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Yield Responses of Maize to Fertilizers in Ghana

IFDC FERARI Research Report No. 2

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ABBREVIATIONS

AEZ	Agroecological Zones
AGRA	Alliance for a Green Revolution in Africa
AS	Ammonium Sulfate
Av. P	Available Phosphorus
CEC	Cation Exchange Capacity
CS	Coastal Savannah
CSIR	Council for Scientific and Industrial Research
DAP	Diammonium Phosphate
FAO	Food and Agriculture Organization of the United Nations
FERARI	Fertilizer Research and Responsible Implementation
GDP	Gross Domestic Product
GOG	Government of Ghana
GS	Guinea Savannah
ha	hectare
IFDC	International Fertilizer Development Center
kg	kilogram
MOFA	Ministry of Food and Agriculture
MOP	Muriate of Potash
OC	Organic Carbon
OLS	Ordinary Least Squares
PBA	Palm Bunch Ash
ppm	parts per million
SARI	Savanna Agricultural Research Institute
SDF	Semi-Deciduous Forest
SRI	Soil Research Institute
SRID	Statistics, Research, and Information Directorate
SS	Sudan Savannah
SSA	Sub-Saharan Africa
t	ton
TAR	Total Annual Rainfall
TN	Total Nitrogen
TS	Transition Savannah

ABSTRACT

Low soil productivity is one of the key challenges limiting maize yields in Ghana. A wide yield gap exists between farm and potential yields across most of the agroecological zones (AEZs) of Ghana. Despite low soil fertility challenges, the low use of fertilizers still predominates the smallholder farming system. To improve crop performance, there is a need for integrated soil fertility management across the AEZs. This calls for site-specific fertilizer recommendations that provide all nutrients in balanced proportions as per the nutrient status of the soil. However, current fertilizer recommendations were developed decades ago and mainly focused on macronutrients (NPK). These recommendations in the current context of soil fertility are considered blanket recommendations and do not take care of site-specific crop nutrient requirements. Secondary data of experimental trials of almost 1,700 data points were used to explore maize yield responses to different fertilizer treatments across various AEZs of Ghana. Maize yield responses to fertilizers were estimated, factors explaining yields were explored, and spatial yield maps were generated. Low to very high (2-10 t ha^{-1}) yield responses were observed across the AEZs. Between 60 and 130 kg N ha^{-1} applied in combination with 45-90 kg P_2O_5 and 45-90 kg K_2O ha^{-1} gave the highest yield responses. Yield responses were even higher where sulfur was applied in combination with NPK. The dataset used did not contain many experiments with micronutrients and therefore could not allow comparisons of yield responses on this aspect. There were observed relationships of soil properties with yield under control (i.e., zero fertilizer application) treatments, though the yields of control plots against percentage of soil organic carbon (% OC), percentage of soil total nitrogen (% TN), available phosphorus (Av. P), and pH varied from low to high, irrespective of their values. This implies that soil property data give us an index of nutrient levels but it is difficult to only rely on these to arrive at fertilizer recommendations. Other factors, such as maize variety potentials in nutrient utilization, rainfall pattern, and disease occurrence should be considered as well. Apart from the impact of individual soil properties on yield, interactions between soil nutrient content and/or other soil properties could also impact crop yields.

Keywords: Maize yield response, fertilizer recommendations, soil properties, spatial variability in yield response

CHAPTER 1: INTRODUCTION

1.1 Background

The key challenge to agriculture in Africa is to overcome low crop productivity emanating from low soil fertility due to nutrient mining and low input use (Hengl et al., 2017; IFDC, 2012). Current cropping yields in sub-Saharan Africa (SSA) are low, often falling well short of water-limited yield potentials (Jayne et al., 2010). This underperformance is due to several factors, including soil nutrient deficiencies, soil physical constraints, pests and diseases, and sub-optimal management (Hengl et al., 2017; Ebanyat et al., 2010). Although there is no data to apportion the contribution of each factor, evidence from long-term trials points that continuous tillage of land without fertilizer application coupled with export of crop residue results in soil fertility degradation and subsequent yield decline. Therefore, trends in crop yields are likely related to soil fertility decline and low crop yields are likely an indicator of poor soil fertility (Bekunda et al., 2002). Bekunda et al. (2002) concluded that soil fertility depletion in smallholder farms is the fundamental biophysical root cause for declining per capita food production in SSA.

According to Buresh et al. (1997), an average of 660 kg N ha^{-1}, 75 kg P ha^{-1}, and 450 kg K ha^{-1} has been lost during the last 30 years from about 200 million ha of cultivated land in 37 African countries. Henao and Baanante (2006) indicated that, during the 2002–2004 cropping season, about 85% of African farmland (185 million ha) had nutrient mining rates of more than 30 kg ha^{-1} of nutrients yearly, and 40% had rates greater than 60 kg ha^{-1} yearly. Rhodes (1995) investigated nutrient depletion by annual crops in Ghana for over 10 years. He found that a total of 428,700 t of nitrogen (N), 73,100 t of phosphorus (P), and 414,900 t of potassium (K) were depleted. Of this, 44% of N, 42% of P, and 56% of K taken up were present in crop residues. According to Stoorvogel and Smaling (1990), Ghana had negative balances of N 35 kg ha^{-1}, P_2O_5 9 kg ha^{-1}, and K_2O 24 kg ha^{-1} in the year 2000.

This rapid rate of nutrient removal calls for integrated soil fertility management with the application of fertilizers as an integral component to improve crop productivity (IFDC, 2012). However, fertilizer use is very low in Ghana at 22.6 kg ha^{-1}; this is above the average fertilizer rate in SSA, but significantly lower than the 50 kg ha^{-1} target by 2015 of the *Abuja Declaration* 2006. It was estimated that only 10% of smallholders with less than 1.0 ha use fertilizer, compared to over 20% of those with more than 5.0 ha (MOFA, 2010). Agricultural economies with low levels of inorganic fertilizer use are characterized by low crop yields, low rural incomes, and high poverty rates (Jayne et al., 2016).

Low use of fertilizer by smallholder farmers is attributed to many factors: high cost and low profitability, the risks of fertilizer use, low use efficiency, and the non-availability of fertilizer (Kelly and Crawford, 2007; Okoboi and Barungi, 2012; Bayite-Kasule, 2009). According to Jayne et al. (2016), causes of low fertilizer use in Africa are often considered to be related to: (i) households' insufficient access to credit to purchase fertilizer in quantities even close to official recommendations, (ii) rural households' lack of information about the benefits of using fertilizer; (iii) risks of using fertilizer even if fertilizer use is expected to raise net household income on average, the risk of loss due to variable rainfall with variable, and even negative yield responses; (iv) weak development of commercial input markets; and (v) price volatility in output markets, which deters farmers from purchasing inputs to produce a marketable surplus. Gondwe and Nkonde (2017) and Jayne et al. (2016) noted that the high cost of fertilizer, fragile output market prices, and lack of a fertilizer recommendation that provides good profitability are some of the factors limiting fertilizer use by farmers in Ghana.

1.2 Statement of the Problem

Current fertilizer recommendations were developed more than three decades ago and have had no serious review/update. Farmers use blanket fertilizer recommendation rates of 60-40-40 kg ha^{-1} N-P_2O_5-K_2O (Tetteh et al., 2018). Many crop varieties have evolved with different nutrient uptake capabilities; there has also been unprecedented soil fertility decline, along with sporadic weather changes (Gondwe and Nkonde, 2017b). Variability in crops, soils, and climatic conditions make the response of crops to fertilizers applied site and situation specific (Kihara et al., 2016). Early fertilizer recommendation also focused majorly on the macronutrient elements (NPK) with little or no attention to secondary (calium [Ca], sulfur [S], magnesium [Mg]) and micronutrients (iron [Fe], zinc [Zn], boron [B], manganese [Mn], molybdenum [Mo], nickel [Ni], chlorine [Cl], and copper [Cu]) (Kihara et al., 2017). Though only needed in small quantities, micronutrients play a very important role in plant physiology, biotic and abiotic stress management, and human health. They are important in enhancing crop yield, increasing the nutrient content of crops, suppressing crop diseases and abiotic stressors, and stimulating biomass production (Dimkpa and Bindraban, 2016). In humans, micronutrients dictate physical and mental development and how humans respond to diseases. Deficiencies of micronutrients lead to a loss in a child's cognitive skills, stunting and, in the worst case, death (Bindraban et al., 2018; Dimkpa and Bindraban, 2016). In plant physiology, Fe, Cu, Mn, and Cl take part in different aspects of plant photosynthesis, as cofactors for different metabolic processes. Fe, Mn, Zn, Cu, Ni, Mo, and Cl all participate in the functioning of different enzymes, including DNA/RNA polymerases, N-metabolizing enzymes, superoxide dismutases, catalases, dehydrogenases, oxidases, and ATPases, among other enzymes (Dimkpa and Bindraban, 2016). The functioning of micronutrients as cofactors is crucial for enzyme and non-enzyme activities in plant metabolism under different environmental conditions. Zn, for instance, plays a role in the enzymatic processes involved in the biosynthesis of plant growth regulator, auxin; Ni is involved in urease enzyme in N metabolism of plants by converting urea to ammonia; and Mo is required for N fixation by both symbiotic and free-living N-fixing bacteria. In plant's defense against diseases, micronutrients cofactors activate enzymes that generate metabolites that suppress the progression of the disease; for example, Mn, Cu, and Zn enhance disease resistance by activating the host defense enzymes (Bindraban et al., 2018), they also play important role in the control of Striga weeds in cereal crops through enhancement of bioavailability of N and P Bindraban et al., 2018). Dimkpa et al. (2017) in their evaluation of drought stress mitigation in soybeans using composite formulations of three micronutrient nanoparticles, zinc oxide (ZnO), boron oxide (B_2O_3), and copper oxide (CuO), and their salts, zinc sulfate ($ZnSO_4 \cdot 7H_2O$), boric acid (H_3BO_3), and copper sulfate ($CuSO_4$), found out that micronutrients such as Zn, Cu, or B as well as non-essential elements positively influence crop responses to drought stress. This is through affecting root growth, the production of reactive oxygen species, and cell wall strengthening. Dimkpa et al. (2019) also indicated that the use of ZnO nanoparticles as a soil fertilizer amendment at judicious doses can increase the resilience of cropping systems to climate change events and increase the use efficiency of N while promoting both the yield and Zn nutrition of crops under otherwise adverse production conditions. Bindraban et al. (2018) also showed that silicon, a non-essential nutrient element, is involved in drought tolerance in grain crops. It reduces leaf and water flow rate in the xylem vessels, facilitates water uptake and transport under drought conditions, and regulates the activities of antioxidant enzymes under drought stress. This, therefore, points to the growing evidence of the importance of micronutrients and the need to have balanced mineral fertilizers to:

- Increase crop yield.
- Increase the nutritional value of plant products that can improve human nutrition and health.
- Have healthier plants that can reduce the need for pesticides and herbicides.
- Improve plant robustness, which enhances tolerance to drought.
- Increase production of metabolites, which improves taste and shelf life (Bindraban et al., 2018).

Stagnating yield levels due to nutrient deficiencies and imbalances require greater effort in increasing nutrient use efficiency and, consequently, yield. To achieve that, conditions under which different responses occur must be understood and fertilizer formulations that include all the limiting plant nutrients elements must be designed and included in fertilization strategies (Bindraban et al., 2015; Kihara et al., 2017). This will facilitate the application of balanced amounts of the most limiting nutrients to obtain optimum yield while minimizing nutrient losses. Fertilizer application, therefore, has to be according to the local soil chemical conditions and specific crop nutrient requirements and under different managements (Rietra et al., 2017). With general fertilizer recommendation rates, it is difficult to ascertain whether the right quantity is being applied in a given soil for given crops under different climatic conditions. This, therefore, calls for improvements with a focus on solid science-based evidence of yield responses.

The sound development of fertilizer recommendations can be a tedious and time-demanding process; fertilizer crop yield responses under different soils and climatic conditions could be used to develop fertilizer recommendations. Experiments have been performed on yield responses of maize, rice, and soybean to the application of different fertilizers over a wide region in Ghana. (Tahiru et al., 2015), fertilizer and genotype effects on maize production (Tetteh et al., 2018), fertilizer recommendation for maize and cassava within the breadbasket zone of Ghana (Atakora et al., 2014), the response of maize growth and development to mineral fertilizers and soil characteristics, (Atakora et al., 2015), low P tolerance of rice varieties in Northern Ghana (Buah et al., 2010), and quality protein maize response to N rates. Available data must be analyzed thoroughly to understand how significant the yield responses are in the respective regions of Ghana. On this basis, it is imperative to assess yield responses to different fertilizers in different agroecological conditions. This will facilitate the generation of region-specific fertilizer rates that give the most profitable response.

1.3 Objectives of the Study

- Estimate fertilizer yield responses of maize in the rainfed production system of Ghana based on fertilizer application trials.
- Recommend site-specific fertilizer recommendations for desired crop yield responses based on the findings.
- Present the data through spatial mapping techniques.

1.4 Research Questions

- How significant is the yield response to the application of different fertilizers in Ghana?
- What are the factors that explain yield responses of maize in Ghanaian AEZs?

1.5 Justification of the Study

Spatial and temporal variability in soil fertility poses a big challenge in coming up with fertilizer recommendations that give the desired crop response. Most governments, development partners, and researchers rely on blanket fertilizer recommendations. Detailed information about factors resulting in positively high, average, and low yield responses is needed to come up with appropriate fertilizer recommendations. This study contributes new knowledge toward the generation of site-specific fertilizer recommendations for sustainable crop production.

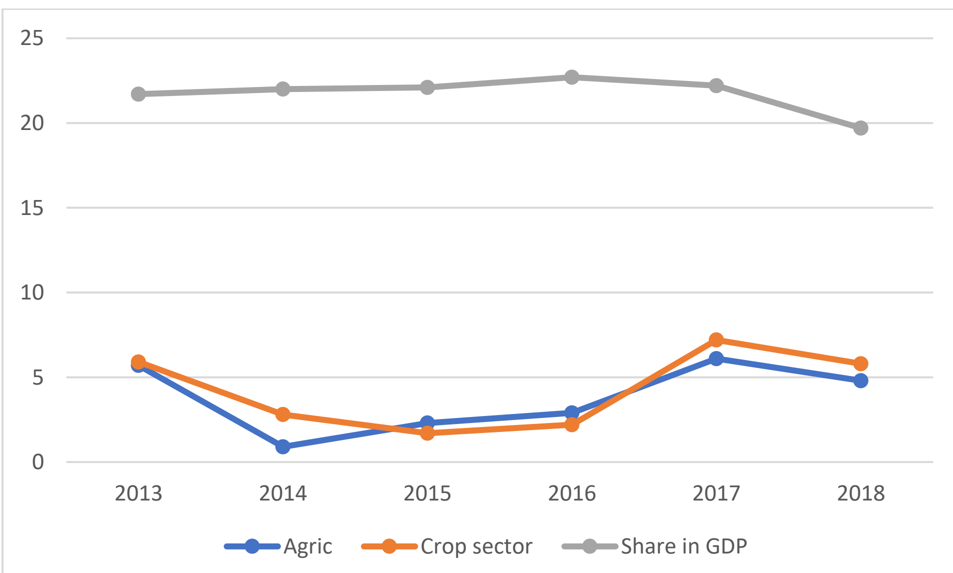
CHAPTER 2: A LITERATURE REVIEW

2.1 Agriculture in Ghana

Land suitable for agricultural production represents 60% of the 24 million ha of total land of Ghana. The country's population as of the 2010 census was 25 million with a population growth rate of 2.5% (MOFA, 2018). The population estimate of 2018 puts it at *29,614,337* with a growth rate of 2.3% (MOFA SRID, 2019).

About 45.4% of the households in Ghana are agricultural households, 73.3% are rural households, and 26.7% are urban. Approximately 90% of the farms are for smallholder farmers with farm size less than 2 ha. Large farms and plantations exist for rubber, oil palm, coconut and, to a lesser extent, rice, maize, and pineapples. Farming is traditional, and rudimentary tools such as hand hoes and cutlasses are used (MOFA, 2013; MOFA, 2019)

Between 2013 and 2018, agriculture's contribution to Ghana's gross domestic product (GDP) did not exceed 23%. The lowest value of 19.7% was recorded in 2018. Agriculture sector growth rates for the years 2013-2018 have been intermittent. The growth rate varied between 0.9% to 5.7%, with an average of 3.8% although it was projected to be 6.0% (World Bank, 2017) (Fig. 1).

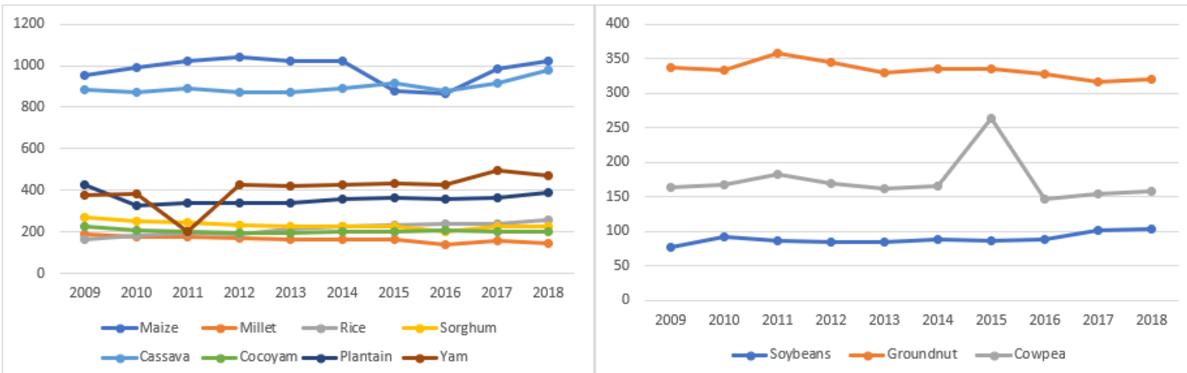


Source: MOFA (2018).

Figure 1. Agriculture and crop sector growth rate and share in GDP, 2013-2018

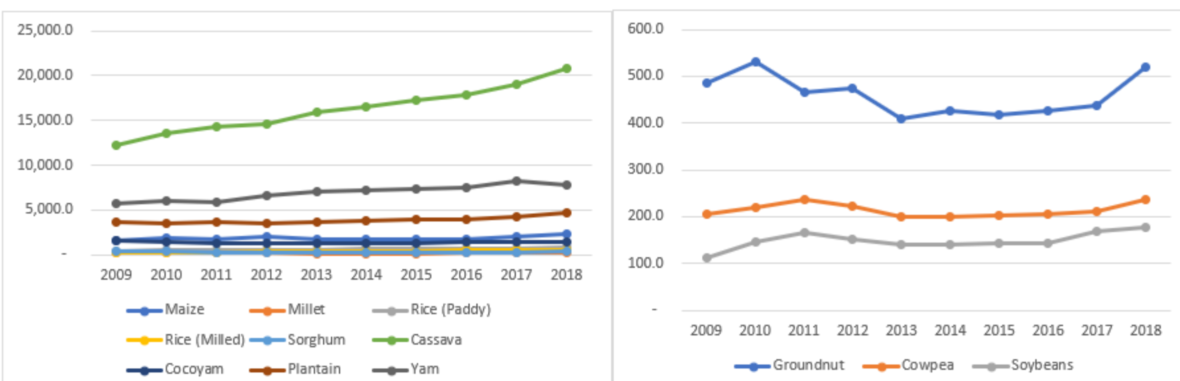
The country earned 1,901,000 Ghana cedi in foreign exchange earnings from non-traditional agricultural export commodities in 2016. Agriculture's contribution to total employment is estimated at 38.3%, making it the second-largest employer after the service (43.5%) and industry (18.2%) sectors (MOFA SRID, 2019). Agriculture also continues to be a very important source of food for the country's increasing population and raw materials for agro-processing industries.

Crops grown are categorized into industrial crops (cocoa, oil palm, coconut, coffee, cotton, kola, rubber, cashew, and shea), starchy and cereal staples (cassava, cocoyam, yam, maize, rice, millet, and sorghum), and plantain, fruits, and vegetables (pineapple, citrus, banana, pawpaw, mango, tomato, pepper, okra, eggplant, onion, and Asian vegetables). Cassava, maize, and cocoa cover the largest cultivated area (MOFA, 2013). However, major staple crops cultivated include maize, cassava, rice, yam, plantain, millet, cowpea, groundnut, soybean, sorghum, and cocoyam. Maize, cassava, and groundnut are cultivated on larger acreages in the categories of cereals, roots, and legumes, respectively. Figs. 2 and 3 show acreage and production of major crops.



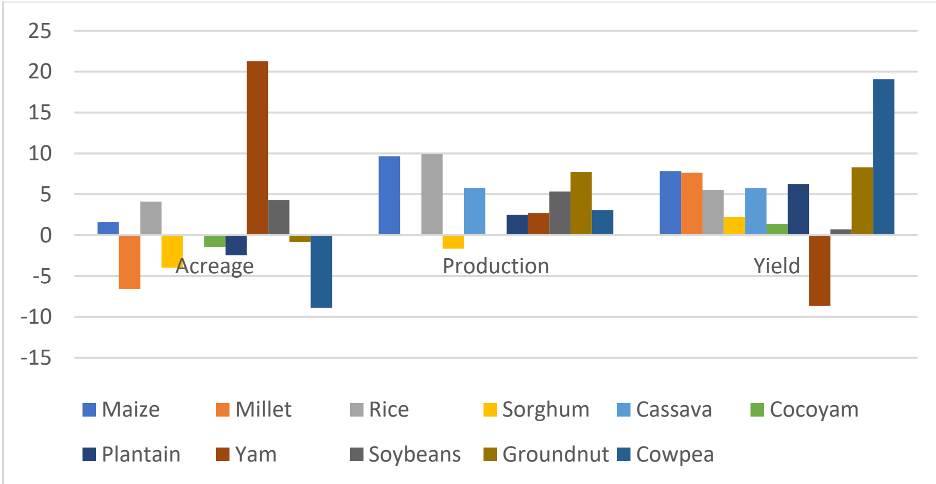
Source: MOFA (2019).

Figure 2. Annual area planted ('000 ha) to major food crops, 2009-2018



Source: MOFA (2019).

Figure 3. Annual production of major food crops ('000 mt), 2009-2018



Source: MOFA (2019).

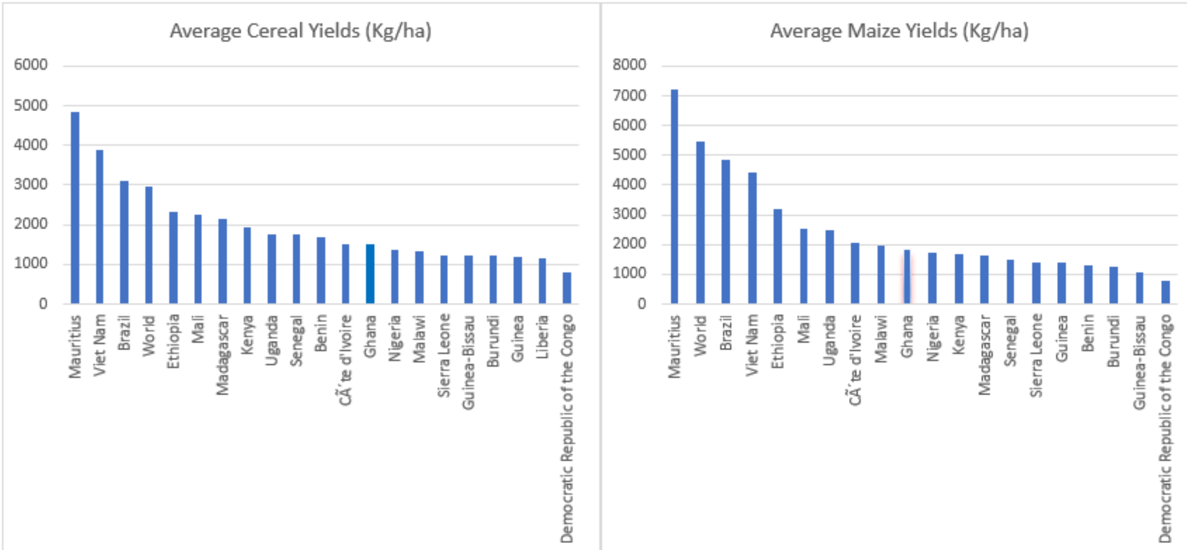
Figure 4. ***Ten-year average percentage change in acreage, production, and yield of major cultivated crops, 2009-2018***

Data over the last decade (2009-2018) indicate an overall percentage increase in output of the major crops cultivated (Fig. 4). Cowpea, groundnuts, plantain, sorghum, cocoyam, yam, and millet registered negative increases in cultivated acreage. Except for yam, other crops had positive yield increases. Ten-year average percentage output growth rates of 6.19%, 2.72%, and 5.27% were achieved for cereals, roots, and legumes, respectively. On the other hand, 5.82%, 1.175%, and 9.36% averages of 10-year yield growth were achieved for cereals, roots, and legume crops, respectively. Except for legumes, the yield growth rate has lagged behind output growth for cereal and root crops. Average on-farm crop yields are low and fall way below yield potentials under good management.

