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Light Use Efficiency Crop Model Effective for Identifying Driving Factors for Maize Yield Gap in Ghana

IFDC FERARI Research Report No. 11

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ABBREVIATIONS

AEZ	Agroecological Zone
APSIM	Agricultural Production Systems Simulator
CEC	Cation Exchange Capacity
CSIR	Council of Scientific and Industrial Research
DSSAT	Decision Support System for Agrotechnology Transfer
FAO	Food and Agricultural Organization of United Nations
GDD	Growing Degree Day
IPAR	Intercepted Photosynthetic Active Radiation
KNUST	Kwame Nkrumah University of Science and Technology
LAI	Leaf Area Index
LINTUL	Light Interception and Utilization
MLR	Multiple linear regression
MoFA	Ministry of Food and Agriculture
R^2	Coefficient of Determination
RMSE	Root Mean Square Error
SARI	Savanna Agricultural Research Institute
VIF	Variance Inflation Factor

SUMMARY

In Ghana, maize (*Zea mays*) is a crucial crop for achieving food security. The population of Ghana, which has grown exponentially over the past decades, consumes about 25% of its calories from maize. In order to assist in decisionmaking and guide investment in Ghana's agricultural intensification process, this study set out to quantify and explain the yield gap for maize using a new methodological approach. The yield gap for maize was found to range from 14% to 96%. The variation in the yield gap within a single station was related to the varying levels of yield obtained with different fertilizer treatments. None of the fertilizer combinations led to total closure of the gap in the studied locations. To identify the drivers for the yield gap, a multiple linear regression (MLR) analysis appeared to explain 68% of the yield difference. The main factors influencing the yield gap in the study areas were soil organic matter, soil water-holding capacity, root zone depth, rainfall, sulfur (S) fertilizer, and nitrogen (N) fertilizer. By adding 1% more soil organic matter, the gap could be reduced by 1.3 metric tons per hectare (mt/ha). However, an increase in the pH of the soil and the application of potassium fertilizer could increase the yield gap of maize in Ghana.

CHAPTER 1: INTRODUCTION

1.1 Background

Ghana is considered a moderately food-insecure country, but the fast demographic growth rate of 2.63% annually (https://www.statista.com), the effects of climate change, and decreasing soil fertility, combined with the high cost of inputs and the low income of farmers, are major challenges to improving food security in Ghana. In fact, the health of a country's agriculture sector determines its overall economic growth and development. In Ghana, agriculture contributes to 19.25% of the gross domestic product (https://www.statista.com). According to the Food and Agricultural Organization of United Nations (FAO), only 8% of cultivated land in Ghana is under irrigation, leaving rainfall as the major source of water to cropping systems across the country.

Weather conditions are highly variable throughout Ghana. In the Sudan and Guinea Savannah agroecological zones (AEZs), the rainfall pattern is unimodal, whereas in the Rainforest, Deciduous Forest, Transitional, and Coastal Savannah AEZs, it is bimodal. The temperature also varies across the country; average daily temperature in the country is between 26.1°C and 28.9°C (Abbam et al., 2018), although it can reach 40°C in the northern part during the dry season (Asante and Amuakwa-Mensah, 2014). Rasul et al. (2011) noted that temperature is a determining factor for crop growth and development, as it impacts the duration of the crop cycle. But a study by Baffour-Ata et al. (2021) reported that temperature variability does not significantly affect crop production in the country. Rainfall strongly impacts the yield of the major crops in Ghana: maize, sorghum, rice, and millet. Rainfall across Ghana, particularly in the northern regions, is erratic and unequally distributed (Wortmann and Stewart, 2021). The extreme change in the rainfall pattern has the potential to affect crop yield and land productivity. In general, crop yield is extremely affected by unexpected drought (Hussain et al., 2019) and heat (Hatfield and Prueger, 2015).

Fertilizer use, primarily nitrogen, phosphorus, and potassium (NPK), increased from 290,156 mt in 2015 to 425,110 mt in 2019 in an attempt to increase Ghana's low yields (https://statsghana.gov.gh). However, this has not lead to significant yield improvement. Adzawla et al. (2021) reported that the maximum maize yield achieved by farmers in the northern part of the country is 1.44 mt/ha, which is far below the potential yield estimated by the Ministry of Food and Agriculture (MoFA, 2018) of 5.5 mt/ha. This highlights the fact that poor soil fertility is not the only determinant of the large yield gap of 80% of the potential yield (Adjei-Nsiah, 2012). Therefore, a comprehensive approach to reassess the production gap in Ghana is required. Yield gap analyses may provide the foundation for this reassessment. The approach can provide a framework for identifying the most relevant crop, soil, and management factors that are limiting farm yields. In addition, the assessment of the yield gap can lead to the prioritization of research, development, and interventions with effective strategies to address the main issues (van Ittersum et al., 2013).

