS**	**F**	**P**
Rep	2	22.5791	11.2895		
MainF	1	4.9536	4.9536	2.82	0.2350
Error Rep*MainF	2	3.5114	1.7557		
SubF	9	8.5709	0.9523	1.96	0.0737
MainF*SubF	9	4.4531	0.4948	1.02	0.4434
Error Rep*MainF*SubF	36	17.4718	0.4853		
Total	59	61.5398			

** = Highly significant at $p < 0.05$, * = significant at $p \leq 0.05$, NS = Not significant $p > 0.05$

Appendix 6.14: Analysis of Variance Table for Leaf Area Index, 8WAP - 2022

Source	**DF**	**SS**	**MS**	**F**	**P**
Rep	2	21.1883	10.5942		
MainF	1	4.4390	4.4390	3.08	0.2211
Error Rep*MainF	2	2.8784	1.4392		
SubF	9	8.2113	0.9124	1.83	0.0970
MainF*SubF	9	3.5177	0.3909	0.78	0.6336
Error Rep*MainF*SubF	36	17.9800	0.4994		
Total	59	58.2148			

** = Highly significant at $p < 0.05$, * = significant at $p \leq 0.05$, NS = Not significant $p > 0.05$

Appendix 6.15: Analysis of Variance Table for leaf Area index 10WAP - 2021

Source	DF	SS	MS	F	P
Rep	2	46.892	23.4462		
MainF	1	8.111	8.1107	2.49	0.2554
Error Rep*MainF	2	6.520	3.2600		
SubF	9	13.995	1.5550	1.79	0.1044
MainF*SubF	9	9.178	1.0198	1.17	0.3404
Error Rep*MainF*SubF	36	31.270	0.8686		
Total	59	115.967			

** = Highly significant at $p < 0.05$, * = significant at $p \leq 0.05$, NS = Not significant $p > 0.05$

Appendix 6.16: Analysis of Variance Table for Leaf Area Index 10WAP - 2022

Source	DF	SS	MS	F	P
Rep	2	47.776	23.8878		
MainF	1	8.978	8.9784	2.90	0.2308
Error Rep*MainF	2	6.195	3.0973		
SubF	9	14.259	1.5844	1.74	0.1162
MainF*SubF	9	8.778	0.9753	1.07	0.4081
Error Rep*MainF*SubF	36	32.839	0.9122		
Total	59	118.825			

** = Highly significant at $p < 0.05$, * = significant at $p \leq 0.05$, NS = Not significant $p > 0.05$

Appendix 6.17: Analysis of Variance Table for SPAD, 4WAP - 2021

Source	**DF**	**SS**	**MS**	**F**	**P**
Rep	2	350.93	175.465		
MainF	1	99.07	99.074	1.34	0.3668
Error Rep*MainF	2	148.02	74.011		
SubF	9	261.18	29.020	1.45	0.2043
MainF*SubF	9	173.14	19.238	0.96	0.4872
Error Rep*MainF*SubF	36	720.70	20.019		
Total	59	1753.05			

** = Highly significant at $p < 0.05$, * = significant at $p \leq 0.05$, NS = Not significant $p > 0.05$

Appendix 6.18: Analysis of Variance Table for SPAD, 4WAP - 2022

Source	**DF**	**SS**	**MS**	**F**	**P**
Rep	2	350.93	175.465		
MainF	1	99.07	99.074	1.34	0.3668
Error Rep*MainF	2	148.02	74.012		
SubF	9	261.18	29.020	1.45	0.2043
MainF*SubF	9	173.14	19.238	0.96	0.4872
Error Rep*MainF*SubF	36	720.70	20.019		
Total	59	1753.05			

** = Highly significant at $p < 0.05$, * = significant at $p \leq 0.05$, NS = Not significant $p > 0.05$

Appendix 6.19: Analysis of Variance Table for SPAD, 6WAP - 2021

Source	**DF**	**SS**	**MS**	**F**	**P**
Rep	2	275.94	137.971		
MainF	1	41.67	41.667	0.88	0.4474
Error Rep*MainF	2	94.79	47.395		
SubF	9	689.88	76.653	4.38	0.0007
MainF*SubF	9	56.29	6.255	0.36	0.9478
Error Rep*MainF*SubF	36	630.31	17.509		
Total	59	1788.88			

** = Highly significant at $p < 0.05$, * = significant at $p \leq 0.05$, NS = Not significant $p > 0.05$

Appendix 6.20: Analysis of Variance Table for SPAD, 6WAP - 2022

Source	**DF**	**SS**	**MS**	**F**	**P**
Rep	2	202.72	101.361		
MainF	1	79.35	79.350	2.22	0.2746
Error Rep*MainF	2	71.44	35.718		
SubF	9	683.78	75.976	3.79	0.0019
MainF*SubF	9	38.21	4.246	0.21	0.9910
Error Rep*MainF*SubF	36	722.35	20.065		
Total	59	1797.85			

** = Highly significant at $p < 0.05$, * = significant at $p \leq 0.05$, NS = Not significant $p > 0.05$

Appendix 6.21: Analysis of Variance Table for SPAD, 8WAP - 2021

Source	**DF**	**SS**	**MS**	**F**	**P**
Rep	2	1.21	0.606		
MainF	1	109.89	109.891	10.12	0.0862
Error Rep*MainF	2	21.71	10.857		
SubF	9	362.34	40.260	2.98	0.0093
MainF*SubF	9	213.84	23.760	1.76	0.1112
Error Rep*MainF*SubF	36	486.31	13.509		
Total	59	1195.31			