Poor rainfall distribution and the amount received, low soil fertility, and low input use are constraints that affect performance in the crop sector. Irrigation only covers 2.6% of cultivated land, implying crop cultivation is mainly rainfed and prone to weather vagaries (World Bank, 2017). Consequently, agricultural productivity is low across most parts of the country (MOFA, 2013).

As a result of the low productivity, Ghana continues to be a net importer of cereal crops, such as rice, wheat, and maize as well as poultry, sugar, and vegetable oils. The country imported 715,027, 830,127, and 81,708 t of wheat, rice, and maize, respectively, in 2018, valued at a total of U.S. $684 million (MOFA, 2019). Overall, Ghana depends on the import of wheat, rice, and maize by 115%, 61%, and 3%, respectively.

Crop yields in Ghana fall way below their potential (Table 1). Yield gaps of staple crops range between 43% and 66%. Though this low yield is not particular to Ghana only, cereal yields in Ghana fall among sister countries in SSA as the lowest. Cereal yields are 1.5 t ha^{-1}, below the average of 2.0 t ha^{-1} for Madagascar, Mali, and Ethiopia and much below the potential of 5.0 t ha^{-1} (Fig. 5).



Source: FAOSTAT.

Figure 5. ***Average cereal yield (kg ha^{-1}) in selected sub-Saharan African countries, compared to Viet Nam, Brazil, and the world, 2009-2018***

Table 1. ***Average yields of selected crops and potential yield gaps***

Crop	Average On-Farm Yield, 2018 (t ha^{-1})	Potential Yield (t ha^{-1})	% Achieved
Cassava	21.3	45.0	47.4
Plantain	12.1	38.0	31.9
Yam	16.6	52.0	31.9
Cocoyam	7.2	20.0	36.0
Maize	2.3	5.5	41.1
Rice (paddy)	3.0	6.0	49.3
Cowpea	1.5	2.5	60.4
Soybean	1.7	3.0	57.3
Groundnut	1.6	3.5	46.6
Millet	1.3	2.0	64.0
Sorghum	1.4	2.0	69.5

Source: *MOFA (2019).*

2.2 Constraints to Maize Production in Ghana

Maize is the most widely grown cereal crop in SSA and covers an estimated 25 million ha, largely on smallholder farms. It accounts for about 20% of the caloric intake of 50% of the population in SSA (Badu-Apraku and Fakorede, 2017). In Ghana, maize is cultivated on about 1.2 million ha (Fig. 2); per capita, annual consumption stands at 62 kg (MOFA, 2019).

Despite this immense importance of maize in Ghana and SSA at large, its production is constrained by many factors that are subdivided into biotic and abiotic constraints (Badu-Apraku and Fakorede, 2017). Among the biotic constraints are pests; chief among them are the locust and fall armyworm (*Spodoptera frugiperda*) pandemic, which have and continue to destroy millions of hectares of maize across Eastern and Southern Africa. Another insect pest of importance is the stem borer and ear rot insects. Weeds, especially Striga (*Striga hermonthica*), cause loss of great economic importance to maize (Adu et al., 2014). Yield losses due to Striga could be as high as 100%, depending on many factors. Kim et al. (2002) reported yield loss of up to 79% of open-pollinated maize varieties across West and Central Africa.

The most important abiotic constraints in SSA are low soil fertility and drought. Particular soils of the savanna, where maize potential is greatest, are low in fertility and soil organic matter (Kugbe et al., 2019). Anthropogenic activities further aggravate these low fertility problems through continuous expansion of land for agriculture, human settlement, and other economic activities. Man has exposed the land to denudation agents, such as wind and water, resulting in increased soil erosion, reduced soil water retention, and increase in the emergence of persistent weeds (Bationo et al., 2018). These different stresses inflict severe damage and contribute to yield losses to maize.

To make matters worse, most soils in Ghana and across SSA are old and have been leached over a long period of time (Bationo et al., 2018); those in humid (high rain forest and semi-deciduous forest [SDF]) zones are an example. The soils are, therefore, characterized by low organic matter content, low water pH, and low nutrient buffer capacities, implying that most soils are physically, chemically, and biologically degraded.

Table 2. Selected soil chemical properties in AEZs of Ghana

		Organic C	**Total N**	**Available P**	**Available K**
AEZ	**pH**			**(%)**	
Semi-Deciduous Forest	5.5-6.2	1.59-4.80	0.15-0.42	0.36-5.22	62.01-84.82
Guinea Savannah	6.2-6.6	0.51-0.99	0.05-0.12	0.18- 3.60	46.23-55.27
Sudan Savannah	6.4-6.7	0.48-0.98	0.06-0.14	0.06-1.80	36.96-44.51
Coastal Savanna	5.6-6.4	0.61-1.24	0.05-1.16	0.18-3.60	48.02-58.71
Forest Transition	5.1-6.4	0.59-0.99	0.04-0.16	0.30-4.68	58.29-72.53

Source: *Bationo et al. (2018).*

Across the AEZs, % organic carbon (OC), total soil N (%), and available P (Av. P) soil properties are described as very low or low to moderate; consequently, soils are low in inherent fertility (Bationo et al., 2028). N and P are severely deficient nutrients in most soils in Ghana because of the very low organic matter content of the soils (Table 2). Kugbe et al. (2019a) indicated that soils of the major maize-growing areas are low in organic carbon (OC, <1.5%), total nitrogen (TN, <0.2%), exchangeable K (<100 mg kg^{-1}), and Av. P (<10mg kg^{-1}).

Continuous crop cultivation has also compounded the problem of soil fertility. In addition to that, traditional practices of bush burning and burning of crop residues have led to loss of organic matter from the soil (Bationo et al., 2018). The loss of soil organic matter, the reserve for soil N, P, and S, means extreme hunger to the maize crop. Besides that, the performance of mineral fertilizers added to the soil is enhanced with the presence of organic matter in the soil. Kihara et al. (2016b) investigated the response of crops to fertilizer and amendments and concluded that increasing soil carbon can improve response to fertilizers. There is, therefore, increased nutrient mining with little or no investment in the rejuvenation of lost nutrients. The need to sustainably increase soil productivity to improve maize yields is warranted across all AEZs of Ghana; this can be achieved through the application of external inputs of nutrients into the nutrient-poor soils. Sources of these external nutrient inputs can be organic and inorganic fertilizers or a combination of both of them.

2.3 Fertilizer Use and Yield Responses

Although the importance of inorganic fertilizer is clearly emphasized in national development plans, its adoption is still low in Ghana (Bationo et al., 2018). Average fertilizer use as of 2019 is about 20.9 kg ha^{-1},[1] which is slightly above the SSA average of about 10 kg ha^{-1} but below the 50 kg ha^{-1} by 2015 set by the 2006 *Abuja Declaration* and much lower than the global average of about 118 kg ha^{-1} (Hill and Kirwan, 2015).

Information on fertilizer use by crop is scarce for Ghana, but fertilizer use and application rates seem to be highest for crops such as cocoa, palm oil, and vegetables, which are mainly cash crops. Application rates for maize are in the intermediate range.

Only 31% of households in Ghana use fertilizers, but this figure varies across regions (Bationo et al., 2018). Approximately 10% of smallholder farmers with less than 1.0 ha use fertilizer, compared to over 20% of those with more than 5.0 ha. Fig. 6 compares apparent fertilizer consumption in Ghana with some selected countries for the years 2010-2018.

[1] https://data.worldbank.org/indicator/AG.CON.FERT.PT.ZS

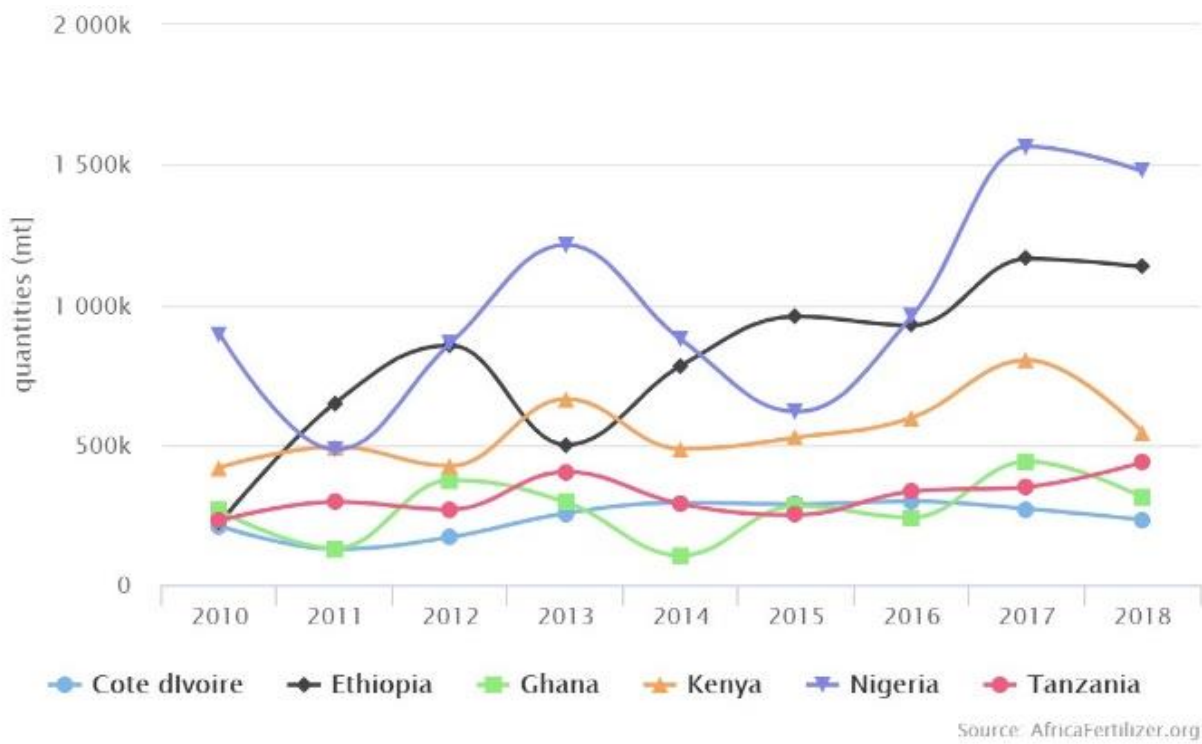


Figure 6. Apparent consumption of fertilizer products in selected countries, 2010-2018

2.4 Fertilizer Yield Responses

According to Ichami et al. (2019), fertilizer response is the incremental crop yield due to fertilization, independent of the quantity or the type of fertilizers applied. They stressed that fertilizer response is a useful concept for identifying responsive and non-responsive soils. Kihara et al. (2016a) divided non-responsive soils into two categories: (i) soils in which low crop yields are observed and where crops respond poorly to fertilizers unless other amendments are applied (e.g., organic matter application, lime), and (ii) soils with a high level of fertility in which crops do not respond to a nutrient application or soil amendments. They then arrived at three crop response categories that distinguish soils as responsive and non-responsive to fertilizer application (i.e., responsive, fertile non-responsive, and degraded non-responsive)

Although factors causing non-responsiveness of the soils are not yet clearly understood, these could include macro- and micronutrient depletion, poor germination due to slaking or topsoil erosion, aluminum toxicity concerning soil acidification, and increased sensitivity to drought conditions (Ichami et al., 2019). Kihara et al. (2016a) found that non-responsive soils had the lowest Zn, B, Cu, Mn, and sodium (Na). Many scholars (Zingore et al., 2007; Fermont et al., 2010; Njoroge et al., 2017; Tittonell, 2007) have demonstrated that marked soil fertility variation exists within and between farms, both as a consequence of inherent factors and differential management. Overall, there is a need for fertilizer recommendations that address the requirement for balanced fertilizer application, including micronutrients, under highly variable soil fertility conditions,

2.5 Fertilizer Recommendation in Ghana

Rigorous work to generate fertilizer recommendations for Ghana was implemented from 1948 until 1970, when the government recommendation rate of 80-40-0 lb $acre^{-1}$ was arrived at for maize (FAO, 2004). Gondwe and Nkonde (2017b), Tetteh et al. (2018), and other scholars have made great efforts in improving the previously developed fertilizer recommendations, and this has resulted in the current N-P_2O_5-K_2O rate of 90-60-60 + 1.7Zn kg ha^{-1} for the Forest Savannah Transition zone and 100-40-40 kg ha^{-1} for the Guinea Savannah zone for maize. The current fertilizer recommendations are intended to increase maize yield from an average of 1.8 t ha^{-1} to 5 t ha^{-1}(IFDC, 2019). However, given the great variability in soils, the underlying factors of yield responses of these rates must be examined to further guide improvement in future recommendations. Otherwise, those recommendation rates can still be considered blanket fertilizer recommendations with limited relevance for heterogeneous smallholder farms. As indicated by Zingore et al. (2007), targeted application of mineral fertilizers and manure according to soil type and past management of fields is imperative for improving crop yields and nutrient use efficiencies.

CHAPTER 3: METHODOLOGY

3.1 Study Area

Research institutions in Ghana have been conducting experiments continuously over the past decades. As much of this legacy data as possible was gathered for this study. Experiments were implemented in five AEZs of Ghana: Guinea Savannah (GS), Semi-Deciduous Forest (SDF), Sudan Savannah (SS), Coastal Savannah (CS), and Transition Savannah (TS). The regions include Ashanti, Eastern, Savannah, Northern, Upper West, Upper East, and North East. Most of the experiments were conducted in the Northern, Ashanti, and Upper West regions (Fig. 7).

Analysis and findings in this report are based on experiments in the two regions highlighted in Fig. 7, mainly Northern and Upper West (GS) and Ashanti and Eastern regions (SDF).

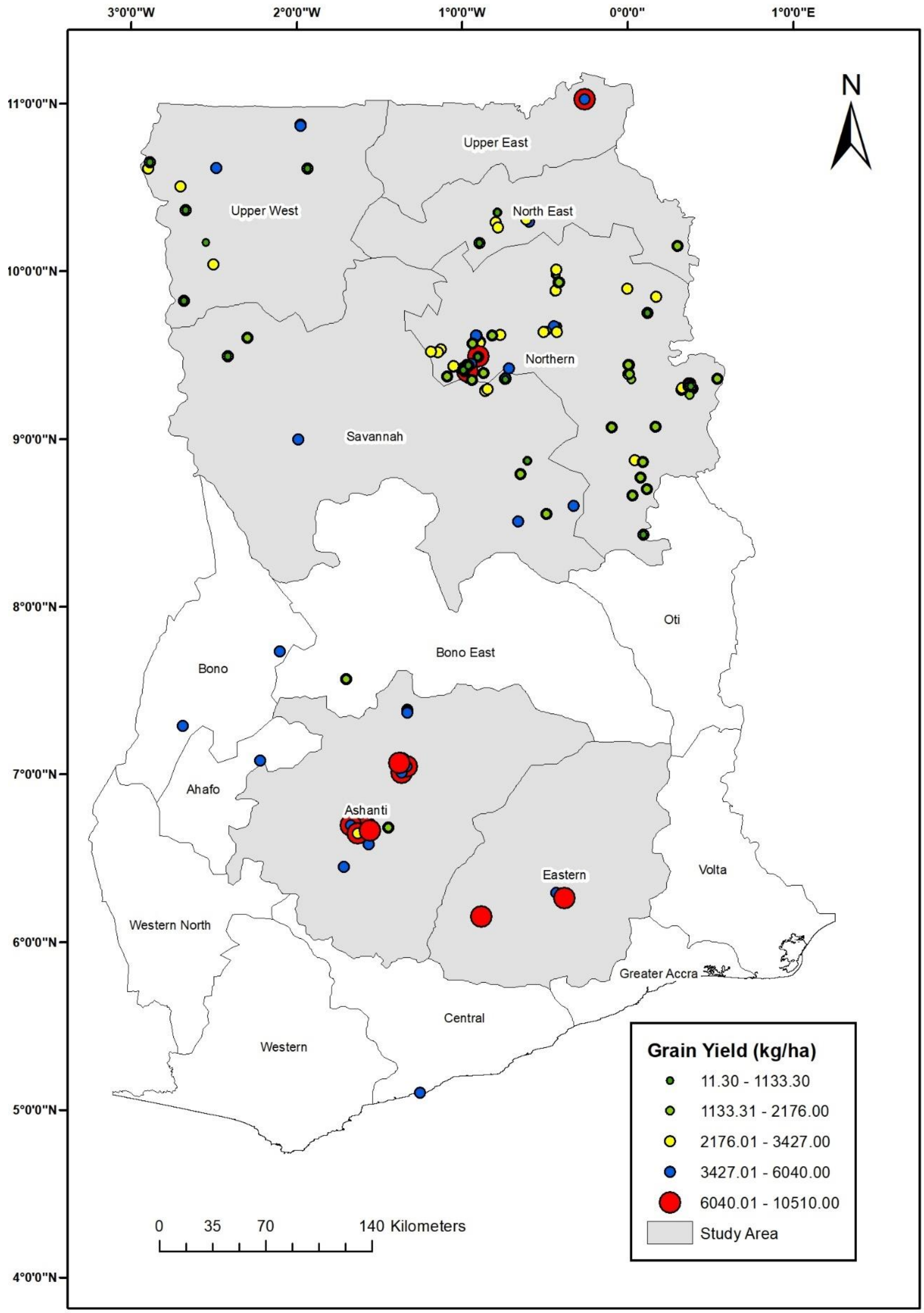


Figure 7. Locations of fertilization yield response trials and the range of yield levels attained in different experiments

3.2 Data Collection

Secondary data from peered-reviewed publications were used in this research. Scientific databases used to retrieve these papers include Google Scholar, African Journals Online, Web of Science, Scopus, and Food and Agriculture Organization of the United Nations (FAO). Key search terms used were maize N grain yield responses, maize N x P grain yield responses, NPK grain yield responses, fertilizer grain yield responses in Ghana, response of maize to fertilizer applications in Ghana, fertilizer yield responses in Ghana, and fertilizer trials in Ghana. These resulted in thousands of search outputs, but specific interest was in experiments with nutrient elements applied as straight or compound as inorganic fertilizers, inorganic fertilizers in combination with organic fertilizers, and organic fertilizers alone. Therefore, a research topic was selected based on the following criteria: (1) the experiment would be implemented in Ghana, (2) the study would be on yield responses of maize to fertilizer application, (3) the study would have at least one of the essential nutrient elements being tested, (4) the experiment would have organic amendments applied either alone or in combination with inorganic fertilizer, and (5) results would be presented clearly in tabular or bar graph format. Using the above criteria, 32 scientific maize publications, with a total of 828 data points, were screened for use in the study (**Annex 1**). About 944 data points came from legacy data from on-farm, and on-station experiments implemented in the greater northern region (Upper West, Upper East, and Northern) (Fig. 7). In total, 1,770 data points were screened to give 1,684 data points used in the study.

3.3 Type of Data

Information collected included the geographical location where the experiment was conducted (coordinates, district, region, and AEZ), year and seasons of experiment, mean grain and biomass yields, soil properties, amount of fertilizers (inorganic and organic) applied, and amount of rainfall (total annual rainfall [TAR]) received in the year of the experiment. Not all of the information on soil, rainfall, season, and biomass yield was available for each experiment.

3.3.1 Soil Data

Soil properties within a depth of 0.2 m of interest were pH, cation exchange capacity (CEC, Cmol kg^{-1} soil), % OC, % TN, Av. P (mg kg^{-1}), exchangeable K (Cmol kg^{-1}), Ca, Mg, S, microelements (Mn, Zn, Fe, Mo, Cu, and B in Cmol kg^{-1} soil) and % sand, % clay, and % silt. However, hardly any experiment analyzed secondary elements (Mg, Ca, and S) or microelements (Mn, Zn, Fe, Mo, and Cu). Missing soil information in some experiments were filled using data obtained from a soil map from Soil Research Institute (SRI), Kwadaso (CSIR, 2020). Geographical coordinates of the experimental site were used to obtain soil information for experiments that had missing soil properties. Percentage of soil organic matter (OM) was converted to % OC by multiplying by 0.58; Av. P units that were reported in parts per million (ppm) were converted to mg kg^{-1}; TN reported in g kg^{-1} soil was converted to % TN. In this research, soil properties used were pH, % OC, % TN, Av. P (mg kg^{-1}), CEC, % sand, % clay, and % silt (Table 3). For the explanation of TAR data, see Section 3.3.3.

Table 3. Summary of soil and climatic data collected from the 32 experiments with 1,684 data points

	TAR (mm)	pH	% OC	CEC (Cmol kg^{-1} soil)	Total N (%)	Av. P (mg kg^{-1})	Sand (%)	Clay (%)	Silt (%)
Mean	1,085.46	5.85	1.25	7.75	0.09	9.57	66.18	13.03	23.55
Min	287.00	4.30	0.10	1.57	0.00	0.02	40.00	0.36	1.65
Max	1,897.70	6.69	4.01	82.87	0.70	44.29	95.75	28.28	52.00
STDEV	221.99	0.44	0.81	10.74	0.08	7.18	7.65	5.31	9.22

3.3.2 Amount of Nutrients Applied

Various types of inorganic and organic fertilizers were used, including NPK 15-15-15; urea; ammonium sulfate (AS); nitrogen, phosphorus, and sulfur (NPS); diammonium phosphate (DAP); NPK 20-10-10; NPK 23-10-5; NPK 20-20-20; muriate of potash (MOP); and potassium sulfate. Organic fertilizer used include poultry manure, cow dung, household waste, market waste, fertisol, biochar, Palm Bunch Ash (PBA), and plant residues (*C. ordorata, C. juncea, and P maximum*) as green manure; chemical compositions are shown in Tables 4, 5, 6, and 7). The quantity of organic fertilizer used ranged from 1.5 t to 20 t ha^{-1}. For inorganic fertilizers, all the rates applied as kilograms of product per hectare were converted to kilograms of nutrient per hectare. All P and K values that were reported as kilogram P or K per hectare were converted to kilogram P_2O_5 or K_2O, respectively, per hectare.

Table 4. Chemical composition of the soil organic amendments used in the experiments

Organic Amendment	pH	% Organic Carbon	% N	P (mg/kg)	K (mg/kg)	Ca (mg/kg)	Mg (mg/kg)
Cow dung	9.25	37.83	1.92	3,610	18,750	17,085	24,502
Goat dropping	9.13	21.06	1.74	2,790	18,750	21,292	24,502
Sheep dropping	9.8	22.23	2.03	4,043	31,750	16,342	38,100
Poultry dropping	7.17	24.18	2.86	13,630	16,250	141,850	38,625
Compost	7.22	17.94	1.26	2,977	7,000	4,605	7,822
Town waste	9.82	2.34	0.32	1,552	9,250	42,650	21,035
Fertisol	8	14.04	1.97	12,795	18,000	83,475	35,575

Source: Kanton et al. (2016).

Table 5. Nutrient contents of the plant residues used as green manure

Plant Material	N	P	K	Ca	Mg	C	C/N	Lignin	Polyphenol
	(mg g^{-1})							(%)	
C. odorata	24.6	4.2	25.6	32.1	23.3	336.4	14.89	10.78	1.62
C. juncea	10.7	3.8	13.8	27.4	24.2	434.7	40.80	12.44	0.73
P. maximum	24.9	3.3	26.1	26.0	20.2	452.5	18.17	13.24	1.48

Source: Fening et al. (2009).

Table 6. Chemical properties of the Palm Bunch Ash used in the experiment

pH ($1:2.5\ H_2O$)	OC	Total N (%)	P Bray (ppm)	Exchangeable Cations K	Ca	Mg	Ng
				(me 100 g^{-1})			
10.90	0.55	0.08	270.27	583.42	35.24	29.24	20.51

Source: Adjei-Nsiah (2012).

Table 7. Chemical composition of biochar used in the experiment

Values are the means of four replicates. Values in parentheses are standard error of means.

Nutrient	N	P	K	Ca	Mg	C	C/N	CEC
	(g kg^{-1})							(cmol kg^{-1})
Value	7.3 (0.1)	0.05 (0.0)	3.6 (0.2)	4.6 (0.1)	0.4 (0.1)	890.7 (3.2)	122 (0.3)	10.9 (0.2)

Source: Badu et al. (2019).

3.3.3 Rainfall Data

Data for TAR received in the year of the experiment was reported in most of the studies. Missing rainfall data for specific years of the experimental trials were obtained from MOFA metrological reports (MOFA, 2019).

3.3.4 Grain Yield Data

Unit of grain yield was reported differently in different publications as (kilogram per hectare, tons per hectare, million grams per hectare). For easy data handling and uniformity, all units were converted to kilograms per hectare. Table 8 shows a summary of treatments with their respective average grain yields.

Table 8. Treatments with their respective average absolute grain yields

Treatment	No. of Observations	Average Yield (kg ha^{-1})
Control	426	1,165.4
Organic	79	2,751
N	137	3,188
P	18	1,273
NP	90	3,162
NK	20	2,548
PK	16	2,000
NPK	466	2,850
NPK + Org	41	2,916
NPKS	301	4,034
NPKS + Org	31	3,755
N + Org	59	2,300
	1,684	2,662

3.4 Data Analysis

3.4.1 Analysis of Variances (ANOVA)

Experiments covered four different AEZs, including Coastal Savannah, Guinea Savannah, Semi-Deciduous Forest, Sudan Savannah, and Transition Savannah, with 9, 1,106, 459, 133, and 63 treatment rows, respectively. Because of the few data points (only nine), Coastal Savannah was dropped.