** = Highly significant at p < 0.05, * = significant at p ≤ 0.05, NS = Not significant p > 0.05

Appendix 6.22: Analysis of Variance Table for SPAD, 8WAP - 2022

Source	**DF**	**SS**	**MS**	**F**	**P**
Rep	2	158.32	79.159		
MainF	1	153.92	153.920	1.39	0.3594
Error Rep*MainF	2	221.11	110.555		
SubF	9	212.28	23.586	1.76	0.1110
MainF*SubF	9	193.30	21.478	1.60	0.1517
Error Rep*MainF*SubF	36	482.53	13.403		
Total	59	1421.46			

** = Highly significant at p < 0.05, * = significant at p ≤ 0.05, NS = Not significant p > 0.05

Appendix 6.23: Analysis of Variance Table for SPAD, 10WAP - 2021

Source	**DF**	**SS**	**MS**	**F**	**P**
Rep	2	394.31	197.157		
MainF	1	56.94	56.940	0.82	0.4607
Error Rep*MainF	2	138.86	69.431		
SubF	9	341.70	37.966	2.41	0.0295
MainF*SubF	9	200.90	22.322	1.42	0.2171
Error Rep*MainF*SubF	36	566.74	15.743		
Total	59	1699.45			

** = Highly significant at p < 0.05, * = significant at p ≤ 0.05, NS = Not significant p > 0.05

Appendix 6.24: Analysis of Variance Table for SPAD, 10WAP - 2022

Source	**DF**	**SS**	**MS**	**F**	**P**
Rep	2	394.93	197.466		
MainF	1	55.01	55.008	0.81	0.4641
Error Rep*MainF	2	136.53	68.264		
SubF	9	340.63	37.848	2.44	0.0278
MainF*SubF	9	204.76	22.751	1.47	0.1977
Error Rep*MainF*SubF	36	558.46	15.513		
Total	59	1690.32			

** = Highly significant at p < 0.05, * = significant at p ≤ 0.05, NS = Not significant p > 0.05

Grand Mean 4.4263

CV(Rep*MainF) 35.72

CV(Rep*MainF*SubF) 26.19

Appendix 7.1: ANOVA table for 2021, 2022 maize groundnut cropping systems

Appendix 5.1: ANOVA Table for Maize grain yield kg ha $^{-1}$ – 2021

Source	DF	SS	MS	F	P
Replicates	2	1023221	511611		
Treatment	5	8119905	1623981	5.14	0.0136
Error	10	3158457	315846		
Total	17	1.230E+07			

** = Highly significant at $p < 0.05$, * = significant at $p \leq 0.05$, NS = Not significant $p > 0.05$

Appendix 7.2: ANOVA Table for Pod yield kg ha $^{-1}$ -2021

Source	DF	SS	MS	F	P
Replicates	2	113936	56968		
Treatment	5	514773	102955	6.80	0.0052
Error	10	151506	15151		
Total	17	780215			

** = Highly significant at $p < 0.05$, * = significant at $p \leq 0.05$, NS = Not significant $p > 0.05$

Appendix 7.3: ANOVA Table maize grain yield kg ha $^{-1}$ -2022

Source	DF	SS	MS	F	P
Replicates	2	719281	359641		
Treatments	5	1.685E+07	3370957	3.22	0.009
Error	8	8370230	1046279		
Total	15				

** = Highly significant at $p < 0.05$, * = significant at $p \leq 0.05$, NS = Not significant $p > 0.05$

Appendix 7.4: ANOVA Table for Pod yield kg ha $^{-1}$ -2022

Source	DF	SS	MS	F	P
Replicates	2	37627	18813		
Treatment	5	1315435	263087	32.72	0.0000
Error	10	80417	8042		
Total	17	1433479			

** = Highly significant at $p < 0.05$, * = significant at $p < 0.05$, NS = Not significant $p > 0.05$

Appendix 7.5: Cost of inputs and farm operations for maize and groundnut cropping systems

Activity/Input	Units/area	Unit cost GHC		Cost (ha^{-1})GHC	
		2021	2022	2021	2022
Land preparation					
Ploughing	Acre	80.00	120.00	200.00	600.00
Harrowing	Acre	40.00	50.00	100.00	250.00
Inputs					
Seed maize (OPV)	9kg/acre	5.00	7.00	125.00	158.00
Groundnut	14kg/acre	6.00	8.00	210.00	280.00
Chemical fertilizer:					
NPK-11-22-21/MN	50 kg bag (5)	280.00	320.00	1400.00	1600.00
Urea	50 kg bag	360.00	400.00	900.00	1000.00
Insecticide(FAW)					
Ema Star TM 112 E.C	Litre	60.00	75.00	150.00	188.00
Labour					
Manual weeding	acre	70.00	100.00	175.00	250.00
Fertilizer application	acre	35.00	45.00	87.50	112.50
	acre	35.00	45.00	87.50	112.50

Insecticide	acre	70.00	100.00	175.00	250.00
application(FAW)	acre	70.00	100.00	175.00	250.00
Maize harvesting	acre	100.00	120.00	250	300.00
Groundnut harvesting	acre	100.00	120.00	250.00	300.00
Shelling & drying Maize	acre	100.00	120.00	250.00	300.00
Processing of groundnut					