There were 63, 27, 32, and 32 different rates of N, P, K, and S, respectively. The lowest and highest rates of N applied were 8 kg ha $^{-1}$ and 180 kg ha^{-1}; common rates were 30 kg ha^{-1}, 60 kg ha^{-1}, and 90 kg ha^{-1}. The lowest and highest rates of P_2O_5 applied were 8 kg ha^{-1} and 253 kg ha^{-1}; common rates were 20, 40, and 60 kg ha^{-1}. The lowest and highest rates of K_2O applied were 5 kg ha^{-1} and 116 kg ha^{-1}; common rates were 20, 40, and 60 kg ha^{-1}. The lowest and highest rates of S applied were 4 kg ha^{-1} and 154 kg ha^{-1}; common rates were 12 kg ha^{-1}, 24 kg ha^{-1}, and 30 kg ha^{-1}.

For analysis, the N-P_2O_5-K_2O rate was characterized as low, medium, or high. For N, rates below 60 kg ha^{-1}, 60-90 kg ha^{-1}, and above 90 kg ha^{-1} were characterized as low, medium, and high, respectively. For P and K, rates below 46 kg ha^{-1}, 46-89 kg ha^{-1}, and above 89 kg ha^{-1} were characterized as low, medium, and high, respectively. With this characterization, 24, 21, and 21 different treatment combinations were generated for N, P, and K, respectively (Table 9). However, treatment combinations did not occur in all the AEZs in equal numbers. SS and TS zones did not have many of the treatment combinations generated because of the limited number of trials. SS and TS were not considered for the subsequent ANOVA and regression analysis, except for correlation and spatial analysis. Even in the GS and SDF zones, common treatment combinations did not occur in equal numbers. To perform a treatment comparison in ANOVA, the number of common treatment combinations in the two zones were equalized. The number of occurrences of common treatment combinations was examined, and six was the minimum reasonable number of occurrences of treatment combination that could be used for further analysis. Therefore, for any common treatment combination to be selected, it had to have six occurrences; those with more than six occurrences had their numbers reduced to six by purposely selecting the best yields in that treatment combination (Tables 10, 11, and 12) for selection procedure of N, P, and K treatment combinations. Treatments not occurring in both zones (uncommon treatment combinations) were not considered.

Data for selected treatment combinations were analyzed using GenStat statistical software. Before analysis, data were subjected to the Shapiro-Wilk normality test and were found to be normal (Annex 2). Mean grain yields were generated using ANOVA, and multiple means comparisons test were done using Duncan's methods to determine the level of significant difference (P<0.05) among treatment means. Bar graphs were generated to help explain mean yield response differences.

Table 9. Treatment characterizations

**H = high level, M = medium level, L = low level, Org. = organic fertilizer*

S/N	Nitrogen Treatments		Phosphorus Treatments		Potassium Treatments	
1	A0	Control	P_H	High phosphorus	K_H	High potassium
2	0A	Organic fertilizer	P_M	Medium phosphorus	K_M	Medium potassium
3	N_H	High nitrogen	P_L	Low phosphorus	K_L	Low potassium
4	N_M	Medium nitrogen	P_HK	High phosphorus with potassium	NK_H	High potassium with nitrogen
5	N_L	Low nitrogen	P_MK	Medium phosphorus with potassium	NK_M	Medium potassium with nitrogen
6	N_HP	High nitrogen with phosphorus	P_LK	Low phosphorus with potassium	NK_L	Low potassium with nitrogen
7	N_MP	Medium nitrogen with phosphorus	P_HN	High phosphorus with nitrogen	PK_H	High potassium with phosphorus
8	N_LP	Low nitrogen with phosphorus	P_MN	Medium phosphorus with nitrogen	PK_M	Medium potassium with phosphorus
9	N_HK	High nitrogen with potassium	P_LN	Low phosphorus with nitrogen	PK_L	Low potassium with phosphorus
10	N_MK	Medium nitrogen with potassium	NP_HK	High phosphorus with nitrogen and potassium	NPK_H	High potassium with phosphorus and nitrogen
11	N_LK	Low nitrogen with potassium	NP_MK	Medium Phosphorus with nitrogen and potassium	NPK_M	Medium potassium with phosphorus nitrogen and
12	N_HPK	High nitrogen with phosphorus and potassium	NP_LK	Medium phosphorus with nitrogen and potassium	NPK_L	Low phosphorus with nitrogen and potassium
13	N_MPK	Medium nitrogen with phosphorus and potassium	NP_HK + Org.	High phosphorus with nitrogen, potassium, and Org.	NPK_H + Org.	High potassium with nitrogen, phosphorus, and Org.
14	N_LPK	Low nitrogen with phosphorus and potassium	NP_MK + Org.	Medium phosphorus with nitrogen, potassium, and Org.	NPK_M + Org	Medium potassium with nitrogen phosphorus, and Org.
15	N_HPK + Org.	High nitrogen with phosphorus, potassium, and Org.	NP_LK + Org.	Medium phosphorus with nitrogen, potassium, and Org.	NPK_L + Org	Low potassium with nitrogen, phosphorus, and Org.
16	N_MPK + Org.	Medium nitrogen with phosphorus, potassium, and Org.	NP_HKS	High phosphorus with nitrogen, potassium, and sulfur	NPK_HS	High potassium with phosphorus, nitrogen, and sulfur
17	N_LPK + Org.	Low nitrogen with phosphorus, potassium, and Org.	NP_MKS	Medium phosphorus with nitrogen, potassium, and sulfur	NPK_MS	Medium potassium with Phosphorus nitrogen, and sulfur
18	N_HPKS	High nitrogen with phosphorus, potassium, and Sulfur	NP_LKS	Low phosphorus with nitrogen, potassium, and sulfur	NPK_LS	Low potassium with phosphorus, nitrogen, and sulfur
19	N_MPKS	Medium nitrogen	NP_HKS	High phosphorus with,	NPK_HS	High potassium with

S/N	Nitrogen Treatments		Phosphorus Treatments		Potassium Treatments	
		with phosphorus, potassium, and sulfur	+ Org.	nitrogen potassium, sulfur, and Org.	+ Org.	nitrogen, phosphorus sulfur, and Org.
20	N_LPKS	Low nitrogen with phosphorus, potassium, and sulfur	NP$_M$KS + Org.	Medium phosphorus with nitrogen, potassium, sulfur, and Org.	NPK$_M$S + Org.	Medium potassium with nitrogen, phosphorus, sulfur, and Org.
21	N_HPKS + Org.	High nitrogen with phosphorus, potassium, sulfur, and Org.	NP$_L$KS + Org.	Low phosphorus with nitrogen, potassium, sulfur, and Org.	NPK$_L$S + Org.	Low potassium with nitrogen, phosphorus, sulfur, and Org.
22	N_MPKS + Org.	Medium nitrogen with phosphorus, potassium, sulfur, and Org.				
23	N_LPKS + Org.	Low nitrogen with phosphorus, potassium, sulfur, and Org.				
24	N_H + Org.	High nitrogen + Org.				
25	N_M + Org.	Medium nitrogen + Org.				
26	N_L + Org.	Low nitrogen + Org.				

Table 10. ***Nitrogen treatment combinations***

****H = high level, M = medium level, L = low level, Org. = organic fertilizer***

Treatment Combination	GS & SDF	GS	SDF	Selected	Screened Treatment Combinations for ANOVA
Organic fertilizer	49	6	43	Yes	Org. (n=6)
Control	401	315	86	Yes	Control (n=6)
N_H	15	7	8	Yes	N_H (n=6)
N_M	68	20	48	Yes	N_M (n=6)
N_L	54	13	41	Yes	N_L (n=6)
N_HP	30	10	20	Yes	N_HP (n=6)
N_MP	28	10	18	Yes	N_MP (n=6)
N_LP	20	-	20	No	Dropped
N_HK	3	1	2	No	Dropped
N_MK	7	-	7	No	Dropped
N_LK	2	-	2	No	Dropped
N_HPK	29	9	20	Yes	N_HPK (n=6)
N_MPK	286	258	28	Yes	N_MPK (n=6)

N_LPK	112	104	8	Yes	N_LPK (n=6)
N_MPK + Org.	9	6	3	No	Dropped
N_LPK + Org.	24	15	9	Yes	N_LPK + Org (n=6)
N_HPKS	9	9	-	No	Dropped
N_MPKS	56	39	17	Yes	N_MPKS (n=6)
N_LPKS	173	169	4	No	Dropped
N_MPKS + Org.	6	6	-	No	Dropped
N_LPKS + Org.	24	13	11	Yes	N_LPKS + Org (n=6)
N_M + Org.	11	-	11	No	Dropped
N_L + Org.	27	15	12	Yes	N_L + Org (n=6)
N_H + Zn	21	-	21	No	Dropped

* Six best yields in that treatment combination were purposely selected.

Table 11. Phosphorus treatment combinations

****H = high level, M = medium level, L = low level, Org. = organic fertilizer***

Treatment Combination	GS & SDF	GS	SDF	Selected	Screened Treatment Combinations for ANOVA
NP_LK + Org	33	21	12	Yes	NP_LK + Org (n=6)
NP_HK	11	3	8	No	Dropped
NP_MK	11	9	2	No	Dropped
NP_LK	372	358	14	Yes	NP_LK (n=6)
NP_LKS + Org	30	20	11	Yes	NP_LKS + Org (n=6)
NP_MKS	65	28	37	Yes	NP_MKS (n=6)
NP_LKS	206	190	16	Yes	NP_LKS (n=6)
P_HK	2	-	2	No	Dropped
P_LK	6	4	2	No	Dropped
NP_H	2	-	2	No	Dropped
NP_M	36	6	30	Yes	NP_M (n=6)
NP_L	40	14	26	Yes	NP_L (n=6)
P_M	10	2	8	No	Dropped
P_L	8	-	8	No	Dropped

Table 12. Potassium treatment combinations

****H = high level, M = medium level, L = low level, Org. = organic fertilizer***

Treatment Combination	GS & SDF	GS	SDF	Selected	Screened Treatment combinations for ANOVA
NPK_M + Org.	6	-	6	No	Dropped
NPK_L + Org	27	21	6	Yes	NPK_L + Org. (n=6)
NPK_H	11	1	10	No	Dropped
NPK_M	13	9	4	No	Dropped

NPK_L	371	361	10	Yes	NPK_L (n=6)
NPK_MS	67	30	37	Yes	NPK_MS (n=6)
NPK_LS	203	187	16	Yes	NPK_LS (n=6)
NPK_LS + org	30	19	11	Yes	NPK_LS + org (n=6)
NK_L + Org	21	-	21	No	Dropped
NK_H	2	-	2	No	Dropped
NK_M	8	1	7	No	Dropped
NK_L	2	-	2	No	Dropped
PK_H	2	-	2	No	Dropped
PK_L	6	4	2	No	Dropped

3.4.2 Regression and Correlation Analysis

GenStat version 12 and SAS version 9.4 statistical packages were used to perform regression and correlations, respectively.

CHAPTER 4: RESULTS

4.1 Grain Yield Responses

Treatments were heterogeneous and included organic fertilizers only, organic fertilizer in combination with inorganic fertilizers, and inorganic fertilizers only. The performance of N was looked at as a single nutrient at high, medium, and low levels, in combination with other nutrients as N, NP, NK, NPK, and NPKS. Characterization of N resulted in 26 different NPK treatment combinations inclusive of control and organic fertilizers (Table 9).

P and K in those combinations were also categorized as high, medium, and low. Organic fertilizer was added to treatments in which it was applied in combination with inorganic fertilizer. As per the categorization, there were seven treatments in which inorganic fertilizer was applied in combination with organic fertilizers. These were NP_LK + Org., N_LPK + Org. NP_LKS + Org., N_LPKS + Org, N_L + Org., NPK_LS + Org., and NK_L + Org. Nutrient composition in different organic amendments was not calculated but recognized as organic fertilizer treatment where it was either applied alone or in combination with inorganic fertilizer. With these categorizations, it was possible to perform ANOVA in GenStat software version 12 (Table 14).

4.2 Yield Responses of P and K at Different Levels of N in Guinea Savannah and Semi Deciduous Forest Zones

As per the categorization of NPK as a low, medium, and high, levels at which the highest yield response can be achieved was investigated. Yield responses to low, medium, and high levels of P and K were examined at the different levels of N, irrespective of whether the treatment combination had organic fertilizer or S embedded into them.

The bubble plots in (Figs. 8 and 9) are for P and K responses at different levels of N; different levels of P and K from low to high are on the x-axis while the different levels of N from low to high are on the y-axis, with their average yield responses represented by bubbles in the middle. Yield responses represented by the bubbles are averages of NP, NK, and NPK treatment combinations. For P, average yields represent combined NP and NPK treatments, whereas for K, average yields are for NK and NPK treatments combined, all at the respective low, medium, and high levels. In GS, there was no high rate of P and K at low and medium levels of N.

In GS, yield responses are higher at medium levels of N, P, and K compared to the low and high levels (Fig. 8). A medium level of N (N_M) applied with a medium level of P (P_M) or K (K_M) as ($N_MP_MK_M$, N_MP_M, or N_MK_M) had higher grain yield responses at about 6.6 t ha^{-1} and 7.3 t ha^{-1} for P and K, respectively, compared to medium N (N_M) applied with low P (P_L) or low K(K_L) as $N_MP_LK_L$, N_MP_L, N_MK_L; P_M and K_M applied with N_L as $N_LP_MK_M$, N_LP_M, and N_LK_M had higher grain yield responses of 5.2 t ha^{-1}compared to P_M and K_M applied with N_H ($N_HP_MK_M$, N_HP_M, and N_HK_M) with the grain yield at 3.4 t ha^{-1} and 3.2 t ha^{-1} for P and K, respectively. Generally, in GS, low levels of P (P_L) and K (K_L) have low yield responses at all levels of N (N_L, N_M, and N_H); this could suggest that P and K are limiting in soils of GS. But specifically for P, there could also be high fixation such that, at low levels, there is hardly any available P in soil solution for plant uptake. This conclusion could be subject to further investigations, especially sorption studies to ascertain P requirements.

In SDF, on the other hand (Fig. 9), medium levels of P (P_M) and K (K_M) had higher grain yield response of 5.2 t ha^{-1} and 5.9 t ha^{-1}, respectively, at the high level of N (N_H) as $N_HP_MK_M$, N_HP_M, and N_HK_M compared to high N (N_H) with low P and K as $N_HP_LK_L$, N_HP_L, and N_HK_L or high NPK as $N_HP_HK_H$, N_HP_H, and N_HK_H with grain yield at 3.7 t ha^{-1} and 2 t ha^{-1} for P_L and P_H, respectively, and 1.9 t ha^{-1} and 1.8 t ha^{-1} for K_L and K_H, respectively. Generally, a medium level of N applied with a low or medium level of P and K ($N_MP_MK_M$ or $N_MP_LK_L$) appeared to have a higher grain yield response than high N (N_H) with high P (P_H) and K (K_H) or medium and low N with high P and K. All levels of N (N_L, N_M, and N_H) with P_M and P_L and K_M and K_L had higher yield responses compared to all levels of N with high P and K (P_H and K_H). There is some evidence pointing that N is the most limiting nutrient in the SDF zone.

For classification, <60 kg ha^{-1}, 60-90 kg ha^{-1}, and > 90 kg ha^{-1} fall in the low, medium, and high levels, respectively, for N, whereas <46 kg ha^{-1}, 46-89 kg ha^{-1}, and >89 kg ha^{-1} fall in the low, medium and high levels, respectively, for P and K. It can be deduced that N rates between 60 and 90 kg N ha^{-1} with P and K rates of 46-89 kg P_2O_5 and K_2O ha^{-1} (N-P_2O_5-K_2O) applied under good agronomic practices can give the highest maximum desired maize yield responses of up to about 5 t ha^{-1} on average.

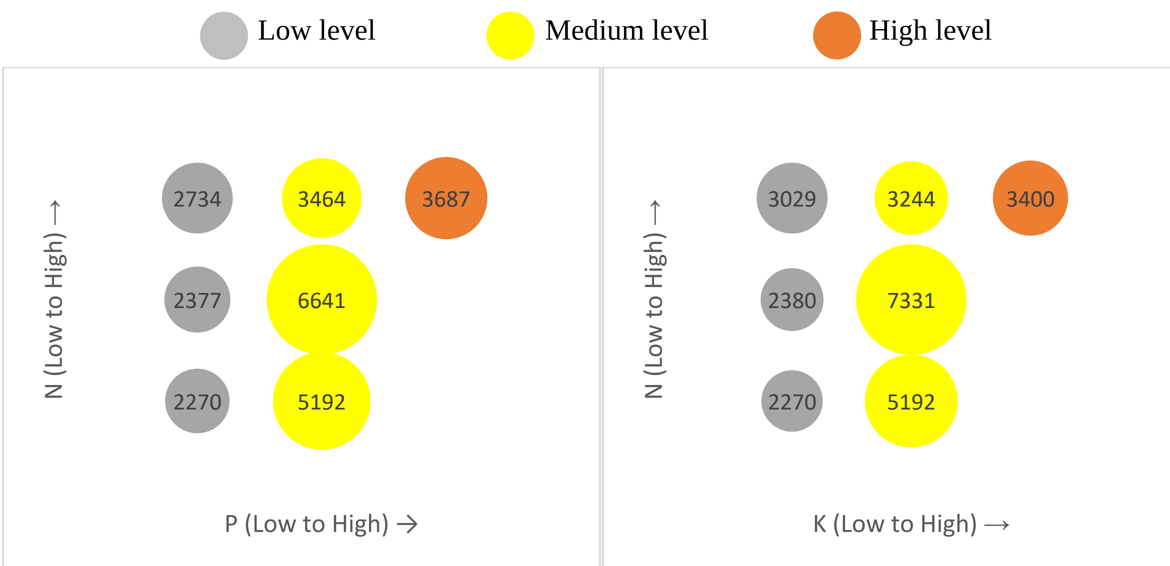


Figure 8. ***Phosphorus (left) and potassium (right) yield responses at different levels of nitrogen in Guinea Savannah***

The colors demonstrate different levels of phosphorus and potassium; on the y-axis are levels of nitrogen at low, medium, and high going upward while the bubbles represent average yields at each level.

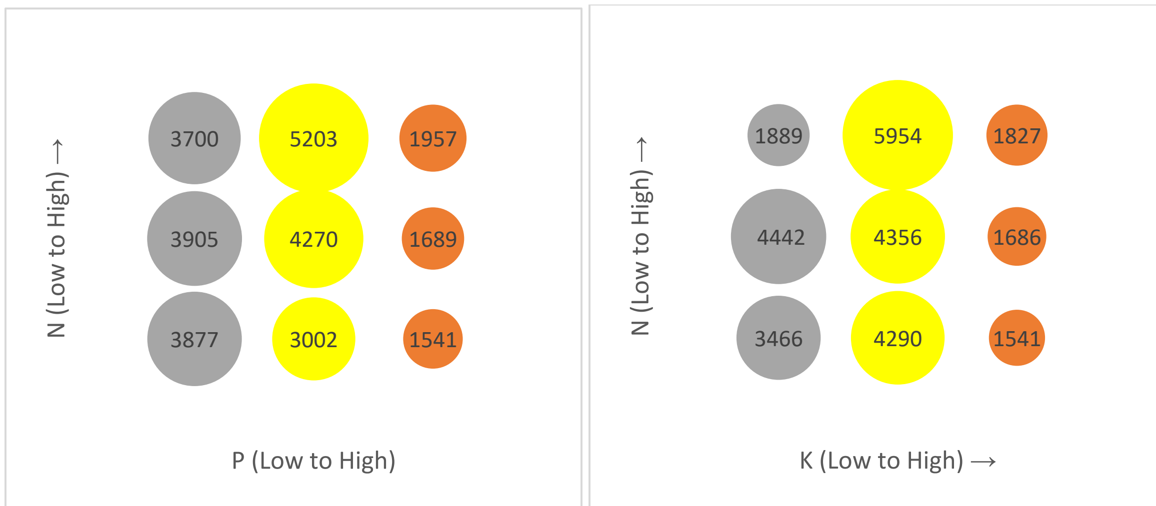


Figure 9. ***Phosphorus (left) and potassium (right) yield responses at different levels of nitrogen in Semi-Deciduous Forest***

The colors demonstrate different levels of phosphorus and potassium; on the y-axis are levels of nitrogen at low, medium, and high going upward while the bubbles represent average yields at each level.

Table 13. ***Generalized yield responses of different levels of phosphorus and potassium at different levels of nitrogen in Guinea Savannah and Semi-Deciduous Forest used to generate Figs. 8 and 9 (GS n= 649, SDF n=227)***

Guinea Savannah				**Semi-Deciduous Forest**			
High Nitrogen	**P-Levels**	**Frequency**	**Average grain yield**		**P-Levels**	**Frequency**	**Average grain yield**
	H	3	3687	High Nitrogen	H	6	1957
	M	10	3464		M	24	5203
	L	15	2734		L	10	3700
	STDEV		498		STDEV		1624
	K-Levels	**Frequency**	**Average grain yield**		**K-Levels**	**Frequency**	**Average grain yield**
	H	1	3400		H	6	1827
	M	10	3244		M	14	5954
	L	8	3029		L	2	1889
	STDEV		186		STDEV		2365
	P-Levels	**Frequency**	**Average grain yield**		**P-Levels**	**Frequency**	**Average grain yield**
	H	-			H	2	1689
	M	20	6641		M	104	4270
Medium Nitrogen	L	299	2377	Medium Level	L	29	3905

	STDEV		3015		STDEV		1397
	K-Levels	**Frequency**	**Average grain yield**		**K-Levels**	**Frequency**	**Average grain yield**
	H	-	-		H	4	1686
	M	17	7331		M	73	4356
	L	292	2380		L	17	4442
	STDEV		3501		STDEV		1567
Low Nitrogen	**P-Levels**	**Frequency**	**Average grain yield**		**P-Levels**	**Frequency**	**Average grain yield**
	H			Low Level	H	2	1541
	M	13	5192		M	10	3002
	L	289	2270		L	40	3877
	STDEV		2066		STDEV		1180
	K-Levels	**Frequency**	**Average grain yield**		**K-Levels**	**Frequency**	**Average grain yield**
	H				H	2	1541
	M	13	5192		M	6	4290
	L	289	2270		L	47	3466
	STDEV		2066		STDEV		1411

H = high, M = medium, L = low.

Further analysis was performed using ANOVA to determine whether there were significant differences among the treatment combinations. In this case, S and organic matter were included in all treatments where they were applied in combination (Table 14 and Fig. 10).

4.3 Yield Responses of Different Treatment Combinations

Table 14. Maize mean grain yield responses at different NPK treatment combinations (n=312)

Variable	**No. of Rep.**	**Guinea Savannah**	**Sig. Dif.**	**Semi-Deciduous Forest**	**Sig. Dif.**	**Combined Zones**	**Sig. Dif.**
Organic fertilizer	6	2120	ab	6209	ef	4165	cde
Control	6	1590	a	2567	a	2078	a
N_H	6	3620	ef	3528	ab	3574	bc
NPK_L +Org.	6	3254	cdef	5107	cde	4180	cde
N_M	6	3335	def	7147	fg	5241	efg
N_L	6	2086	ab	5415	cde	3750	bc
N_HP	6	3126	cdef	4664	bcd	3895	bcd
N_MP	6	2604	bcd	4527	bc	3565	bc
N_HPK	6	3649	ef	7745	g	5697	fg
NP_LK + Org.	6	3254	cdef	5967	def	4610	cdef
N_MPK	6	4785	g	6077	ef	5431	efg
N_LPK	6	3882	f	3622	ab	3752	bc

N_LPK + Org.	6	2302	ab	4611	bcd	3457	bc
NP_LK	6	4804	g	7925	g	8543	g
NP_LKS + Org.	6	4850	g	4408	bc	4606	cdef
N_MPKS	6	6072	h	5354	cde	5102	defg
N_LPKS + Org	6	4850	g	6183	ef	6128	g
NP_MKS	6	9162	j	5354	cde	5102	defg
NP_LKS	6	5324	g	6089	ef	5707	fg
NP_M	6	3102	cde	4645	bcd	3873	bcd
NP_L	6	2634	bcd	4558	bcd	3596	bc
N_L + Org	6	2567	bc	2957	a	2762	ab
NPK_L	6	4804	g	4408	bc	4606	cdef
NPK_MS	6	6823	i	7925	g	7374	h
NPK_LS	6	5324	g	6089	ef	5707	fg
NPK_LS +org	6	4850	g	5354	cde	5102	defg
Mean		4030		5324		4677	
SED		333		603		524	
CV (%)		14.3		19.6		27.4	
P<0.05		<.001		<.001		<.001	

*H = high level, M = medium level, L = low level: *means followed by the same letter within each column are not significantly different at *P*=0.05, for total number observations for each treatment combination refer to Tables 6, 7, and 8.

Across the two AEZs, significant yield differences ($P<0.05$) were observed between treated and control except in the SDF zone, where a low N rate in combination with the organic matter did not show a significant yield difference ($P<0.05$) from the control.

In the GS zone, an extremely high average grain yield of up to 9 t ha^{-1} was attained with a treatment combination of NP_MKS. Treatment combinations that followed were N_MPKS and NPK_MS with grain yields at 6.07 t ha^{-1} and 6.8 t ha^{-1}, respectively; this could imply that $N_MP_MK_M$S responds highly significantly in GS. Treatment combinations of NP_LK, N_MPK, NP_LKS + Org, NPK_L, NPK_LS, NPK_LS + Org, N_LPKS + Org, and NP_LKS had significantly higher grain yields from the control, but their grain yields did not differ significantly ($P<0.05$) from each other; their grain yields ranged from 4.7 t ha^{-1} to 5.3 t ha^{-1}. Treatment combinations with S had relatively higher grain yields of between 46 kg and 520 kg. The rest of the treatment combinations had grain yields below 4 t ha^{-1} but significantly ($P<0.05$) differed from the control, and their average yields ranged from 2.12 t $ha^{-1}$to 3.88 t ha^{-1}.

In the SDF zone, on the other hand, N_HPK and NP_LK had significantly higher yield responses than other treatment combinations; average yields were 7.7 t ha^{-1} and 7.9 t ha^{-1}, respectively, and did not differ from each other significantly ($P<0.05$). Organic fertilizer only, N_MPK, N_LPKS + Org., NP_LKS, and NPK_LS had yield responses ranging from between 6.0 t $ha^{-1}$to 6.2 t ha^{-1} and did not differ significantly among themselves. However, their grain yields significantly ($P<0.05$) differed from NPK_LS + Org., N_MPKS, N_L, and NPK_L + Org., which had average grain yields between 5.1 t ha^{-1} and 5.4 t ha^{-1} and did not vary from each other much. Treatment combinations that had average grain yield responses between 4.4 t ha^{-1} and 4.6 t ha^{-1} were N_MP, NP_LKS + Org., N_HP, N_LPK + Org., NP_M, and NP_L; the other treatment combinations had yield responses below 4.0 t ha^{-1}.

In both AEZs, most treatment combinations in the NPKS category had above average grain yields. Overall, the average yield response of NPK is less than that of NPKS by 0.73 t ha^{-1}. In GS, SDF, and SS, NPKS yielded higher than NPK; average yields were 4.4 t ha^{-1}, 3.1 t ha^{-1}, and 3.3 t ha^{-1} for NPKS in SDF, GS, and SS, respectively, whereas the average grain yields for NPK were 4.0 t ha^{-1}, 2.2 t ha^{-1}, and 1.8 t ha^{-1} in SDF, GS, and SS respectively (Figure 11). It should be noted that S in the NPKS treatment combination comes mainly from AS fertilizer. The challenge with AS fertilizer is its acidification effect in the soil; with increased and continued application, there could be reduced yields due to very low pH values created by AS fertilizer.

Organic fertilizer treatment alone also responded positively in both AEZs, but the response was higher and very significant in the SDF zone. In SDF, response to organic fertilizer treatment only was 6.2 t ha^{-1}, compared to 2.2 t ha^{-1} in GS. The high yield response difference cannot be easily explained because, in this study, the performance of different organic materials was not explored but it could be attributed to the quality of organic materials used. Most treatment combinations with both inorganic and organic fertilizers had average or above average yield responses. Organic matter plays an important role in improving the physical and chemical properties (aeration, bulk density, structure), pH, and CEC, as well as the nutrient content of the soil, which could also improve the performance of inorganic fertilizer though this was not investigated in this study.

Findings from this ANOVA allude that high N rates applied with medium or low rates of P and K also give high yield responses. A data gap exists on high P and K applied with high N; this could be explored to further understand yield responses at high levels. It can also be deduced that yield response is higher when S is added to NPK fertilizers.

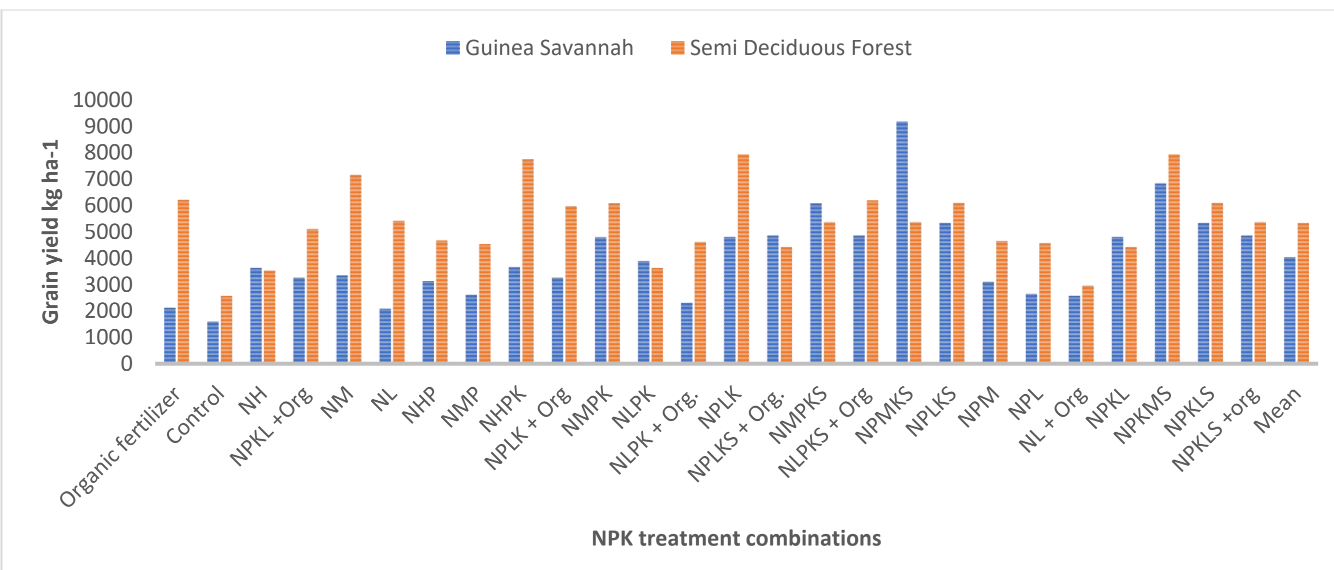


Figure 10. Grain yield responses of different treatment combinations in GS and SDF zones

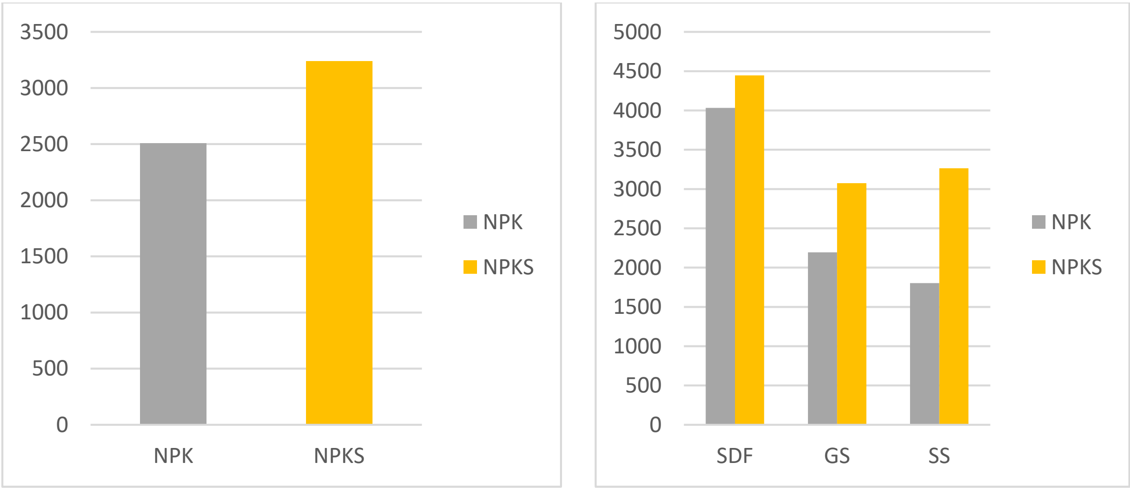


***Figure 11.** Overall average yield responses of NPK and NPKS (left) and average yield responses of NPK and NPKS in SDF, GS, and SS zones (right)*

NPK GS n =391, SDF n = 68, and SS n = 14: NPKS GS n = 237, SDF n = 32, and SS n = 63

4.4 Representation of Grain Yields versus Nitrogen (N), Phosphorus (P_2O_5), and Potassium (K_2O) Rates

In Figs. 12, 13, and 14, grain yield responses to different treatment combinations were plotted against rates of N, P_2O_5, and K_2O, respectively, in GS and SDF. From those graphs, it can be observed that the majority of the grain yields fall below 6 t ha^{-1}. However, from the N graph, at 90 kg N ha^{-1}, responses were higher than average in both zones, although in SDF, a rate of 135 kg N ha^{-1} also had higher grain yield response than average.

An application rate of 60 kg P_2O_5 ha^{-1} had higher grain yield than average in both AEZs, although, in SDF, 40 kg P_2O_5 ha^{-1} also showed a similar grain yield response. Applying 60 kg K_2O ha^{-1} and 45 kg K_2O ha^{-1} achieved higher average yields in GS and SDF, respectively.

All the rates of N, P_2O_5, and K_2O achieving higher average yields in both zones fall under the characterization of medium or low rates. At a very high N rate of about 200 kg N ha^{-1}, yields appear to be lower than average at about 2 t ha^{-1} in the SDF zone, whereas in the GS zone at that same rate, response was at an above average range of about 3 t ha^{-1}.

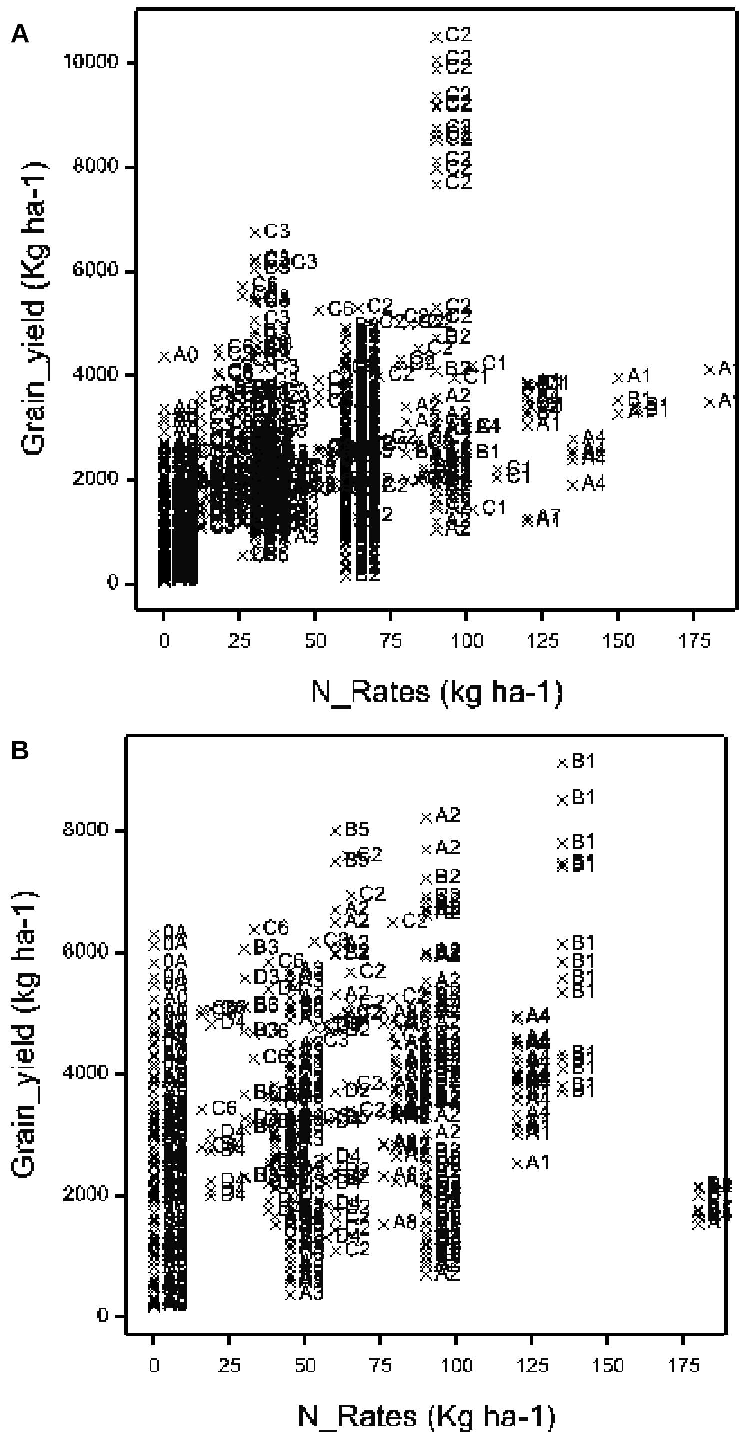


Figure 12.** **Grain yield versus nitrogen rates at different treatment combinations in (A) GS and (B) SDF

***Treatment combinations:** 0A = Organic fertilizer only, A0 = Control, A1 = N_H, A2 = N_M, A3 = N_L, A4 =N_HP, A5 = N_MP, A6 = N_LP, A7 = N_HK, A8 = N_MK, A9 = N_LK, B1 = N_HPK, B2 = N_MPK, B3 = N_LPK, B4 = N_HPK + Org., B5 = N_MPK + Org., B6 = N_LPK + Org., C1 = N_HPKS, C2 = N_MPKS, C3 = N_LPKS, C4 = N_HPKS + Org., C5 = N_MPKS + Org, C6 = N_LPKS +Org., D1 = N_H + Org., N_M + Org., NL + Org. (H= High, M= Medium and L= Low*

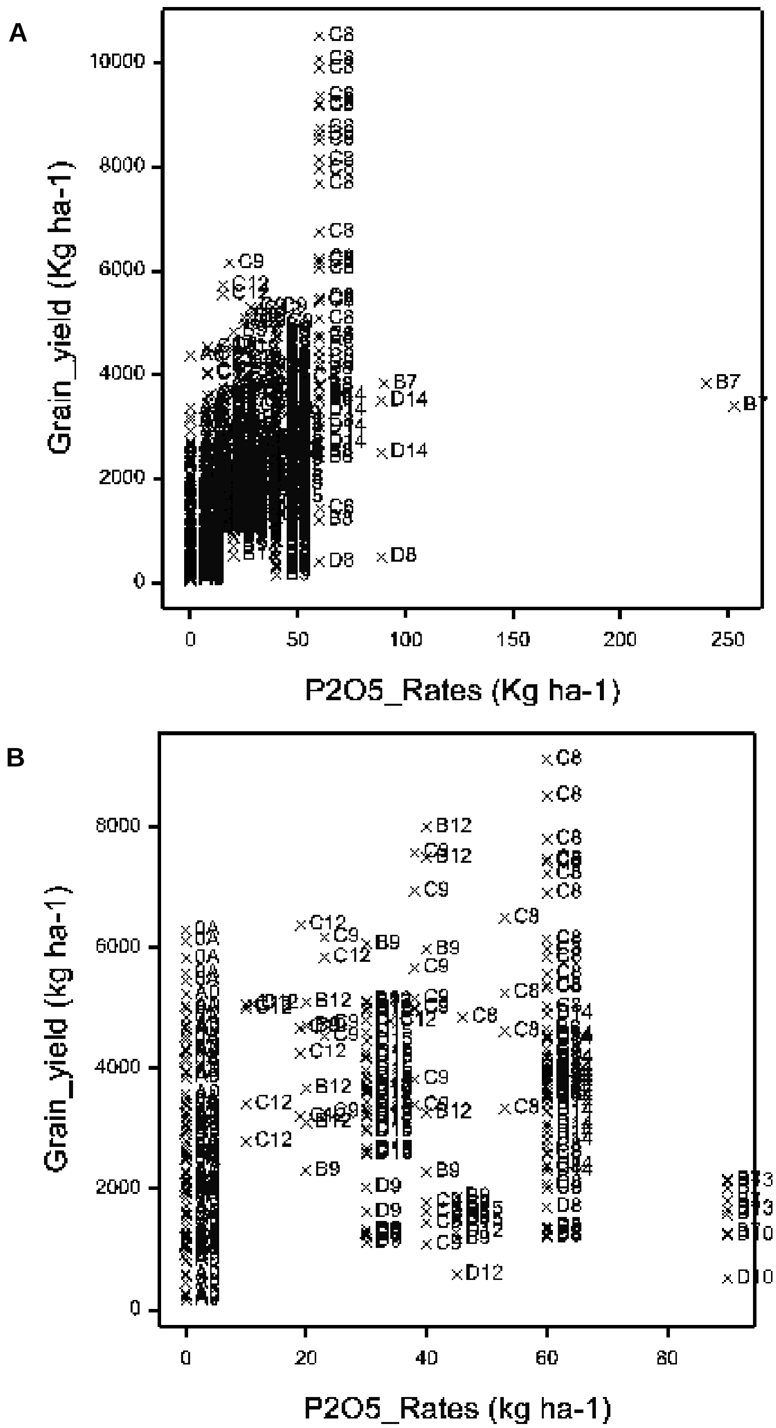
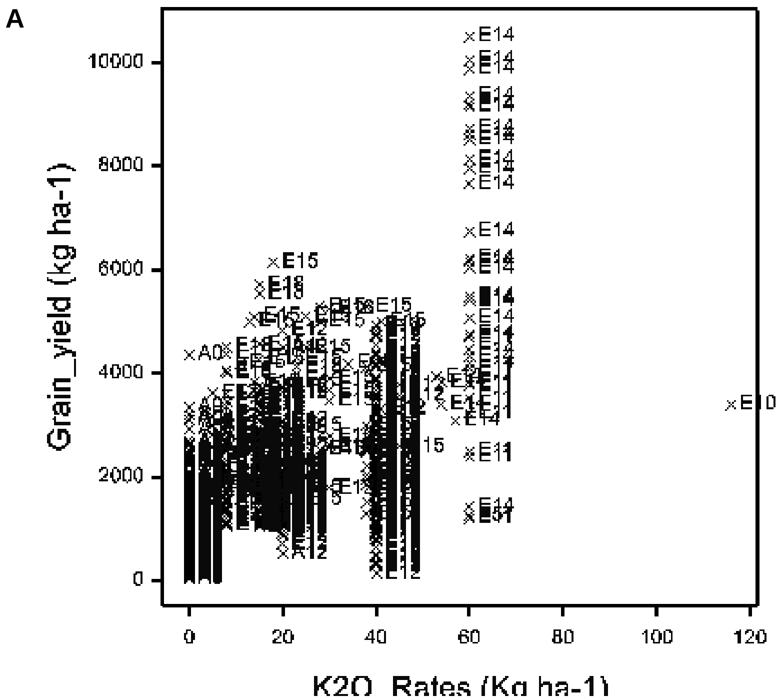


Figure 13. Grain yield versus phosphorus rates at different treatment combinations in (A) GS and (B) SDF

***Treatment combinations:** 0A = Organic fertilizer only, A0 = Control, D7 = P_H, D8 = P_M, D9 = P_L, D10 = P_HK, D11 = P_MK, D12 = P_LK, D13, P_HN, D14 = P_MN, D15 = P_LN, B7 = NP_HK, B8 = NP_MK, B9 = NP_LK, B10 = NP_HK + Org., B11 = NP_MK + Org., B12 = NP_LK + Org., C7 = NP_HKS, C8 = NP_MKS, C9 = NP_LKS, C10 = NP_HKS + Org., C11 = NP_MKS + Org., C12 = NP_LKS + Org.*



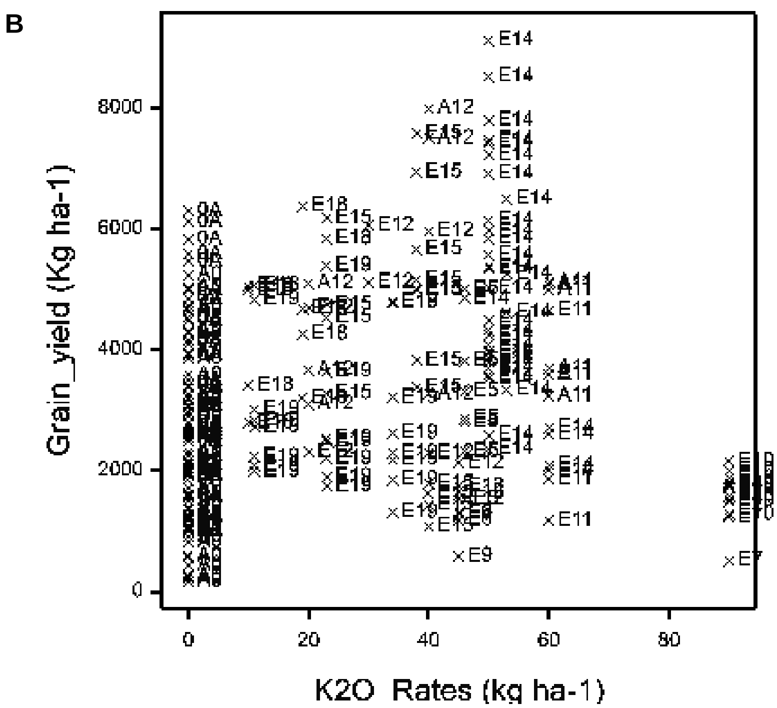


Figure 14. Grain yield versus potassium rates at different treatment combinations in (A) GS and (B) SDF

***Treatment combinations:** 0A = Organic fertilizer only, A0 = Control, E1 = K_H, E2 = K_M, E3 = K_L, E4 = NK_H, E5 = NK_M, E6 = NK_L, E7 = PK_H, E8 = PK_M, E9 = PK_L, E10 = NPK_H, E11 = NPK_M, E12 = NPK_L, E13 = NPK_HS, E14 = NPK_MS, E15 = NPK_LS, E16 = NPK_HS + Org., E17 = NPK_MS + Org., E18 = NPK_LS + Org., E19 + NK_L + Org.*

4.5 Regression and Correlation Analysis

4.5.1 Summary Statistic of Soil Variables Used in the OLS Regression Model

In the two zones, the average soil pH is moderately acidic. However, soil pH values fall within very strong to slightly acidic ranges. Average soil OC (%) was 1.40 and 1.06 but was as high as 3.37 and 4.01 for GS and SDF, respectively. The average soil TN (%) was 0.07 and 0.16 and as high as 0.7 and 0.16 for GS and SDF zones, respectively. For soil Av. P, average values were 7.82 and 13.94 and the highest values were 28.36 mg kg^{-1} and 44.29 mg kg^{-1} soil in GS and SDF, respectively (Tables 15 and 16).

Table 15. Summary statistics of variables used in the OLS regression model (GS) Soil parameters are from within a soil depth of 0.2 m (n = 1009).

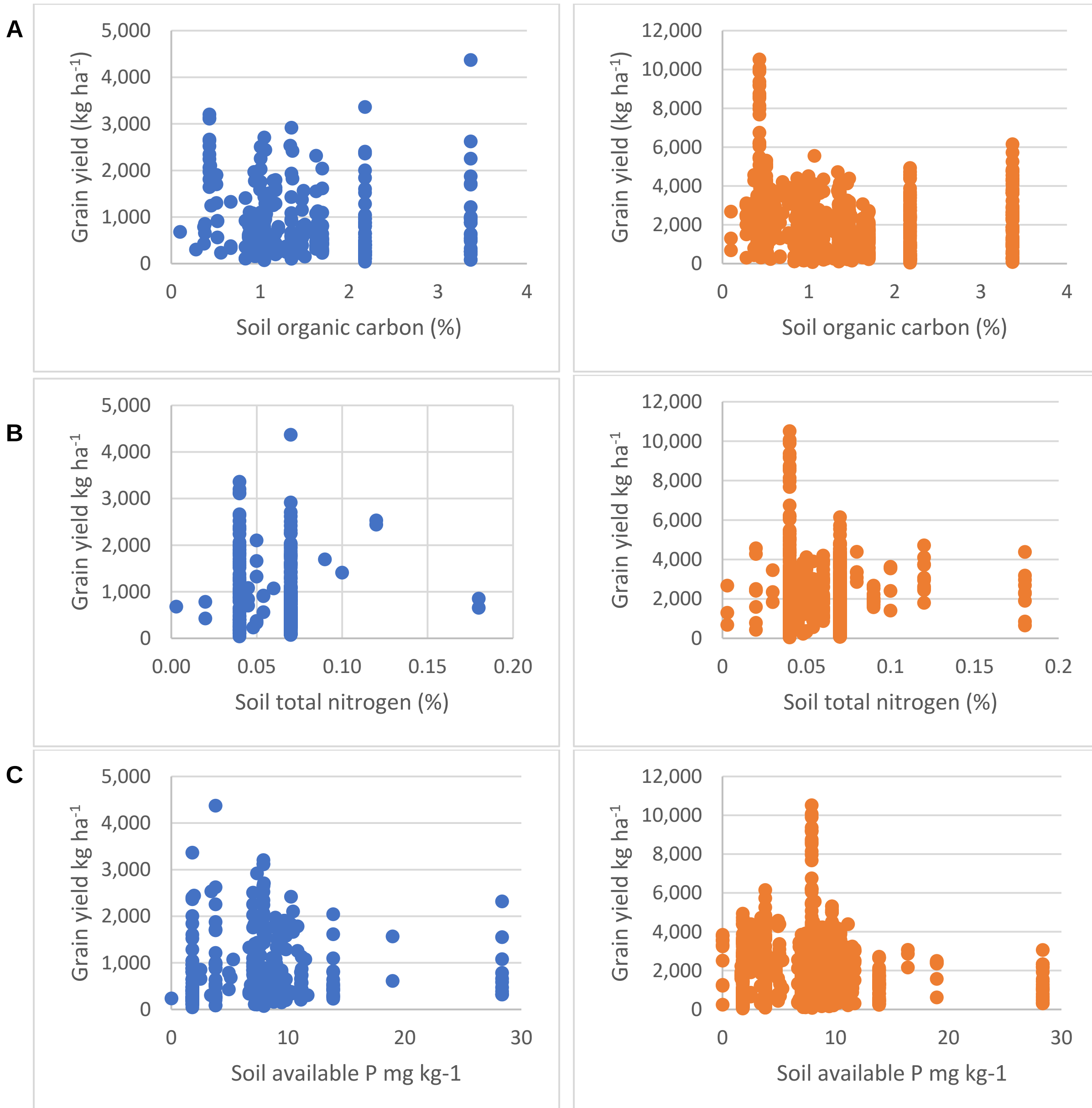
GS	TAR (mm)	pH	% OC	CEC (Cmol/kg soil)	Total N (%)	Av. P mg kg^{-1}	Sand (%)	Clay (%)	Silt (%)
Mean	1,056.23	5.90	1.40	5.71	0.07	7.82	65.24	12.14	26.57
Minimum	300.00	4.53	0.10	2.10	0.00	0.02	53.60	0.36	1.65
Maximum	1,897.70	6.55	3.37	17.47	0.70	28.36	95.75	27.01	46.00
STDEV	192.94	0.35	0.81	2.87	0.05	4.76	7.39	5.25	7.53

Table 16. Summary statistics of variables used in the OLS regression model (SDF) Soil parameters are from within a soil depth of 0.2 m (n = 420).

SDF	TAR (mm)	pH	%OC	CEC (Cmol/kg soil)	Total N (%)	Av. P mg /kg	Sand (%)	Clay (%)	Silt (%)
Mean	1,211.38	5.80	1.06	13.56	0.16	13.94	67.29	14.72	19.15
Minimum	287.00	4.30	0.12	1.57	0.03	1.30	40.00	3.00	6.50
Maximum	1,750.00	6.60	4.01	82.87	0.26	44.29	87.50	28.28	52.00
STDEV	290.35	0.47	0.76	19.49	0.10	10.62	7.55	4.82	8.28

4.5.2 Grain Yields versus Soil Variables (% OC, % TN, Av. P, and pH)

In GS, grain yields are generally low, at an average of about 0.7 t ha^{-1} for the control in the blue graph (Fig. 15). Grain yield responses were below 4 t ha^{-1} for most soil OC (%) values. However, at about 0.4% and 3.4%, grain yields were above 4 t ha^{-1}. For % soil TN, grain yields at 0.06% and 0.07% were above 4.0 t ha^{-1}. Initial grain yields were also higher at high soil N values. In the graphs of available soil P and pH, grain yields are higher at about 7 mg kg^{-1} P and soil water pH of about 5.8. Soil water pH of 5.8 is conducive for maize growing; however, the soil's Av. P of 7 mg kg^{-1} is below the critical level of about 10-12 mg kg^{-1}, which could explain the response of maize to P application in GS.



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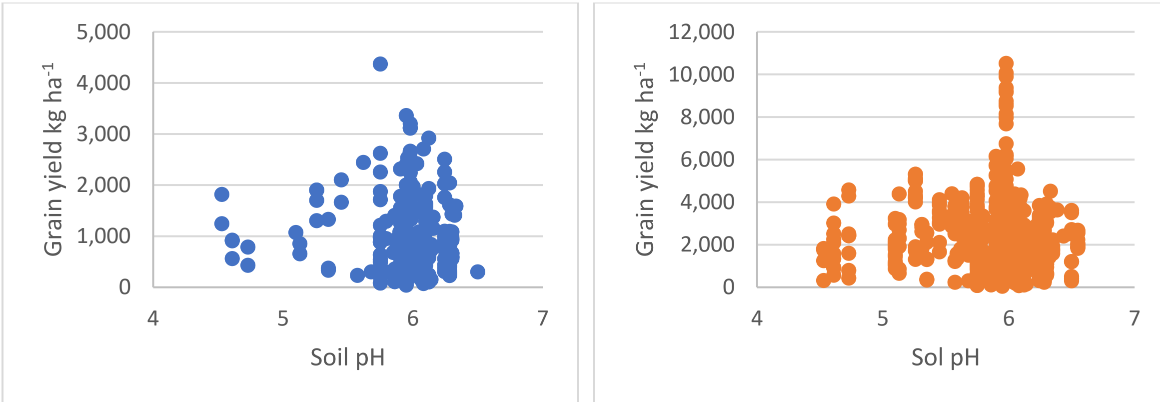
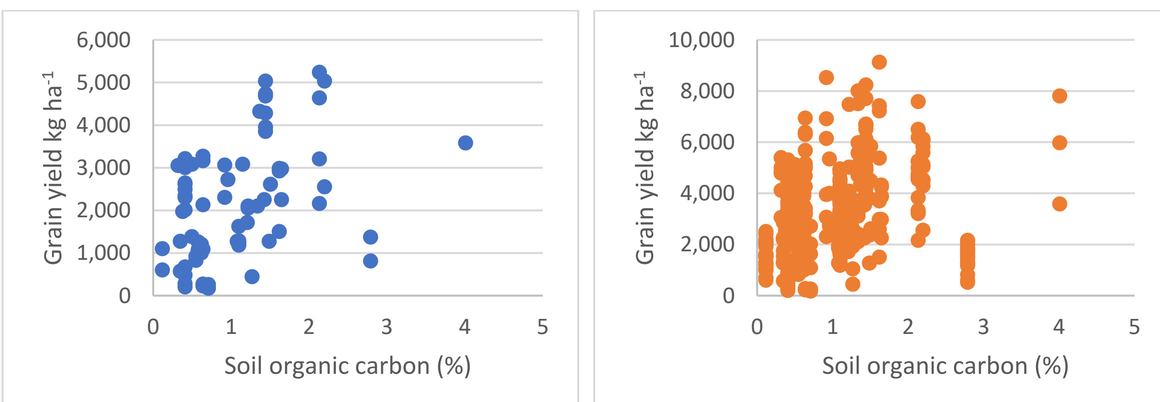


Figure 15.** **Grain yield versus soil variables of (A) soil organic carbon (%); (B) soil total nitrogen (%); (C) soil available phosphorus (mg kg^{-1}); and (D) soil water pH in Guinea Savannah

Blue represents control yield while orange is for treated yield in kg ha^{-1}.

In SDF (Fig. 16), the average control yield was at about 2 t ha^{-1}, and it is also evident that the majority of grain yields exceed 4 t ha^{-1}. Initial grain yields tend to be higher with increasing levels of soil OC (%), TN (%), and Av. P (mg kg^{-1} soil) in both the control and treated graphs. However, grain yields increase with increasing levels of pH values but drop at near-neutral pH of 6.5. At low and high soil water pH of less than 4.8 and above 7, grain yield responses could be low due to P fixation and aluminum toxicity problems. Both control and treated yield were higher at Av. P of about 44 mg kg^{-1} soil. However, treated grain yield did not differ that much from the control treatment. It is not surprising because, at such a high level of soil Av. P, there is little or no response at all to the applied P fertilizer.

E



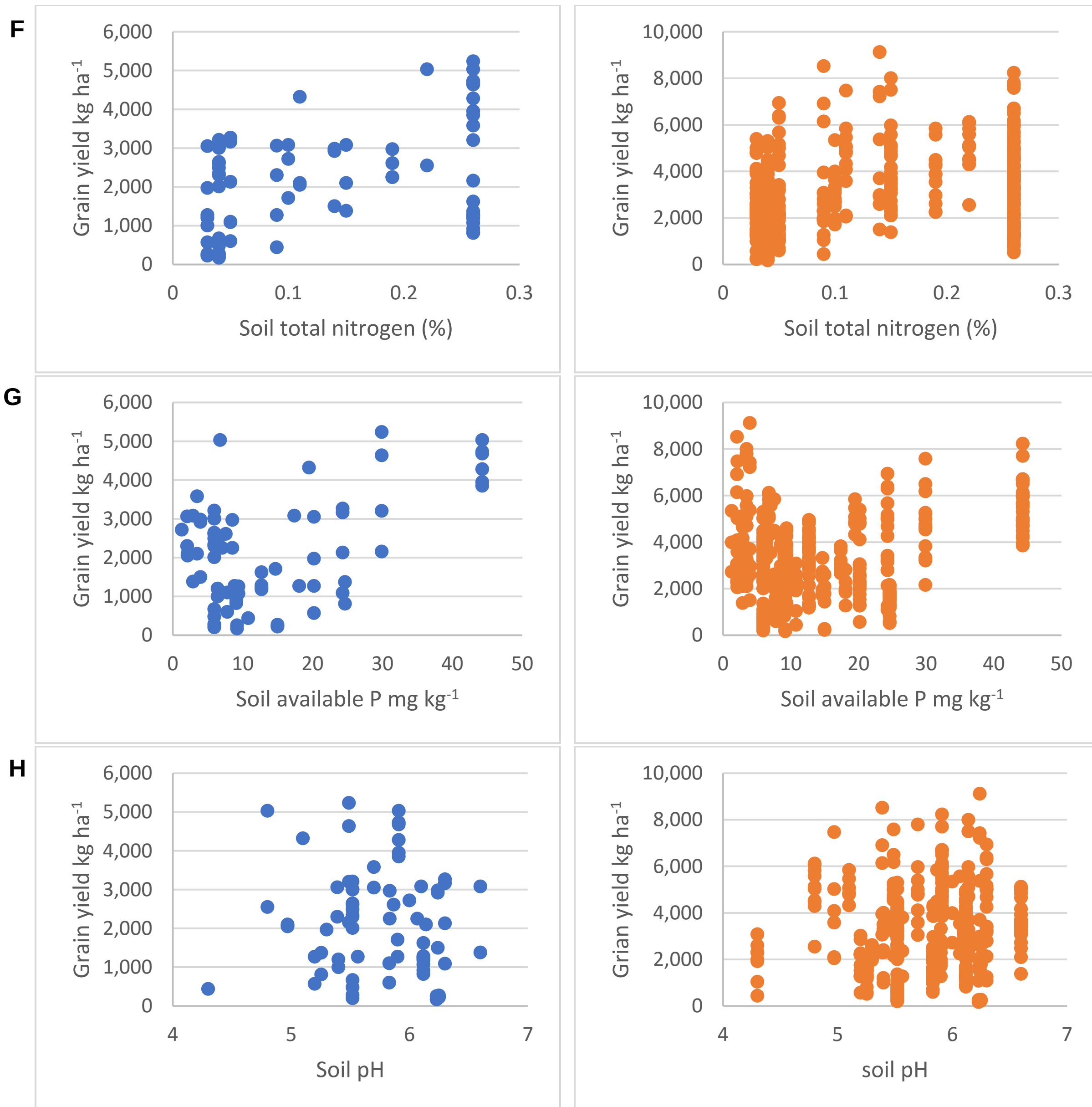


Figure 16. Grain yield versus soil variables of (E) soil organic carbon (%); (F) soil total nitrogen (%); (G) soil available phosphorus mg kg^{-1}; and (H) soil water pH in Semi-Deciduous Forest

Blue represents control yield while orange represents treated yield in kg ha^{-1}.

4.6 Regression Analysis

Yield defining factors were investigated using multiple linear regression in GenStat version 12. The yield was the response variate while total annual rainfall, pH, soil organic carbon (%), CEC, total soil N (%), available P mg kg^{-1}, and proportions of sand, clay, and silt were the explanatory variates. Different rates of N, P, K, and S were also included in the model. The group of edaphic and climatic variables was investigated alone and also in combination with nutrients fertilization rates to see each category's contribution to maize grain yields.

From the results in Table 17, it is evident that soil variables only explain very little yield variation in both AEZs (R = 14.6 and 10) for GS and SDF, respectively. Soil CEC, proportions of clay and sand in the soil, Av. P, and TAR explained most of the yield variations in GS. They all had a strong negative effect on grain yields except the proportion of sand, which had a positive effect. This signifies that unit increase in soil CEC, proportion of clay, available P, and TAR will likely lead to a decrease in maize grain yields by 95 kg ha^{-1}, 29 kg ha^{-1}, 23 kg ha^{-1}, and 1.2 kg ha^{-1}, respectively, while a proportional increase in sand will likely lead to increasing in grain yield by 50.06 kg ha^{-1}.

In SDF on the other hand, soil OC, CEC, proportion of clay and silt, and pH explained most of the variations in yield. It was only soil pH and soil OC that exhibited a profound positive effect on grain yield, implying that increase in soil OC and pH by 1% ha^{-1} will likely lead to an increase in grain yield by 804 kg ha^{-1} and 755 kg ha^{-1}, while unit and proportion increase in soil clay, silt, and CEC will probably lead to yield reduction by 10 kg ha^{-1}, 83 kg ha^{-1}, and 34 kg ha^{-1}, respectively.

***Table 17.** OLS regression coefficient of yield-defining variables, only edaphic and climatic factors across two agroecological zones (GS and SDF) for both treated yield and control*

Variable	**Guinea Savannah Estimate**	**St. Err**	**Semi-Deciduous Forest Estimate**	**St. Err**
%OC	-108.2	61.2	804**	190
CEC_cmol_kg_soil	-95.2**	18.4	-10.24*	4.76
Clay_%	-29.3**	10.4	-83.2**	24.4
P_mg_kg	-23.4*	10.9	1.36	1.4
Sand_%	50.06**	7.34	-2.5	11.7
Silt_%	2.89	7.67	-33.9**	15.8
TAR_MM	-1.167**	0.211	0.122	0.305
Total_N_%	6.5	10.3	-391	1286
pH	188	113	755**	192
R-Square	14.6		10	

* = Significant at 5%; ** = Significant at 1%.

From results in Table 18, the addition of nutrient rates (N, P_2O_5, K_2O, and S) to the model grossly increased the R-square values from 14.6% to 44.8% and 10% to 31.8% for GS and SDF, respectively. Only the P_2O_5 fertilization rate did not show any significant effect on grain yield. Soil variables and fertilization are not the only factors that lead to higher yield. There appear to be so many salient factors unexplained. Parameters such as timeliness in farm operations (planting, weeding, application of fertilizers and pest control, harvesting), land preparation, plant population, and crop varieties are some of the relevant factors that should be looked at critically when designing fertilizer recommendations. Figure 17 are plots of regression analysis for Av. P, % TN, % OC, and pH for combined treated and control yields.

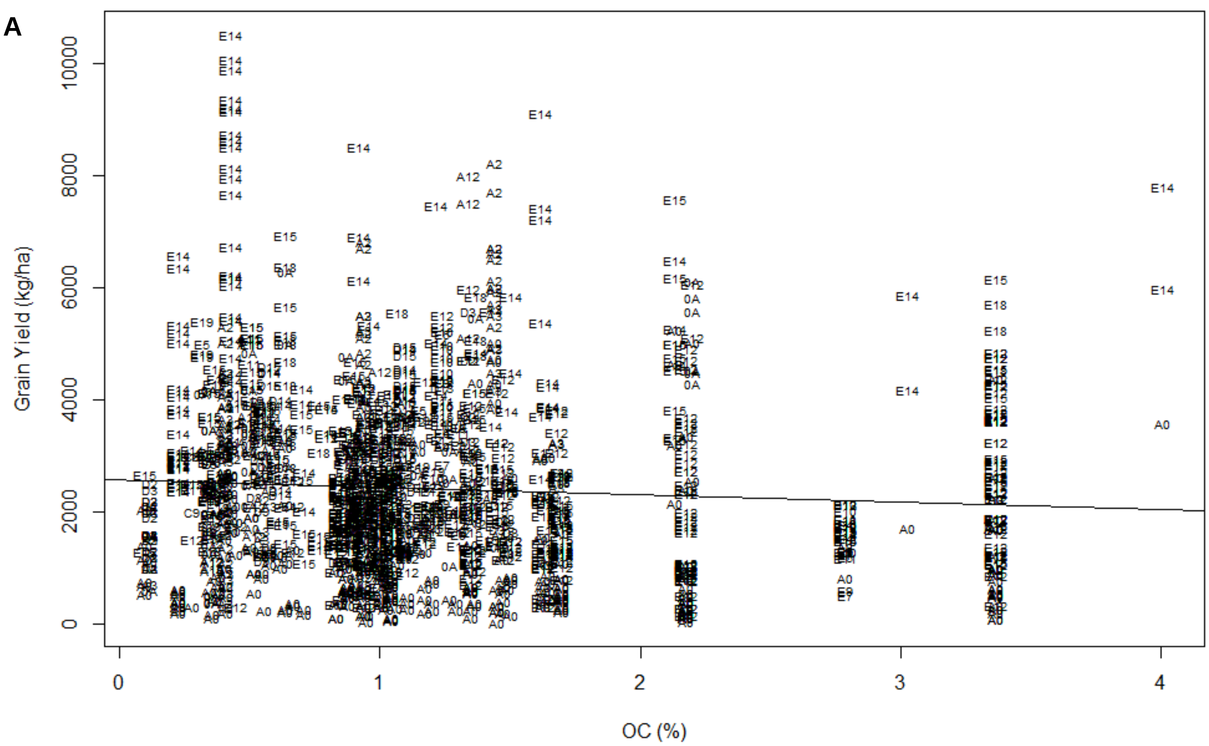
Table 18. ***OLS regression coefficient of edaphic and climatic factors inclusive of fertilization rates (N, P_2O_5, K_2O, and S rates) across two agroecological zones (GS and SDF) for both control and treated yields***

	Guinea Savannah		**Semi-Deciduous Forest**	
Variable	**Estimate**	**St. Err**	**Estimate**	**St. Err**
%OC	-13.4	50.3	438*	192.
CEC_cmol_kg_soil	-77.1**	15.1	-18.05**	4.22
Clay_%	-21.65*	8.86	-4.9	22.7
K_2O fertilization rates	27.04**	3.75	-12.95**	4.53
Nitrogen fertilization rate	6.17**	1.57	8.47**	1.82
P_2O_5 fertilization rates	2.55	3.60	-6.93*	3.70
P_mg_kg	-7.90	9.08	-1.29	1.29
S fertilization rates	34.35**	3.54	22.75**	2.36
Sand_%	46.68**	6.01	-14.6	10.4
Silt_%	3.37	6.49	-18.8	14.0
TAR_MM	-0.655**	0.184	0.409	0.282
Total_N_%	-539.	801.	-913	1202.
pH	-87.6	94.8	617**	171.
R-Square	**44.8**		**31.8**	

* = Significant at 5%; ** = Significant at 1%.

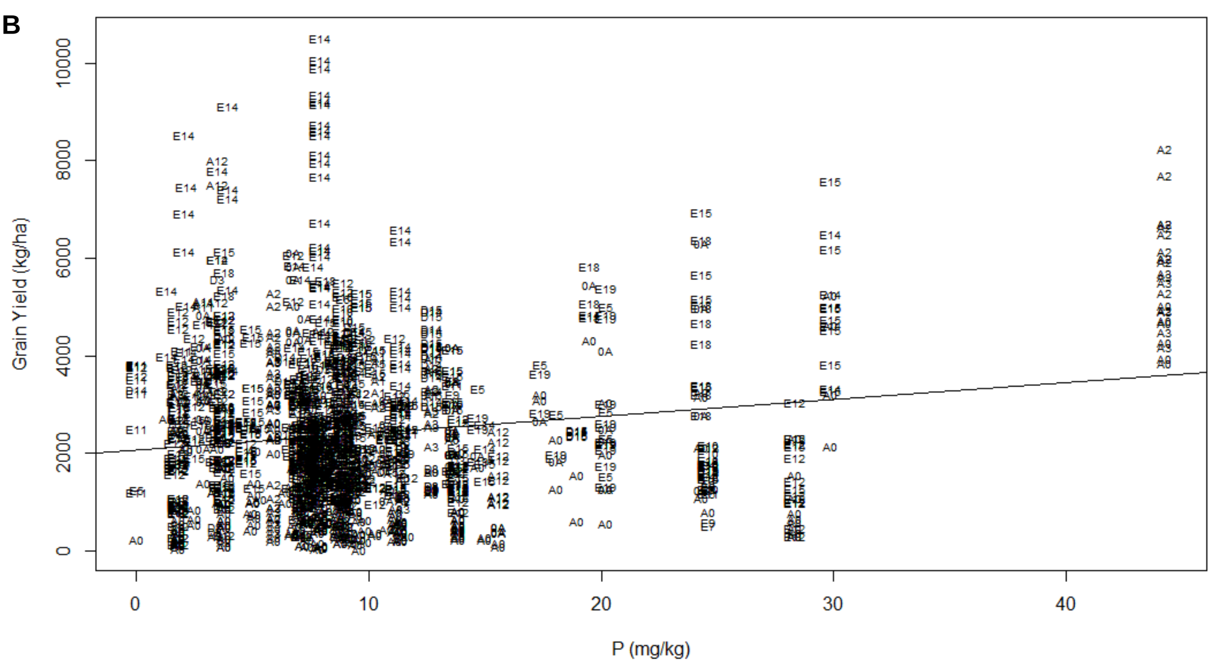
Grain Yield vs OC
[Y = 2568.3 -129.82X , Adj R2 =0.0034494, P =0.0097027]

A



Grain Yield vs P
[Y = 2059 +34.567X , Adj R2 =0.023657, P =4.0233e-10]

B



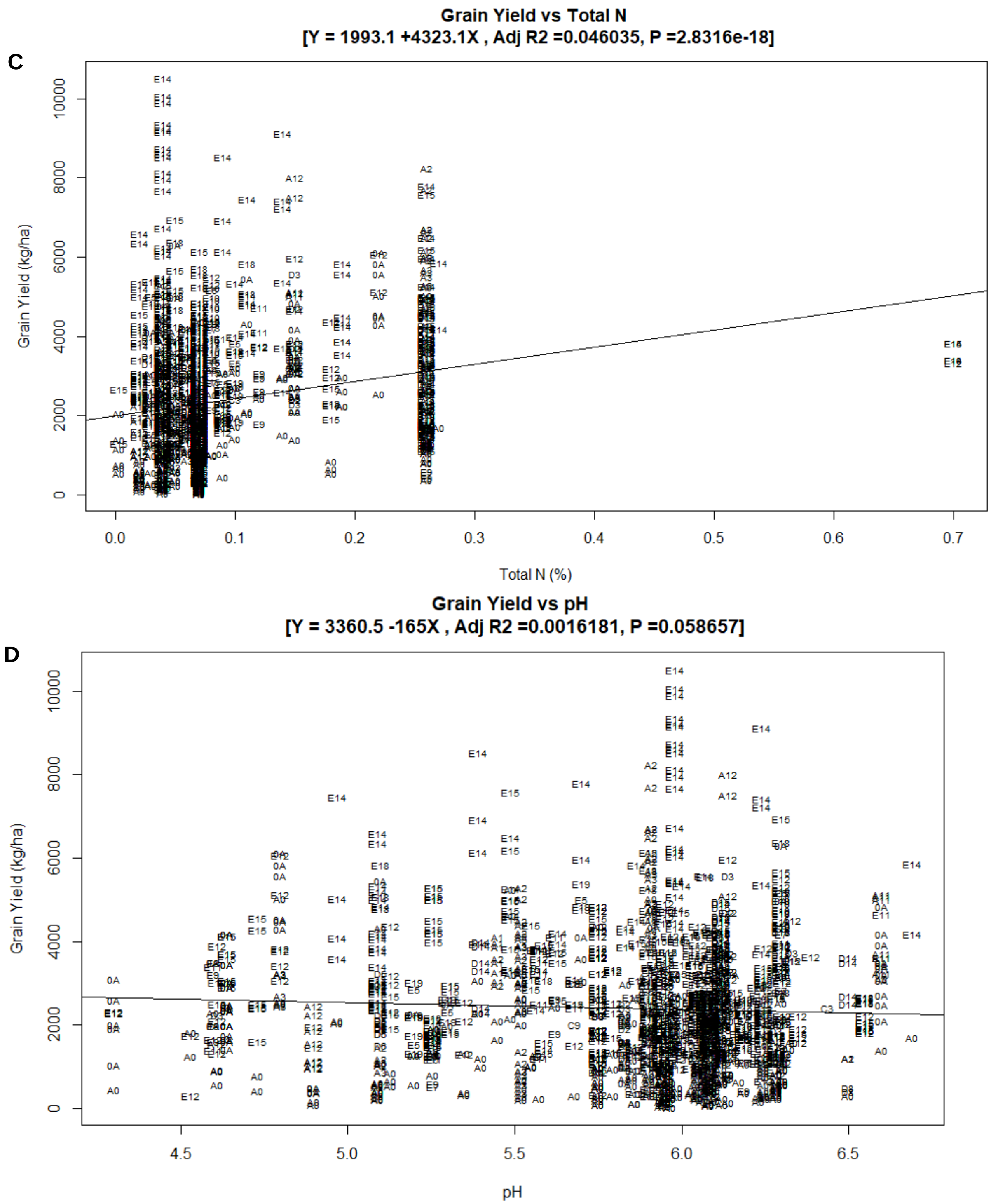


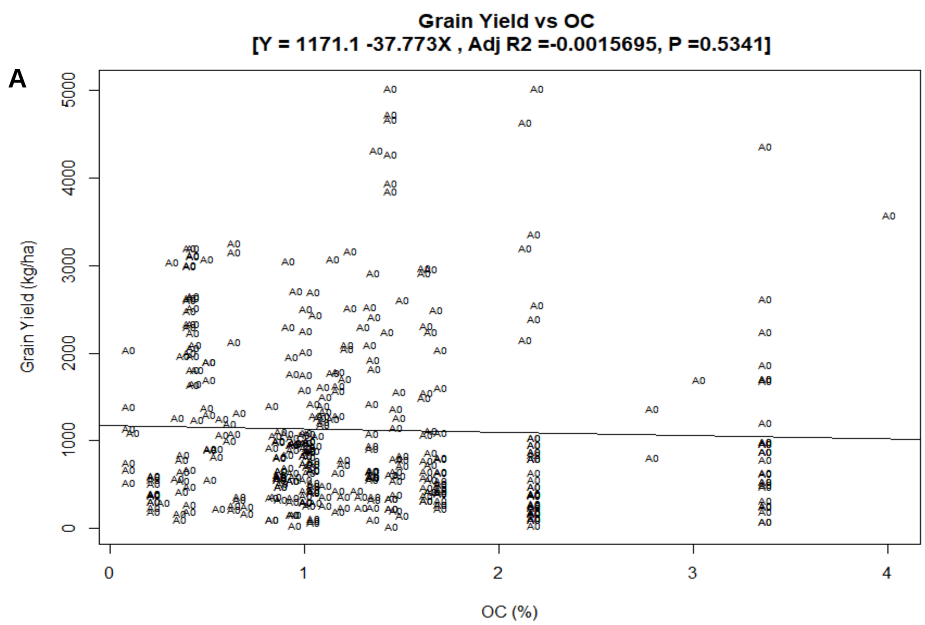
Figure 17. Graphical plots of the regression analysis for the different soil properties (A) soil organic carbon; (B) available phosphorus; (C) total nitrogen; and (D) pH on maize grain yields

In Table 19, the effects of edaphic and climatic factors on control yields only were also investigated in the two AEZs. Results indicate that CEC (Cmol kg^{-1}), proportion of sand, and TAR had a significant effect in GS, whereas soil OC and soil Av. P exhibited a significant effect on grain yield in the SDF zone. Soil factors, especially soil OC and Av. P, were found to explain more of the control yield with R = 0.267 (26.7%) in SDF than in GS with only R = 0.196 (19.6%). Figure 18 shows the general regression graph for control yields.

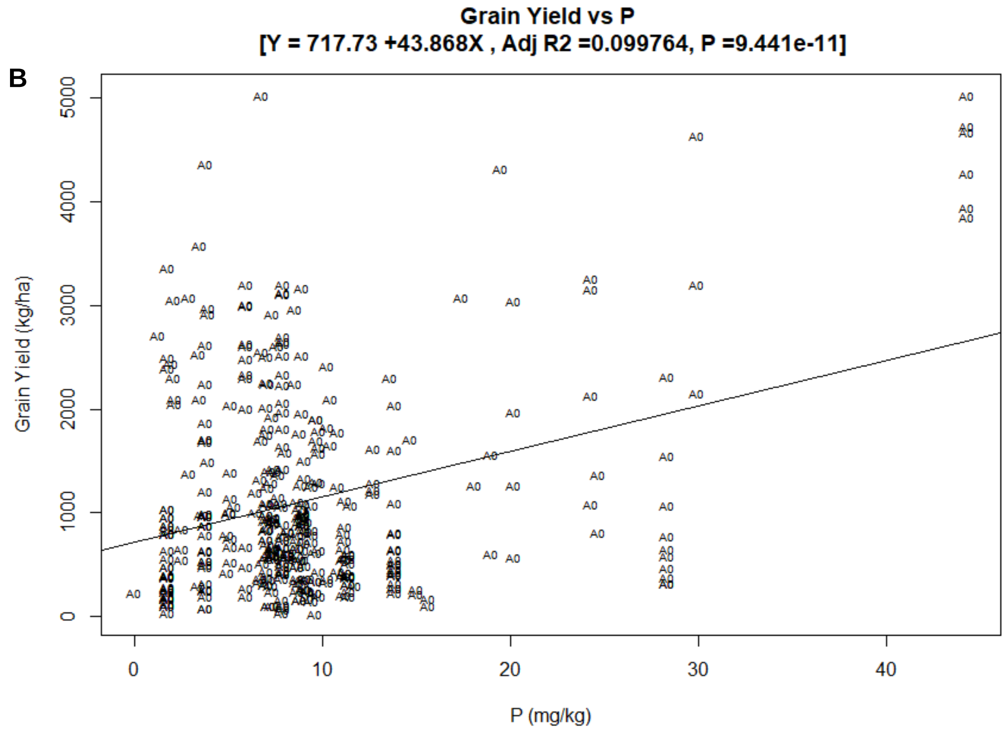
Table 19. OLS regression coefficient of edaphic and climatic factors for only control yields across two agroecological zones (GS and SDF)

	Guinea Savannah		Semi-Deciduous Forest	
Variable	**Estimate**	**St. Err**	**Estimate**	**St. Err**
%OC	-76.2	61.2	701*	315
CEC_cmol_kg_soil	-42.7*	18.4	-2.2	11.4
Clay_%	0.32	10.4	-42.5	38.3
P_mg_kg	-0.67	10.9	48.6**	15.4
Sand_%	34.08**	7.34	25.0	20.0
Silt_%	-2.36	7.67	4.1	26.1
TAR_MM	-0.949**	0.211	0.090	0.621
Total_N_%	2717	10.3	269	2550
pH	-6	113	-100	316.
R-Square	**19.6**		**26.7**	

* = Significant at 5%; ** = Significant at 1%.

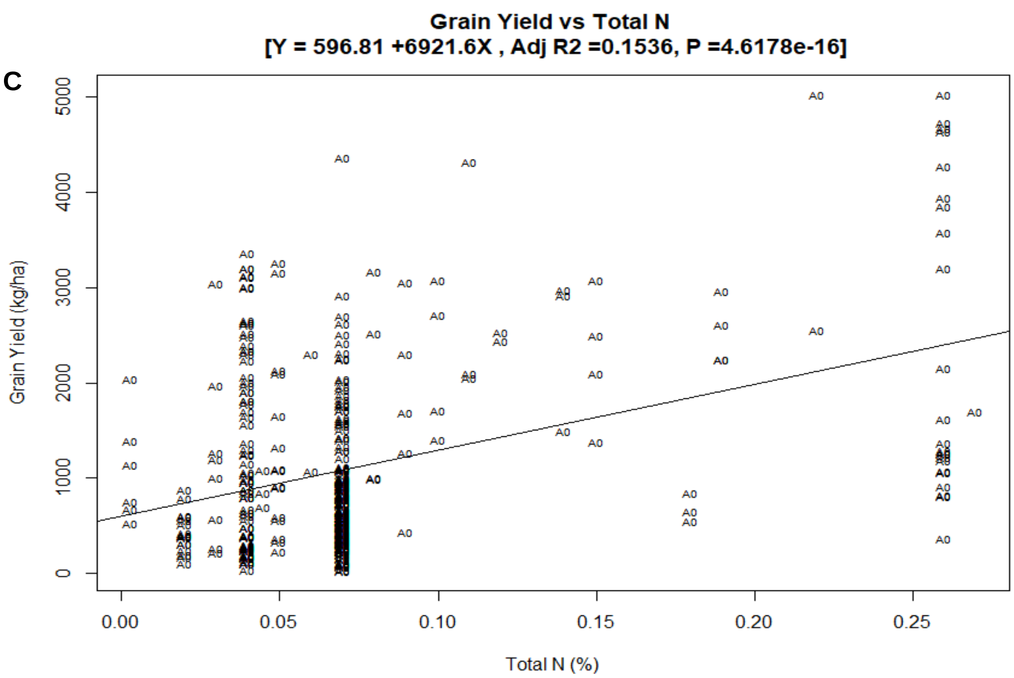


B



Grain Yield vs P
[Y = 717.73 +43.868X , Adj R2 =0.099764, P =9.441e-11]
Grain Yield (kg/ha)
P (mg/kg)

C



Grain Yield vs Total N
[Y = 596.81 +6921.6X , Adj R2 =0.1536, P =4.6178e-16]
Grain Yield (kg/ha)
Total N (%)

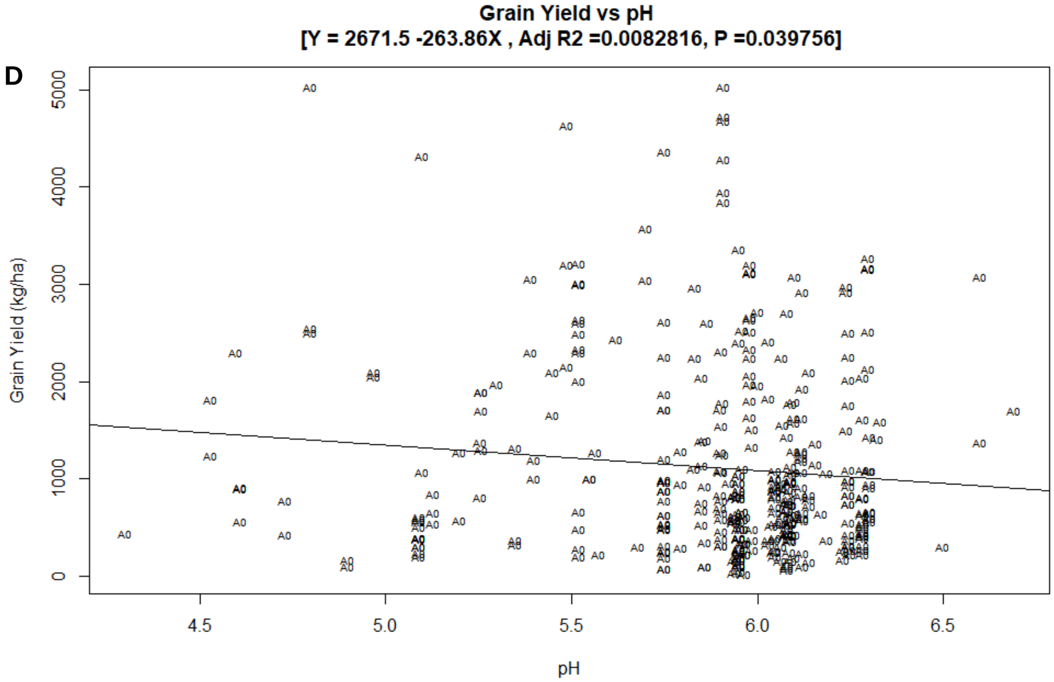


Figure 18. Graphical plots of the regression analysis for the different soil properties (A) soil organic carbon; (B) available phosphorus; (C) total nitrogen; and (D) pH on maize grain yields

4.7 Correlation Analysis

In seeking to understand the relationship between edaphic and climatic variables, a correlation analysis was performed in SAS software package version 9.4. Correlations between control (no fertilizer treatment) yields and edaphic and climatic variables and the correlation between treated yields and edaphic and climatic factors were investigated.

The results of the analysis indicate a significant correlation between grain yields and most of the soil variables. At treated yield level, there was a significant weak positive correlation of soil OC (%), soil TN (%), Av. P, and soil silt proportion R = 0.11, 0.10, 0.12, and 0.07, respectively, while pH weakly negatively related with grain yield R = -0.10 (Table 20).

At the control (no fertilizer treatment) yield (Table 21), evidence existed of a significant weak correlation between grain yields and soil pH, CEC, soil TN, Av. P, sand, and silt. Soil total N and available P had stronger correlation (R = 0.33 [33%] and 0.32 [32%]), respectively, compared to proportion of silt and sand in the soil (R = 0.29 [-29%] and 0.18 [18%]), respectively, and CEC 0.13 (13%). The proportion of silt in the soil correlated negatively with maize grain yield. Soil pH also related negatively and weakly at control yield (R = -0.1 [10%]).

Table 20. Correlation analysis of maize yield with edaphic and climatic variables (control and treated) (n=1684)

	TAR	pH	OC	CEC	N	P	Sand	Clay	Silt	Yield
TAR	1									
pH	0.077*	1								
OC	0.256**	0.424**								
CEC	0.171**	-0.034	-0.106**							
N	0.002	0.042	-0.071*	-0.049						
P	0.032	-0.024	0.049	-0.067*	-0.043					
Sand	-0.248**	-0.355**	-0.549**	-0.149**	-0.200**	-0.225**				
Clay	0.029	0.118**	0.238**	0.005	0.019	0.101**	-0.312**			
Silt	0.088**	-0.069*	0.167**	0.073*	0.289**	0.060	-0.687**	-0.094**		
Yield	0.015	-0.101**	0.111**	0.012	0.103**	0.123**	-0.053	-0.047	0.077*	1

* = Significant at 5%; ** = Significant at 1%.

Table 21. Correlation analysis of maize yield with edaphic and climatic variables (control) (n=1684)

	TAR	pH	OC	CEC	N	P	Sand	Clay	Silt	Yield
TAR										
pH	0.13**									
OC	0.17**	0.08								
CEC	0.06	0.15**	-0.11*							
N	0.42**	0.08	0.06	0.26**						
P	0.02	-0.06	-0.14**	0.36**	0.38**					
Sand	-0.24**	-0.09	-0.40**	0.07	-0.05	0.19**				
Clay	0.10*	0.10*	0.45**	0.01	0.08	-0.05	-0.31**			
Silt	0.18***	0.13**	0.33**	-0.11*	-0.15**	-0.28**	-0.87**	0.03		
Yield	-0.07	-0.10*	-0.08	0.13**	0.33**	0.32**	0.18**	-0.04	-0.29**	

* = Significant at 5%; ** = Significant at 1%.

4.8 Spatial Variation of Maize Grain Yield Responses

4.8.1 Data Used

There were 1,650 spatial data points for maize, which were plotted on the map. About 34 data points were dropped because they did not have coordinates.

4.8.2 Data Transformation (Projection)

Coordinates accessed from various publications and Google Maps were cleaned and processed to convert them to GIS files. The coordinates were then projected from a geographic coordinate system (WGS 1984) to a projected coordinate system (UTM zone 30N), a coordinate system that supports measurements and interpolations.

The distribution was across the Ashanti, Northern, Upper West, Upper East, Eastern, and Savanna regions. Greater north had a higher distribution than the Ashanti and Eastern regions. The northern region alone has the most distributions. Some data gaps between GS and SDF zones exist; to assess, in general, whether the data points were closer to each other in space or dispersed as a preliminary check for any form of interpolation, the average nearest neighbor analysis, which depends on averaging the distance to the closest point for each data point, was performed and resulted in an index less than 1 with a statistically significant probability of 0, indicating that the points were spatially closer to each other. The analysis report with statistical figures is reported in Fig. 19, showing the position of a negative z-score in a clustered zone.

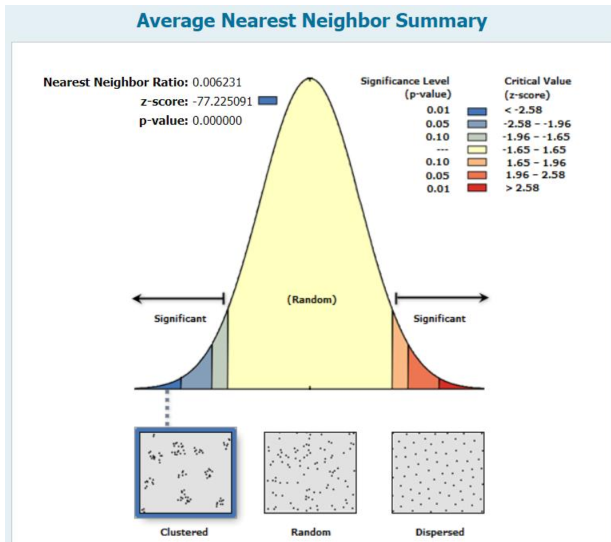


Figure 19. Nearest neighbor summary

The blue-squared box indicates the significance of spatial closeness of points.

To use the existing maize grain yield to predict the yield of unknown locations, it was important to determine and quantify the tendency that near data points have similar grain yields, as opposed to far data points. This was analyzed using Moran's I autocorrelation test, which quantifies an ideal clustering of similar values as 1. Having processed using the grain yield variable, the Moran index was reported to be 0.32 with a statistically significant probability of 0, which indicates that there was some level of near data points bearing similar values in the dataset. However, the Moran index not being more than 0.5 could be a result of some spatial gaps that existed in the dataset. The autocorrelation analysis report with statistical figures is as reported in Fig. 20, showing the position of a positive z-score in a clustered zone, signifying that interpolation of the grain yield values would be possible.

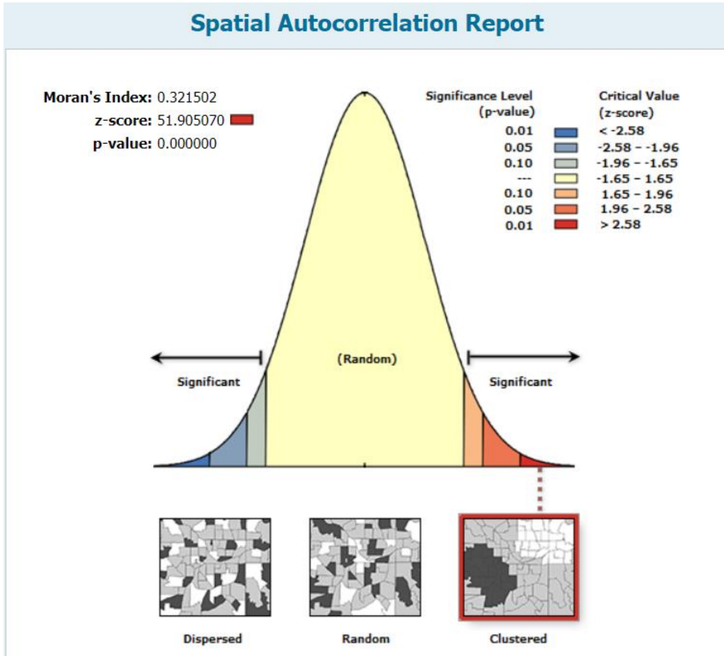


Figure 20. Spatial autocorrelation report

The red-squared box indicates the clustering significance.

4.8.3 Selection of Interpolation Technique

To predict the grain yields for all the unknown locations over the entire study area, the spatial structure in the data points as a function of the grain yield was analyzed using a semivariogram, and it was found that, though the data exhibited a clustered spatial distribution according to the Moran I analysis, there was a minimal spatial structure having a range of 0.0014 and a sill of 1005 but a nugget effect of 0, which tends to explain the level of errors in measurement. However, because there are secondary data points from various sources, the nugget effect of zero might be misleading (Fig. 21).

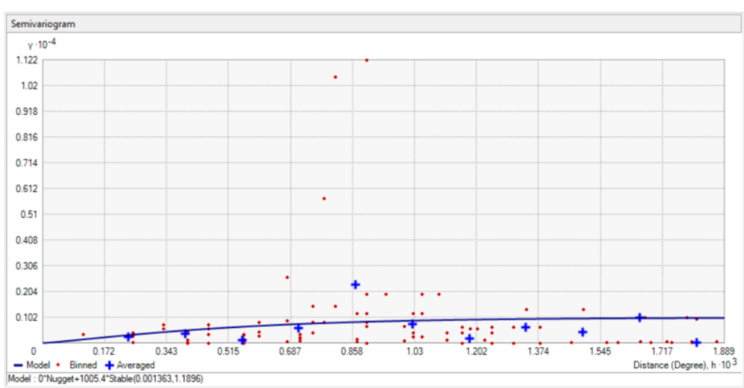


Figure 21. Semivariogram of the sample points

Given the preliminary analysis performed on the dataset, as shown above, it can be concluded that a deterministic interpolation technique would produce better results than a stochastic technique given the results of the variogram above. The Inverse Distance Weight (IDW) interpolation technique was then selected as the estimator for the unknown values over the study area.

The maps shown in Fig. 22 describe the grain yields at zero treatment and all treatments (control and different N, P_2O_5, K_2O, and S fertilization rates). This was processed in an R analysis environment using IDW (a function on the gstat package) on the raw data covered by Guinea Savannah, Sudan Savannah, Transition Savannah, and Semi-Deciduous Forest, with a higher concentration of points in the greater northern part. The inverse distance that served as the weight of the individual data points was raised to the second power to account for the level of influence of near points to the unknown location over points that are far away.

4.8.4 Control Yield Map

In Fig. 22, which is the spatial distribution of control yields in Ghana, it can be observed that, in the greater northern part, yields in most locations fall within the low value with an average of about 0.75 t ha^{-1}. Within the central region, yields tend to move upward near average yield values. Whereas in the southern part, most yield values are at an average of about 2 t ha^{-1}. This is an indication that maize grain yields are higher in the southern than in the northern part, with the central region having near average yield values. The highest yield value of about 4.5 t ha^{-1} was achieved in the southern part of Ghana even with no fertilizer application, meaning that fertile soils coupled with very good agronomic management can give desired yields.

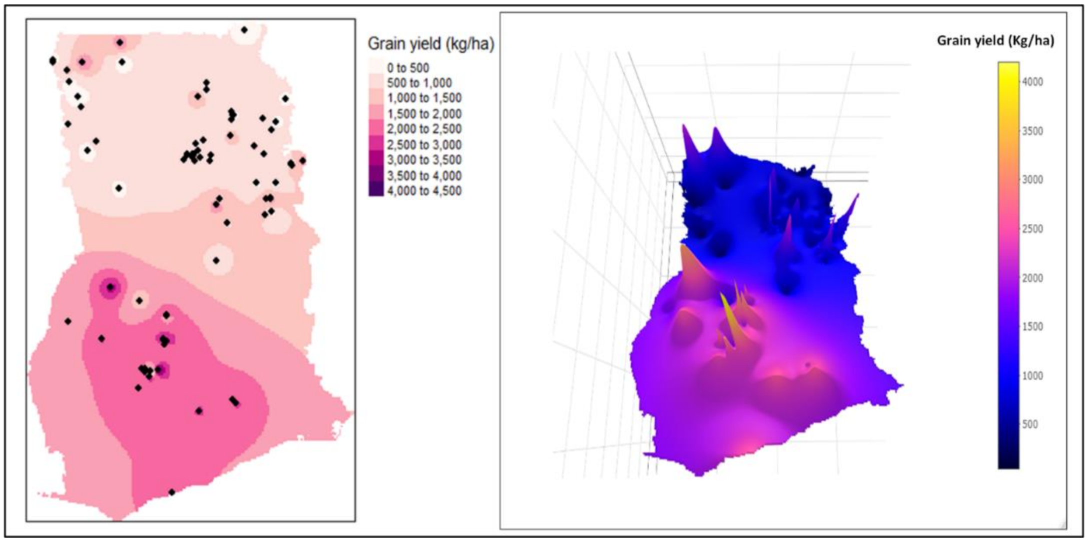


Figure 22. Map of Ghana showing the spatial distribution of control yields (2-D representation on the left and 3-D representation on the right)

4.8.5 Control and Treated Yield Map

In Fig. 23, which is the spatial distribution of treated yields in Ghana, locations in the extreme northwestern and eastern regions, show a slight change in maize grain yield compared to the control. Generally, in the north, maize grain yield increased to an average of about 2.7 t ha^{-1}, with maize grain yields in some locations reaching as high as 7 t ha^{-1}. In the southern part, the average yield response climbed up to about 3.5 t ha^{-1}, up from about 2 t ha^{-1}. Spatial variability is observed in yield responses, with some location showing very high, high, and low response to fertilizers.

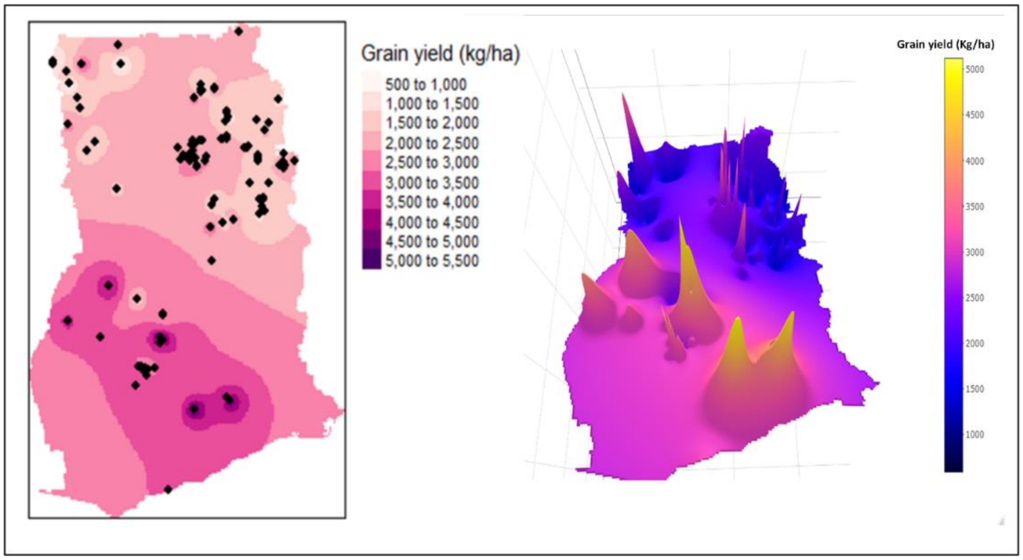


Figure 23. Map of Ghana showing the spatial distribution of both control and treated yields (2-D representation on the left and 3-D representation on the right)

CHAPTER 5: DISCUSSIONS AND CONCLUSION

5.1 Discussions

5.1.1 Yield Responses

In exploring the yield responses of maize to fertilizer application in Ghana, a total of 32 peer-reviewed publications were used. The experiments were conducted in the Ashanti, Eastern, Northern, Upper West, Upper East, and North East regions of Ghana.

The results show that yield ranges from as low as 0.14 to 10 t ha^{-1}. The maximum control grain yield attained was about 4.5 t ha^{-1}, i.e., yield at zero fertilizer application, while the maximum grain yield achieved was about 10 t ha^{-1} under fertilizer application. Grain yields varied across the agroecological regions of Ghana, with some locations showing responses of up to or above 7 t ha^{-1}, while other regions showed negligible grain yield responses, mainly in the Guinea Savannah AEZ. Yields in the Semi-Deciduous Forest zone are higher at 5.3 t ha^{-1}, compared to 4.0 t ha^{-1} in Guinea Savannah, averaged for the best treatment combinations.

In assessing the nutrient rates with the desired yield responses, in GS, a medium level of N (N_M, 60-90 kg N ha^{-1}) applied with a medium level of P (P_M, 46-89 kg P_2O_5 ha^{-1}) and K (K_M, 46-89 kg K_2O ha^{-1}) had high and significant yield response, an average of about 7 t ha^{-1} in some locations. In SDF, on the other hand, medium to slightly high N (N_H, 60 to >90 kg N ha^{-1}) applied with medium P (P_M, 46-89 kg P_2O_5 ha^{-1}) and medium K (K_M, 46-89 kg K_2O ha^{-1}) gave significantly high grain yields, ranging from 6.0 t ha^{-1} to 7.7 t ha^{-1}. But generally, across the two AEZs, N rates in the medium level (60-90 kg ha^{-1}) applied with a medium level of P and K gave better yield responses. This finding tends to agree with that of Dicko et al. (2018), who in their study of the response of rice, maize, and millet to fertilizers in Mali found that the best maize yield was achieved when 90 kg N ha^{-1} in combination with 30 or 40 kg P was applied although K had a very limited effect on the yield. Serme et al. (2018), while investigating the response of maize to fertilizers in ferrosol and luvisol of the South Sudan zone of Burkina Faso, also found that application of 90N-15P-30K and 90N-15P-20K-15S-10Mg-2.5Zn-0.5B produced the highest grain and stover yield in luvisol and ferrosol, respectively (Oueddraogo et al., 2018), while using a DSSAT model with experimentation to update fertilizer recommendation rates in Burkina Faso showed that 80N-30P-40K represents the best combination for intensive maize production. In yet another study, Tetteh et al. (2018), in their work to review and update fertilizer recommendation for maize and cassava in Ghana, found that maximum maize yield obtained across SDF, GS, and TS zones varied from 2 t ha^{-1} to 9 t ha^{-1}, with an optimum application rate of 90 kg N ha^{-1} when 60 kg P_2O_5 and 70 kg K_2O ha^{-1} were applied as basal. They indicated that in some districts yield continued to increase with up to about 135 kg N ha^{-1} but after which there was no further increase with additional units of N.

There was a tendency for higher yield responses when S was applied in combination with NPK as NPKS. The S in NPK came from AS as an additional source of N added at topdressing. Whereas increasing the N rate was intended with this application, the S contained in the AS may have been relevant in achieving higher yield responses. There was, therefore, intended rate for S application, resulting in application amounts varying from 8 to 154 kg S ha^{-1}. S is one of the essential nutrients for plant growth and, as one of the secondary elements, plays specific functions in plant growth, metabolism, and enzymatic reactions (Khan et al., 2006). Its importance in cereal production is gaining growing interest.

Many studies on maize response have shown an increasingly higher response to S fertilization in similar environments in Western African countries. Kang and Osiname (1976), for instance, reported a yield of 6.7 t ha^{-1} when 30 kg S ha^{-1} was added, compared to 5.9 t ha^{-1} without S, and Friesen (1991) achieved up to 3.9 t ha^{-1} with 5-10 kg S ha^{-1} compared to 3.2 t ha^{-1} without S. Yield gains from S have also been reported in India. Khan et al. (2006) reported a yield response of about 7.5 t ha^{-1} at 60 kg S ha^{-1} and 5.0 t ha^{-1} without S. Rasheed et al. (2004) obtained a yield of about 8.6 t ha^{-1} when 30 kg S ha^{-1} was applied, compared to 3.8 t ha^{-1} without S. In Ghana, S applied at a rate of between 10 kg ha^{-1}to 68 kg ha^{-1} was also found to increase yields in rice from 1.2 t ha^{-1} to 2.6 t ha^{-1}, an average of three years (Tsujimoto et al., 2017).

In this study, the highest yield response of about 9 t ha^{-1} was achieved in GS and 7.9 t ha^{-1} in the SDF zone with treatment combinations NP_MKS and NPK_MS, respectively, and rates of S applied varied from 8 to 154 kg S ha^{-1}, of course depending on the AS fertilizer that was applied to obtain a specific rate of N fertilizer. On average, yield gains of 1.5 t ha^{-1}, 0.9, t ha^{-1}, and 0.4 t ha^{-1} from S application were found for SS, GS, and SDF.

It would be important to specifically investigate critical levels of S for maize and other cereal crops to ascertain S rates. Just like N, it would also be interesting to investigate whether a split application of S could have implications for yield. Limited data exists on maize yield response to micronutrients (Zn, Mn, B, Fe), which did not allow further analysis. It is suggested to specifically investigate the impact of these micronutrients and their interactive effects on yield responses and grain concentrations of micronutrients.

5.1.2 Responses to Organic and a Combination of Organic and Inorganic Fertilizer

There were significant yield responses to organic fertilizer application in both GS and SDF zones. The average grain yield attained was 2.2 t ha^{-1} and 6.2 t ha^{-1} in GS and SDF zones, respectively, when rates ranging between 1.5 t ha^{-1} and 20 t ha^{-1} of organic fertilizer were applied. Different sources of organic materials, including cattle manure, chicken manure, household waste, and plant materials, were applied. In a similar treatment in three districts in central Kenya, Kimani et al. (2007) found significant yield differences in control and treatment with compost and manure. They obtained the highest maize grain yield of 4.7, 4.5, and 3.0 t ha^{-1} at rates of 5 t ha^{-1} and 10 t ha^{-1} of *tithonia*, manure, and compost, respectively. Chivenge et al. (2011) also found that the sole addition of organic fertilizers resulted in 60% greater maize yields than the no input control. In yet another study in Argentina, Ferras et al. (2006) found significant yield differences in control and all plots amended with 20 t ha^{-1} and 10 t ha^{-1} of chicken and horse/rabbit manure, an average yield of 19.3 t ha^{-1} and 13 t ha^{-1} at rates of 20 t ha^{-1} and 10 t ha^{-1}, respectively. They also found that organic amendment at the rate of 20 t ha^{-1} improved soil structure, soil organic carbon, and microbial activity (Ferras et al. 2006). Soil organic carbon mineralized by micro-organisms releases nutrients required by the crops. Zhao et al. (2016) found a significant positive relationship between soil organic matter and soil available N, P, and K, meaning that soil organic matter supplies soil nutrients through mineralization. Therefore, responses to the organic amendment are a result of improved soil physical and chemical conditions. In this study, a higher grain yield of 6.2 t ha^{-1} in SDF was attained with organic fertilizer alone. This could not be easily explained, though it could be attributed to the quality of organic amendment.

There were moderate to high grain yield responses to organic fertilizer in combination with inorganics in both GS and SDF zones. The average yield ranged from 2.5 t ha^{-1} to 4.8 t ha^{-1} in GS and 2.9 t ha^{-1} to 6.1 t ha^{-1} in SDF. In this study, the interactive effect of specific organic amendment applied with mineral fertilizers was not investigated to allow a conclusion on which organic amendment gives the best grain yield or what rate is appropriate. Consequently, this paper will not discuss further the interactive effects of organic amendments.

5.1.3 Factors Explaining Yield Responses

In exploring factors explaining yield responses, the following parameters were used: soil pH, OC (%), TN (%),Av. P (mg kg^{-1}), CEC (Cmol kg^{-1}), the proportion of clay, silt, and sand in the soil, TAR (mm), and fertilization rate. The effects on grain yield were investigated in both the control (no fertilizer treatment) and when the control grain yield was in combination with treated. In the combined grain yield, effects of soil parameters and TAR were investigated separately and in combination with fertilization rates.

Results showed that soil parameters and TAR had low R^2 values of $R^2 = 0.15$ and $R^2 = 0.10$ in GS and SDF zones, respectively, implying that they explain only 15% and 10% of the yield variations. With the addition of fertilization rates (N, P_2O_5, K_2O, and S), the percentage of grain yield variation explained increased from 15% to 44.8% in GS and 10% to 31.8% in SDF. In a similar finding in Ethiopia, Elias et al. (2018) reported that interaction between the fertilizers and the soil properties together explained 79% of the wheat grain yield variation. At the control grain yield, soil parameters and TAR had values of $R^2 = 0.196$ and $R^2 = 0.267$, implying that they explain 19.6% and 26.7% of the variations in control grain yield in GS and SDF, respectively. Similarly, Beza et al. (2017), in their review of yield-explaining factors, showed that soil factors only explain about 20% of the yield variations. The finding indicates that soil factors (pH, % OC, % TN, Av. P, CEC, % sand, % silt, and % clay) and fertilization in isolation only explain part of yield variations or responses. This agrees with the conclusion of Adeoye and Agboola (1985) that soil nutrients alone are not the only limiting factors to maize yield. Salient factors, such as timeliness in farm operation (timely land preparation, planting, fertilizer application, pest control, and harvesting), plant population, level of tillage, and crop varieties, are as well very important in explaining yield. Because of the data gap, management factors outlined above were not further explored in this study. However, Tittonell (2007) found that between 40% and 60% of the variation in maize yield was explained by multiple regression models that considered only management factors, such as planting date, plant density, resource use, and weed infestation. According to Beza et al. (2017), the timely application of fertilizer is also an important parameter in explaining yield variation rather than the quantity of fertilizer applied.

Although edaphic factors did not explain much of the yield response, there was a significant correlation between them and treated and control grain yield. These were, however, weak correlations indicated by low R^2 values: soil OC (%) (R^2 = 0.11, P<0.01), soil TN (%) (R^2 = 0.103, P<0.01), Av. P (mg kg^{-1} soil, R^2= 0.123, P<0.01), soil silt proportion (%) (R^2 = -0.077, P<0.05), and pH (R^2 = -0.101, P<0.01). At control (no fertilizer treatment) grain yield, R^2 values for TN (%) and Av. P (mg kg^{-1}) were higher compared to the control and treated combined (R^2 = 0.33 and 0.32, P<0.01), respectively. At combined grain yield, there could have been the confounding effect of added nutrients (Zhao et al., 2016). In exploring soil properties, yield, and landscape relationships in South-Central Saskatchewan Canada, Noorbakhsh et al. (2008) found a correlation between soil pH, OC, P, N, and K with R^2 values (pH R^2 = -0.46, OC R^2 = 0.27, K, N, and P R^2 = 0.18). The Li et al. (2001) study of cotton lint yield variability in heterogeneous soil in the USA also found a correlation between lint yield and soil N (R^2 = 0.35). This implies that grain yields increase with increasing levels of soil OC, TN (%), Av. P (mg kg^{-1}), CEC (Cmol kg^{-1} soil), and soil silt proportion. This finding is in unison with Tittonell (2007), who found that maize grain yields tended to increase with increasing contents of soil OC, TN, extractable P, and exchangeable bases. There was an inverse correlation with pH, meaning that an increase in levels of pH negatively affect yield. Findings in this study indicate that a pH in the range between 5.5 and 6.5 was associated with high grain yield. The pH is likely a factor in functions such as organic matter decomposition and nutrient availability that control yield (Noorbakhsh et al., 2008). As a result, it is viable to implement agricultural management practices that improve soil physical and chemical properties across all the AEZs of Ghana but particularly in the low-yield regions.

A plot of control (no fertilizer treatment) grain yield against % OC, % TN, Av. P (mg kg^{-1}), and soil pH demonstrate the relationship between these and grain yields. Grain yield increased with an increase in the levels of % OC, % TN, Av. P, and pH. However, it is worth noting that grain yield also tended to vary from low to high irrespective of the levels of % OC, % TN, Av. P, and pH. This is an indication that the soil parameters are the index of soil nutrient levels, though they cannot be solemnly relied upon while designing fertilizer recommendations. Management factors, such as the timing of activities (planting, fertilizer application, weeding, pest control), plant population, land preparation, weather, and crop varieties, need to be considered while coming up with fertilizer recommendations. Although data used in this study came from controlled experiments, there were variations in seasons, rainfall, varieties of crops used, and crop management practices. These variations were because of the data gap and were not investigated in this study.

5.1.4 Spatial Map Representation of Yield Responses

The spatial map of yield responses also enabled clear visualization of yield variability; yields are generally lower in the northern region than the southern part. According to Bationo et al. (2018), maize grain yield in GS of Ghana rarely exceeds 1 t ha^{-1} in farmers' fields. They also remarked that the observed low maize grain yields in the farmers' fields, despite the application of NPK compound fertilizer, indicate possible deficiencies of other nutrients. The highly weathered and sandy-textured nature of the GS zone tends to be limiting in micronutrients, hence calling for balanced fertilization (Bationo et al., 2018). The finding further stimulates interest in the determination of variability in the soil properties both within and between the AEZs to understand their relationship with maize grain yields. The spatial mapping technic will be vital in understanding maize response to soil type, weather conditions, management, and identifying suitable nutrient formulations.

5.2 Conclusion

A total of 1,700 data points from legacy and peer-reviewed publications were used in exploring the yield responses of maize to fertilizer application in Ghana. The experiments were implemented in the Ashanti, Eastern, Northern, Upper West, Upper East, and North East regions of Ghana.

The results show that grain yield responses to fertilization are highly variable across the agroecological regions of Ghana. Some locations showed significant grain yield responses, while other areas in the GS AEZ had small grain yield responses. Yields in the SDF zone are higher than in GS. Based on this result, medium to slightly high N rates (60-130 kg ha^{-1}) applied in combination with medium rates of P and K (45-90 kg ha^{-1}) with S would be the desired rates for better yield responses. These rates would vary from location to location within the AEZs depending on the level of fertility, crop variety, and other agronomic management practices. Also, researchers should undertake studies to determine the critical levels of S in the soils and source, rate, time, and placement of S fertilizers.

Edaphic and climatic variables and fertilization rates in isolation do not explain much of the yield variations, and knowing soil parameters does not guarantee designing appropriate fertilizer recommendations. Salient factors, such as timeliness in land preparation, planting, fertilizer application, pest control, and harvesting, as well as plant population, level of tillage, and crop varieties, are critical in the generation of the appropriate fertilizer recommendations to obtain desirable yield responses.

Although edaphic factors did not explain much of the yield responses, there was a significant relationship between these (soil OC (%), soil TN (%), Av. P, soil silt proportion, and pH) and grain yield. Practices that maintain, improve, and increase organic matter levels should be promoted across all the AEZs to enhance soil physical and chemical conditions.

The spatial map of yield responses also enabled clear visualization of yield variability across the AEZs of Ghana. This technique should further be used in studying the spatial-temporal yield responses, maize varietal soil suitability, yield responses under varying weather conditions, and yield responses under different crop management practices. Given the spatial-temporal dynamics of nutrients in the soil and the corresponding variations in yield responses to fertilizer applications, studies should focus on developing a spatial-temporal tool for nutrient management.

REFERENCES

Abunyewa, A. A., & Mercie-Quarshie, H. (2004). Response to maize to magnesium and zinc application in the semi-arid zone of West Africa.

Abunyewa, A. A., Osei, C., Safo, E. K., & Asiedu, E. Y. (2007). Integrated manure and fertilizers use, maize productivity in the sub-humid region west Africa. In *Journal of Agronomy* (Vol. 6, Issue 2, pp. 392–309).

Adeoye, G. O., & Agboola, A. A. (1985). Critical levels for the soil pH, available P, K, Zn, and Mn and maize ear-leaf content of P, Cu, and Mn in sedimentary soils of South-Western Nigeria.

Adjei-Nsiah, S. (2012). Responses of maize (*Zea mays L.*) to different rates of palm bunch ash application in the semi-deciduous forest agro-ecological zone of Ghana. *Applied and Environmental Soil Science*, *2012*. https://doi.org/10.1155/2012/870948

Adu, G. B., Alidu, H., Amegbor, I. K., Abdulai, M. S., Nutsugah, S. K., Obeng-Antwi, K., Kanton, R. A. L., Buah, S. S., Kombiok, M. J., Abudulai, M., & Etwire, P. M. (2018). Performance of maize populations under different nitrogen rates in northern Ghana. *Annals of Agricultural Sciences*, *63*(2), 145–152. https://doi.org/10.1016/j.aoas.2018.10.001

Adu, G.B., Abdulai, M.S., Alidu., H., Nustugah, S.K., Buah. S. S., Kombiok, J. M., Obeng-Antwi, K., Abudulai, M. Etwire, P. M. (2014). Recommended production practices for maize in Ghana. *Growing Africa's Agriculture*, *2*(October 2014), 1–19. https://doi.org/10.13140/2.1.4376.3527

Aflakpui, G. K. S., Anchirinah, V. M., & Asumadu, H. (2005). The response of a quality protein maize hybrid to N supply and plant density in the forest zone of Ghana. *Tropical Science*, *45*(1), 3–7. https://doi.org/10.1002/ts.36

Atakora, W. K., Fosu, M., Safo, E. Y., Tuffour, H. O., & Tetteh, F. M. (2014). Response of maize growth and development to mineral fertilizer and soil characteristics in Northern Ghana. International *Journal of Advance Agricultural Research*, *2*(2014), 67–76.

Atakora, W. K., Fosu, M., Abebrese, S. O., Asante, M., & Wissuwa, M. (2015). Evaluation of low Phosphorus tolerance of rice varieties in Northern Ghana. *Sustainable Agriculture Research*, *4*(4), 109. https://doi.org/10.5539/sar.v4n4p109

Badu-Apraku, B., & Fakorede, M. A. B. (2017). Advances in genetic enhancement of early and extra-early maize for sub-Saharan Africa. *Advances in Genetic Enhancement of Early and Extra-Early Maize for Sub-Saharan Africa*, 1–604. https://doi.org/10.1007/978-3-319-64852-1

Badu, E., Kaba, J. S., Abunyewa, A. A., Dawoe, E. K., Agbenyega, O., & Barnes, R. V. (2019). Biochar and inorganic nitrogen fertilizer effects on maize (Zea mays L.) nitrogen use and yield in the moist Semi-Deciduous Forest zone of Ghana. *Journal of Plant Nutrition*, *42*(19), 2407–2422. https://doi.org/10.1080/01904167.2019.1659347

Bationo, A., Fening, J. O., & Kwaw, A. (2018). Assessment of soil fertility status and integrated soil fertility management in Ghana. In *Improving the Profitability, Sustainability, and Efficiency of Nutrients Through Site-Specific Fertilizer Recommendations in West Africa Agro-Ecosystems* (pp. 93-138). Springer, Cham.

Bayite-Kasule, S. (2009). Inorganic fertilizer in Uganda: Knowledge gaps, profitability, subsidy, and implications of national policy. International Food Policy Research Institute (IFPRI).

Bekunda, M. A., Nkonya, E., Mugendi, D., & Msaky, J. J. (2002). Soil fertility status, management, and research in East Africa. *East African Journal of Rural Development*, *20*(1), 94–112. https://doi.org/10.4314/eajrd.v20i1.28362

Beza, E., Silva, J. V., Kooistra, L., & Reidsma, P. (2017). Review of yield gap explaining factors and opportunities for alternative data collection approaches. *European Journal of Agronomy*, *82*, 206–222. https://doi.org/10.1016/j.eja.2016.06.016

Bindraban, P. S., Dimkpa, C., Nagarajan, L., Roy, A., & Rabbinge, R. (2015). Revisiting fertilizers and fertilization strategies for improved nutrient uptake by plants. *Biology and Fertility of Soils*, *51*(8), 897–911. https://doi.org/10.1007/s00374-015-1039-7

Bindraban, P. S., Dimkpa, C. O., Angle, S., & Rabbinge, R. (2018). Unlocking the multiple public good services from balanced fertilizers. *Food Security*, *10*(2), 273–285. https://doi.org/10.1007/s12571-018-0769-4

Boateng, S., Zickermann, J., & Kornahrens, M. (2009). Poultry manure effect on growth and yield of maize. *West African Journal of Applied Ecology*, *9*(1), 1–11. https://doi.org/10.4314/wajae.v9i1.45682

Buah, S. S.J., Abatania, L. N., & Aflakpui, G. K. S. (2010). Quality protein maize response to nitrogen rate and plant density in the Guinea savanna zone of Ghana. *West African Journal of Applied Ecology*, *16*, 9–21. https://doi.org/10.4314/wajae.v16i1.55865

Buah, S. S. J., Ibrahim, H., Derigubah, M., Kuzie, M., Segtaa, J. V., Bayala, J., Zougmore, R., & Ouedraogo, M. (2017). Tillage and fertilizer effect on maize and soybean yields in the Guinea Savanna zone of Ghana. *Agriculture and Food Security*, *6*(1), 1–11. https://doi.org/10.1186/s40066-017-0094-8

Buresh, R. J., Sanchez, P. A., Calhoun, F., Sanchez, P. A., Shepherd, K. D., Soule, M. J., Place, F. M., Buresh, R. J., Izac, A.-M. N., Mokwunye, A. U., Kwesiga, F. R., Ndiritu, C. G., & Woomer, P. L. (1997). Soil fertility replenishment in Africa: An investment in natural resource capital. *51*, 1–46. https://doi.org/10.2136/sssaspecpub51.c1

Chivenge, P., Vanlauwe, B., & Six, J. (2011). Does the combined application of organic and mineral nutrient sources influence maize productivity? a meta-analysis. *Plant and Soil*, *342*(1–2), 1–30. https://doi.org/10.1007/s11104-010-0626-5

Council of Scientific and Industrial Research (CSIR) (2020)

Dapaah, H., Ennin, S., & Asafu-Agyei, J. (2009). Combining inorganic fertilizer with poultry manure for sustainable production of quality protein maize in Ghana. *Ghana Journal of Agricultural Science*, *41*(1), 49–57. https://doi.org/10.4314/gjas.v41i1.46144

Dicko, M. K., Traoré, L., Kouyaté, Z., Koné, M., Sidibé, B., Kamissoko, N., ... & Diakité, C. H. (2018). The response of rice, maize, and millet to Fertilizers in Mali. In *Improving the Profitability, Sustainability, and Efficiency of Nutrients Through Site-Specific Fertilizer Recommendations in West Africa Agro-Ecosystems* (pp. 139-155). Springer, Cham.

Dimkpa, C. O., & Bindraban, P. S. (2016). Fortification of micronutrients for efficient agronomic production: a review. *Agronomy for Sustainable Development*, *36*(1), 1–26. https://doi.org/10.1007/s13593-015-0346-6

Dimkpa, C. O., Bindraban, P. S., Fugice, J., Agyin-Birikorang, S., Singh, U., & Hellums, D. (2017). Composite micronutrient nanoparticles and salts decrease drought stress in soybean. *Agronomy for Sustainable Development*, *37*(1), 1–13. https://doi.org/10.1007/s13593-016-0412-8

Dimkpa, C. O., Singh, U., Bindraban, P. S., Elmer, W. H., Gardea-Torresdey, J. L., & White, J. C. (2019). Zinc oxide nanoparticles alleviate drought-induced alterations in sorghum performance, nutrient acquisition, and grain fortification. *Science of the Total Environment*, *688*, 926–934. https://doi.org/10.1016/j.scitotenv.2019.06.392

Ebanyat, P., de Ridder, N., de Jager, A., Delve, R. J., Bekunda, M. A., & Giller, K. E. (2010). Drivers of land-use change and household determinants of sustainability in smallholder farming systems of Eastern Uganda. *Population and Environment*, *31*(6), 474–506. https://doi.org/10.1007/s11111-010-0104-2

Elias, E., Okoth, P. F., & Smaling, E. M. A. (2018). Geoderma Explaining bread wheat (Triticum aestivum) yield differences by soil properties and fertilizer rates in the highlands of Ethiopia. *Geoderma*, *December*, 0–1. https://doi.org/10.1016/j.geoderma.2018.12.020

Essilfie, M., Dapaah, H., Darkwa, K., Timpabi, D., & Boateng, D. (2017). Varietal Response of maize (*Zea mays*) to integrated nutrient management of NPK and chicken manure amendments. *Journal of Experimental Agriculture International*, *18*(1), 1–13. https://doi.org/10.9734/jeai/2017/36722

Fening, J. O., Yeboah, E., Adjei-Gyapong, T., & Gaizie, E. (2009). On-farm evaluation of the contribution of three green manures to maize yield in the Semi Deciduous Forest zone of Ghana. *African Journal of Environmental Science and Technology*, *3*(9), 234–238. https://doi.org/10.5897/AJEST09.074

Fermont, A. M., Tittonell, P. A., Baguma, Y., Ntawuruhunga, P., & Giller, K. E. (2010). Towards understanding factors that govern fertilizer response in cassava: Lessons from East Africa. *Nutrient Cycling in Agroecosystems*, *86*(1), 133–151. https://doi.org/10.1007/s10705-009-9278-3

Ferreras, L., Gómez, E., Toresani, S., Firpo, I., & Rotondo, R. (2006). Effect of organic amendments on some physical, chemical, and biological properties in a horticultural soil. *Bioresource Technology*, *97*(4), 635-640

Food and Agriculture Organization of the United Nations. (2004). Improving soil fertility in Africa. 189–198. https://doi.org/10.11606/issn.2176-7262.v37i3/4p189-198

Fosu-Mensah, B. Y., MacCarthy, D. S., Vlek, P. L. G., & Safo, E. Y. (2012). Simulating the impact of seasonal climatic variation on the response of maize (Zea mays L.) to inorganic fertilizer in sub-humid Ghana. *Nutrient Cycling in Agroecosystems*, *94*(2–3), 255–271. https://doi.org/10.1007/s10705-012-9539-4

Friesen, D. K. (1991). Fate and efficiency of sulfur fertilizer applied to food crops in West Africa. *Fertilizer Research*, *29*(1), 35–44. https://doi.org/10.1007/BF01048987

Gondwe, B., & Nkonde, D. (2017a). Optimizing fertilizer use within the context of integrated soil fertility management in Zambia. *Fertilizer Use Optimization in Sub-Saharan Africa*, 210–219. https://doi.org/10.1079/9781786392046.0210

Gondwe, B., & Nkonde, D. (2017b). Optimizing fertilizer use within the context of integrated soil fertility management in Zambia. *Fertilizer Use Optimization in Sub-Saharan Africa*, *April*, 210–219. https://doi.org/10.1079/9781786392046.0210

Härdter, R., Horst, W. J., Schmidt, G., & Frey, E. (1991). Yields and land-use efficiency of maize-cowpea crop rotation in comparison to mixed and monocropping on an Alfisol in Northern Ghana. *Journal of Agronomy and Crop Science*, *166*(5), 326–337. https://doi.org/10.1111/j.1439-037X.1991.tb00922.x

Henao, J., & Baanante, C. (2006). Agricultural production and soil nutrient mining in Africa: Implications for resource conservation and policy development. Summary prepared by www.ifdc.org soil nutrient mining in Africa report Final.doc: https://vtechworks.lib.vt.edu/bitstream/handle/10919/68832/4566_Henao2006_Ag_production_nutrient_mining_.pdf?sequence=1

Hengl, T., Leenaars, J. G. B., Shepherd, K. D., Walsh, M. G., Heuvelink, G. B. M., Mamo, T., Tilahun, H., Berkhout, E., Cooper, M., Fegraus, E., Wheeler, I., & Kwabena, N. A. (2017). Soil nutrient maps of Sub-Saharan Africa : assessment of soil nutrient content at 250 m spatial resolution using machine learning. *Nutrient Cycling in Agroecosystems*, *109*(1), 77–102. https://doi.org/10.1007/s10705-017-9870-x

Hill, A., & Kirwan, B. (2015). Maize response to inorganic fertilizer use by farmers in Ghana https://doi.org/10.13140/RG.2.1.4446.2566

Ichami, S. M., Shepherd, K. D., Sila, A. M., Stoorvogel, J. J., & Hoffland, E. (2019). Fertilizer response and nitrogen use efficiency in African smallholder maize farms. *Nutrient Cycling in Agroecosystems*, *113*(1), 1–19. https://doi.org/10.1007/s10705-018-9958-y

IFDC (2012). Ghana Fertilizer Assessment. 40. Investing for food and jobs (ifj): an agenda for transforming ghana’s agriculture (2018-2021).

IFDC (2019).Ghana fertilizer value chain optimization study.

Kang, B. T., & Osiname, O. A. (1976). Sulfur Response of Maize in Western Nigeria 1. *Agronomy Journal*, *68*(2), 333–336. https://doi.org/10.2134/agronj1976.00021962006800020032x

Kankam-Boadu, I., Sarkodie-Addo, J., & Amagloh, F. (2018). Nitrogen use efficiency and maize productivity in the Guinea Savanna agro-ecological zone of Ghana. *Journal of Experimental Agriculture International*, *23*(3), 1–15. https://doi.org/10.9734/jeai/2018/41305

Kanton, R. A. L., Buah, S. S. J., Larbi, A., Mohammed, A. M., Bidzakin, J. K., & Yakubu, E. A. (2017). Soil amendments and rotation effects on soybean and maize growths and soil chemical changes in Northern Ghana. *International Journal of Agronomy, 2017*. https://doi.org/10.1155/2017/4270284

Kanton, R. A. L., Prasad, P. V. V., Mohammed, A. M., Bidzakin, J. K., Ansoba, E. Y., Asungre, P. A., Lamini, S., Mahama, G., Kusi, F., & Sugri, I. (2016). Organic and inorganic fertilizer effects on the growth and yield of maize in a dry Agro-Ecology in Northern Ghana. *Journal of Crop Improvement*, *30*(1), 1–16. https://doi.org/10.1080/15427528.2015.1085939

Kelly, V., & Crawford, E. (2007). Policies and actions to stimulate private sector fertilizer marketing in sub-Saharan Africa. *Occasional Paper - Agricultural Management, Marketing, and Finance, FAO*, 78-pp. http://www.fao.org/ag/AGS/subjects/en/agmarket/aqmarket.html

Khan, M. J., Khan, M. H., Khattak, R. A., & Jan, M. T. (2006). The response of maize to different levels of sulfur. *Communications in Soil Science and Plant Analysis*, *37*(1–2), 41–51. https://doi.org/10.1080/00103620500403804

Kihara, J., Nziguheba, G., Zingore, S., Coulibaly, A., Esilaba, A., Kabambe, V., Njoroge, S., Palm, C., & Huising, J. (2016a). Understanding variability in crop response to fertilizer and amendments in sub-Saharan Africa. *Agriculture, Ecosystems and Environment*, *229*(August), 1–12. https://doi.org/10.1016/j.agee.2016.05.012

Kihara, J., Nziguheba, G., Zingore, S., Coulibaly, A., Esilaba, A., Kabambe, V., Njoroge, S., Palm, C., & Huising, J. (2016b). Understanding variability in crop response to fertilizer and amendments in sub-Saharan Africa. *Agriculture, Ecosystems, and Environment*, *229*, 1–12. https://doi.org/10.1016/j.agee.2016.05.012

Kihara, J., Sileshi, G. W., Nziguheba, G., Kinyua, M., Zingore, S., & Sommer, R. (2017). The application of secondary nutrients and micronutrients increases crop yields in sub-Saharan Africa. *Agronomy for Sustainable Development*, *37*(4). https://doi.org/10.1007/s13593-017-0431-0

Kim, S. K., Adetimirin, V. O., Thé, C., & Dossou, R. (2002). Yield losses in maize due to Striga hermonthica in West and Central Africa. *International Journal of Pest Management*, *48*(3), 211–217. https://doi.org/10.1080/09670870110117408

Kimani, S. K., Esilaba, A. O., Odera, M. M., Kimenye, L., Vanlauwe, B., & Bationo, A. (2007). Effects of organic and mineral sources of nutrients on maize yields in three districts of central Kenya. In *Advances in integrated soil fertility management in Sub-Saharan Africa: Challenges and Opportunities* (pp. 353-358). Springer, Dordrecht.

Kugbe, J. X., Kombat, R., & Atakora, W. (2019a). Secondary and micronutrient inclusion in fertilizer formulation impact on maize growth and yield across northern Ghana. *Cogent Food & Agriculture*, *5*(1). https://doi.org/10.1080/23311932.2019.1700030

Kugbe, J. X., Kombat, R., & Atakora, W. (2019b). Secondary and micronutrient inclusion in fertilizer formulation impact on maize growth and yield across northern Ghana. *Cogent Food & Agriculture*, *5*(1). https://doi.org/10.1080/23311932.2019.1700030

Kwakye, P. K. & Aforo, D. (1995) Comparative effectiveness of nitrogen applied as straight and in compound fertilizers on maize on a coastal savanna ultisol. *Ghana Journal of Agricultural Science*, 28–29, 17–21

Li, H., Lascano, R. J., Booker, J., Wilson, L. T., & Bronson, K. F. (2001). Cotton lint yield variability in a heterogeneous soil at a landscape scale. *Soil and Tillage Research*, *58*(3-4), 245-258.

Maccarthy, D. S., & Vlek, P. L. G. (2012). Improving Soil Fertility Recommendations in Africa using the decision support system for agrotechnology transfer (DSSAT). *Improving Soil Fertility Recommendations in Africa Using the Decision Support System for Agrotechnology Transfer (DSSAT)*. https://doi.org/10.1007/978-94-007-2960-5

Mamudu, D., Mensah, G. W. K., & Borketey-La, E. B. (2017). The Responses of three maize varieties to four levels of nitrogen in the Forest-Transitional zone of Ghana. 7(14).

MOFA and SRID 2013 Ghana Agriculture, “facts and figures.” *Probe* 14(9):420.

MOFA, (2018). “Investing for food and jobs (IFJ): An agenda for transforming Ghana’s agriculture (2018-2021).”

MOFA, (2019). Agriculture in Ghana facts and figures.

Naab, J. B., Mahama, G. Y., Koo, J., Jones, J. W., & Boote, K. J. (2015). Nitrogen and phosphorus fertilization with crop residue retention enhance crop productivity, soil organic carbon, and total soil nitrogen concentrations in sandy-loam soils in Ghana. *Nutrient Cycling in Agroecosystems*, *102*(1), 33–43. https://doi.org/10.1007/s10705-015-9675-8

Ngoma, H., Sitko, N. J., Jayne, T., Chapoto, A., & Maredia, M. (2016). Feed the Future Innovation Lab for Food Security Policy.

Njoroge, S., Schut, A. G. T., Giller, K. E., & Zingore, S. (2017). Strong spatial-temporal patterns in maize yield response to nutrient additions in African smallholder farms. *Field Crops Research*, *214*(May), 321–330. https://doi.org/10.1016/j.fcr.2017.09.026

Noorbakhsh, S., Schoenau, J., Si, B., Zeleke, T., & Qian, P. (2008). Soil properties, yield, and landscape relationships in south-central Saskatchewan Canada. *Journal of plant nutrition*, *31*(3), 539-556.

Okebalama, C. B., Safo, E. Y., Yeboah, E., Abaidoo, R. C., & Logah, V. (2016). Fertilizer micro-dosing in the humid forest zone of Ghana: An efficient strategy for increasing maize yield and income in smallholder farming. *Soil Science Society of America Journal*, *80*(5), 1254–1261. https://doi.org/10.2136/sssaj2016.03.0065

Okoboi, G., & Barungi, M. (2012). Constraints to fertilizer use in Uganda: Insights from Uganda census of agriculture 2008/9. *Journal of Sustainable Development*, *5*(10). https://doi.org/10.5539/jsd.v5n10p99

Ouedraogo, J., Youl, S., & Mando, A. (2018). Combining the DSSAT model with experimentation to update recommendations of fertilizer rates for rice and maize in Burkina Faso. In *Improving the Profitability, Sustainability, and Efficiency of Nutrients Through Site-Specific Fertilizer Recommendations in West Africa Agro-Ecosystems* (pp. 1-22). Springer, Cham.

Pias, O. H. D. C., Tiecher, T., Cherubin, M. R., Mazurana, M., & Bayer, C. (2019). Crop yield responses to sulfur fertilization in Brazilian no-till soils: A systematic review. *Revista Brasileira De Ciencia Do Solo*, *43*, 1–21. https://doi.org/10.1590/18069657rbcs20180078

Rasheed, M., Ali, H., & Mahmood, T. (2004). Impact of nitrogen and sulfur application on growth and yield of maize (Zea Mays L.) Crop. *J. Res. Sci*, *15*(2), 153–157.

Rhodes, E. R. (1995). Nutrient depletion by food crops in Ghana and soil organic nitrogen management. *Agricultural Systems*, *48*(1), 101–118. https://doi.org/10.1016/0308-521X(95)93648-W

Rietra, R. P. J. J., Heinen, M., Dimkpa, C. O., & Bindraban, P. S. (2017). Effects of nutrient antagonism and synergism on yield and fertilizer use efficiency. *Communications in Soil Science and Plant Analysis*, *48*(16), 1895–1920. https://doi.org/10.1080/00103624.2017.1407429

Sakyi, C. A., Abunyewa, A. ., Nyamekye, A. I., & Safo, E. Y. (2005). Integrated nutrient management: preliminary results from a 2-year field trial using cow dung, mineral fertilizer, and maize test crop in the interior savanna zone of Ghana.

Serme, I., Ouattara, K., Traore, I. O., Ouedraogo, S., Youl, S., Ouattara, B., ... & Wortmann, C. (2018). Maize response to fertilizer on Ferralsol and Luvisol in the South Sudan zone of Burkina Faso. In *Improving the Profitability, Sustainability, and Efficiency of Nutrients Through Site-Specific Fertilizer Recommendations in West Africa Agro-Ecosystems* (pp. 195-214). Springer, Cham.

Stoorvogel, J. J., & Smaling, E. M. A. (1990). Assessment of soil nutrient depletion in Sub-Saharan Africa*: 1983-2000*. 134.

Tahiru, F., Fosu, M., Gaiser, T., Becker, M., Inusah, B. I. Y., Mutari, A., Buah, S. S. J., Atakora, W. K., & Mohammed, A. M. (2015). Fertilizer and genotype effects on maize production on two soils in the Northern region of Ghana. *Sustainable Agriculture Research*, *4*(4), 76. https://doi.org/10.5539/sar.v4n4p76

Tetteh, F. M., Ennim, S. A., Issaka, R. N., Buri, M., Ahiabor, B. A. K., & Fening, J. O. (2018). Fertilizer recommendation for maize and cassava within the breadbasket zone of Ghana. *Improving the Profitability, Sustainability, and Efficiency of Nutrients Through Site-Specific Fertilizer Recommendations in West Africa Agro-Ecosystems*, *2*, 161–184. https://doi.org/10.1007/978-3-319-58792-9_10

Tittonell, P. (2007). Heterogeneity of crop productivity and resource use efficiency within smallholder Kenyan farms : Soil fertility gradients or management intensity gradients ? 94, 376–390. https://doi.org/10.1016/j.agsy.2006.10.012

World Bank Group, & Agriculture Global Practice in West Africa. (2017). Ghana: Agriculture sector policy note. June, 63.

Zhao, Y. N., He, X. H., Huang, X. C., Zhang, Y. Q., & Shi, X. J. (2016). Increasing soil organic matter enhances inherent soil productivity while offsetting the fertilization effect under a rice cropping system. Sustainability, 8(9), 879.

Zingore, S., Murwira, H. K., Delve, R. J., & Giller, K. E. (2007). Soil type, management history, and current resource allocation: Three dimensions regulating variability in crop productivity on African smallholder farms. *Field Crops Research*, *101*(3), 296–305. https://doi.org/10.1016/j.fcr.2006.12.006

Annex 1. Peer-Reviewed Publications Used in the Study

S/No.	Reference	Experimental Year(s)	Description of the Experiment
1	Addai, I.K., & Kombat, R.K. (no year of publication)	2015	Growth and yield of maize (*Zea Mays L.*) as affected by application rates of different NPK fertilizer formulations in Northern Ghana
2	Dogor, Michael Mawusi Kweku (2013)	2011	The effect of fertilizer formulation on yield components and yield of hybrid maize (*Zea mays L.*) varieties in Guinea
3	Naab et al. (2015)	2003-2007	Nitrogen and phosphorus fertilization with crop residue retention enhances crop productivity, soil organic carbon, and total soil nitrogen concentrations in sandy-loam soils in Ghana
4	Okebalama et al. (2016)	2012-2013	Fertilizer microdosing in the humid forest zone of Ghana: An efficient strategy for increasing maize yield and income in smallholder farming
5	Härdter et al. (1991)	1985	Nitrogen and phosphorus use in maize sole cropping and maize/cowpea mixed cropping systems on an Alfisol in the northern Guinea Savanna of Ghana
6	Kankam-boadu et al. (2018)	2014 & 2015	Nitrogen use efficiency and maize productivity in the Guinea Savanna agroecological zone of Ghana
7	Badu et al. (2019)	The Year of the experiment wasn't indicated	Biochar and inorganic nitrogen fertilizer effects on maize *(Zea mays L.)* nitrogen use and yield in the moist Semi-Deciduous Forest zone of Ghana
8	Pearl Kpotor (2012)	2011	Evaluation of newly released maize varieties in Ghana for yield and stability under three nitrogen application rates in two agroecological zones
9	Kanton et al. (2016)	2012-2014	Organic and inorganic fertilizer effects on the growth and yield of maize in a dry agroecology in Northern Ghana
10	Abunyewa et al. (2007)	1996	Integrated manure and fertilizer use, maize production, and sustainable soil fertility in the sub-humid zone of West Africa
11	Tetteh et al. (2018)	2005-2006	Fertilizer recommendation for maize and cassava within the breadbasket zone of Ghana
12	Tahiru et al. (2015)	2011	Fertilizer and genotype effects on maize production on two soils in the Northern Region of Ghana

S/No.	Reference	Experimental Year(s)	Description of the Experiment
13	Abunyewa & Mercer Quarshie (2004)	1997-1999	The response of maize to magnesium and zinc application in the semi-arid zone of West Africa
14	Essilfie et al. (2017)	2015	The varietal response of maize (*Zea mays)* to integrated nutrient management of NPK and chicken manure amendments
15	Buah et al. (2017)	2013	Tillage and fertilizer effect on maize and soybean yields in the Guinea Savanna zone of Ghana
16	Kwakye & Aforo, (1995)	1990	Comparative effectiveness of nitrogen applied as straight and in compound fertilizers on maize on Coastal Savannah
17	Aflakpui et al. (2005)	2002-2003	The response of a quality protein maize hybrid to N supply and plant density in the forest zone of Ghana
18	Mamudu et al. (2017)	Year of experiment was not indicated	The responses of three maize varieties to four levels of nitrogen in the forest-transitional zone of Ghana
19	Dapaah et al. (2009)	2002-2003	Combining inorganic fertilizer with poultry manure for sustainable production of quality protein maize in Ghana
20	Sakyi et al. (2005)	1996-1997	Integrated nutrient management: preliminary results from a two-year field trial using cow dung, mineral fertilizer, and maize test crop in the interior Savanna zone of Ghana
21	Atakora et al. (2014)	2010	The response of maize growth and development to mineral fertilizer and soil characteristics in Northern Ghana
22	Adjei-Nsiah (2012)	2010	The response of maize (*Zea mays L.)* to different rates of Palm Bunch Ash (PAB) application in the Semi-Deciduous Forest agroecological zone of Ghana
23	Kanton et al. (2017)	2014-2016	Soil amendments and rotation effects on soybean and maize growths and soil chemical changes in Northern Ghana
24	MacCarthy & Vlek (2012)	2007	The response of maize to N fertilization in a sub-humid region of Ghana: understanding the processes using a crop simulation model
25	Fosu-Mensah et al. (2012)	2008	Simulating the impact of seasonal climatic variation on the response of maize *(Zea mays L.)* to inorganic fertilizer in sub-humid Ghana
26	Boateng et al. (2009)		Poultry manure effect on growth and yield of maize
27	Kugbe et al. (2019)	2017	Secondary and micronutrient inclusion in fertilizer formulation impact on maize growth and yield across northern Ghana

S/No.	Reference	Experimental Year(s)	Description of the Experiment
28	(*Ghks.pdf*, n.d.)		
29	Gabriel Willie Quansah (2010)	2004	Effect of organic and inorganic fertilizers and their combinations on the growth and yield of maize in the Semi-Deciduous Forest zone of Ghana
30	Fening et al. (2009)	2008	On-farm evaluation of the contribution of three green manures to maize yield in the Semi-Deciduous Forest zone of Ghana
31	Arthur (2014)	2010	Effects of tillage and NPK 15-15-15 fertilizer application on maize performance and soil properties
32	Adu et al. (2018)	Year of the experiment was not indicated	Performance of maize populations under different nitrogen rates in northern Ghana

Annex 2. Test of Assumptions for ANOVA (figures in red indicate non-normal distribution or non-homogeneity of variance)

Variable	Shapiro Wilk Test of Normality		Bartlett's Test for Homogeneity of Variance		
Nitrogen	**W**	**Conclusion**	**Chi-square**	***P*<0.05**	**Conclusion**
Combined yield	0.962	Normal	68.14	< 0.001	Equal variance
Combined TAR	0.936	Normal	49.96	< 0.001	Equal variance
Combined % OC	0.821	Normal	70.03	< 0.001	Equal variance
Combined CEC	0.919	Normal	46.18	< 0.001	Equal variance
Combine P_mg_kg	0.286	Not normally distributed	504.22	< 0.001	Equal variance
Combined Total N%	0.183	Not normally distributed	1136.79	< 0.001	Equal variance
Combined PH	0.947	Normal	36.39	< 0.001	Equal variance
Combined Sand	0.961	Normal	68.12	< 0.001	Equal variance
Combined Clay	0.956	Normal	12.06	0.601	Non equal variance
Combined Silt	0.958	Normal	82.29	< 0.001	Equal variance
Phosphorus					
Combined yield	0.957	Normal	30.82	< 0.001	Equal variance
Combined TAR	0.945		18.12	0.011	Equal variance
Combined % OC	0.825	Normal	27.98	< 0.001	Equal variance
Combined CEC	0.891	Normal	18.74	0.009	Equal variance
Combined P_mg_kg	0.819	Normal	40.01	< 0.001	Equal variance
Combined Total N%	0.088	Not normally distributed	574.61	< 0.001	Equal variance
Combined PH	0.911	Normal	27.02	< 0.001	Equal variance
Combined Sand	0.941	Normal	34.58	< 0.001	Equal variance
Combined Clay	0.964	Normal	11.28	0.127	Non equal variance
Combined Silt	0.939	Normal	18.87	0.009	Equal variance
Potassium					
Combined yield	0.961	Normal	44.62	< 0.001	Equal variance
Combined TAR	0.905	Normal	60.18	< 0.001	Equal variance
Combined % OC	0.873	Normal	61.91	< 0.001	Equal variance

Variable	**Shapiro Wilk Test of Normality**		**Bartlett's Test for Homogeneity of Variance**		
Nitrogen	**W**	**Conclusion**	**Chi-square**	***P*<0.05**	**Conclusion**
Combined CEC	0.326	Not normally distributed	231.54	< 0.001	Equal variance
Combine P_mg_kg	0.249	Not normally distributed	12.85	0.076	Non equal variance
Combined Total N%	0.076	Not normally distributed	315.79	< 0.001	Equal variance
Combined PH	0.887	Normal	16.92	0.018	Equal variance
Combined Sand	0.945	Normal	41.02	< 0.001	Equal variance
Combined Clay	0.969	Normal	21.50	0.003	Equal variance
Combined Silt	0.982	Normal	25.55	< 0.001	Equal variance
NPK					
Combined yield	0.965	Normal	108.54	< 0.001	Equal variance
Combined TAR	0.953	Normal	82.41	< 0.001	Equal variance
Combined % OC	0.823	Normal	132.60	< 0.001	Equal variance
Combined CEC	0.902	Normal	101.48	< 0.001	Equal variance
Combined P_mg_kg	0.267	Not normally distributed	898.36	< 0.001	Equal variance
Combined Total N%	0.138	Not normally distributed	2171.27	< 0.001	Equal variance
Combined PH	0.940	Normal	80.81	< 0.001	Equal variance
Combined Sand	0.950	Normal	138.99	< 0.001	Equal variance
Combined Clay	0.962	Normal	33.49	0.148	Non equal variance
Combined Silt	0.957	Normal	111.42	< 0.001	Equal variance