Crop modeling has been used to simulate the potential yield of several crops (Espe et al., 2016; Gimplinger and Kaul, 2009). LINTUL, a model developed by Spitters and Schapendonk (1990), is based on the light intercepted and light use efficiency to simulate crop growth and yield. LINTUL can assess the effect of weather variability on the yield by simulating the daily growth of the crop (Adiele et al., 2021). Several versions of LINTUL have been developed. LINTUL-1 simulates the potential yield (Haverkort et al., 2015), while LINTUL-2 is used to simulate the water-limited yield (Moreno-Cadena et al., 2021). LINTUL is a simple model that requires few data. This will allow us to calculate the yield gap of maize in Ghana and explain the major constraints to achieving the potential yield in different AEZs.

1.2 Problem Statement

The increased use of fertilizer in Ghana has barely improved the yield of maize (Agyin-Birikorang et al., 2022; Adzawla et al., 2021), which indicates that soil fertility may not be the only problem farmers here are facing. Weather conditions across the country are highly variable. However, the weather conditions in the northern regions are more extreme than those in the south (Wortmann and Stewart, 2021). Identifying the effect of the weather variability on maize growth and yield is critical to understanding the drivers for the current low yields of maize.

Increasing the yield of maize in Ghana requires an understanding of the yield gap, the factors limiting the yield, and their interactions. Hence, quantifying the potential yield is critical. Field experiments to measure the potential yield are costly and time-consuming (Menge et al., 2013). Also, controlling all the biotic and abiotic stressors under field conditions is difficult. Indeed, crop growth simulation models have been suggested as a more appropriate way to estimate the yield gap because they provide the most reliable way to estimate yield potential and water-limited or exploitable yield (MacCarthy et al., 2018). Several models have been used in Ghana to simulate the potential yield, such as the Agricultural Production Systems Simulator (APSIM; Danquah et al., 2020) and Decision Support System for Agrotechnology Transfer (DSSAT; MacCarthy et al., 2018). The problem with these simulation models is that they require a lot of data about soil, crop, management, and weather (Nassiri Mahallati, 2020), which is not readily available for Ghana. LINTUL is a simplified crop growth simulation model with a low requirement for data compared to other detailed models. It is calibrated through crop parameters from a field experiment or from literature and uses meteorological data as input.

1.3 Activity Statement

Data from field trials of maize in 2020 were used to calibrate the basic parameters of LINTUL for use in Ghana. Radiation use efficiency, allocation coefficient of dry matter, and thermal time parameters should be derived from the field data and from the literature. The model will be considered valid for Ghana if the simulated potential yield is comparable to the reported potential yield in the literature, because the water supply for maize growth during these experiments was based on the rainfall, and therefore, it cannot be considered in the potential yield. To calibrate the model, the use of the best treatments is important to ensure that the crop performed as well as possible, close to the optimal conditions.

1.4 Hypotheses

H01 – LINTUL-1 is an effective crop model to simulate the potential yield of maize in Ghana.

H02 – The yield gap for maize in Ghana is high.

H03 – Fertilizer is not the only factor that determines the yield gap of maize in Ghana.

1.5 Objectives

- Calibrate LINTUL-1 for maize in Ghana.
- Simulate the potential of maize in the FERARI study area.
- Simulate the potential yield of maize for the entire country of Ghana and build a potential yield map.
- Calculate the yield gap of maize under different fertilizer applications for the study area.
- Build an empirical model based on FERARI field experiments to explain the yield gap in Ghana.

1.6 Research Questions

- What is the potential yield of maize in Ghana, and what is the yield gap of maize?
- How do fertilizers contribute to closing the yield gap?
- What are the factors that explain the gap between the actual and potential yield of maize in Ghana?

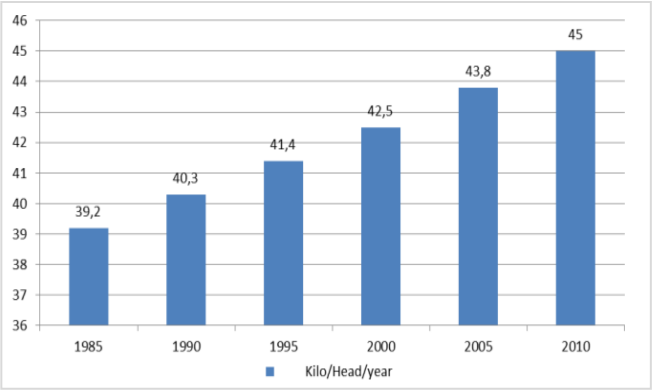
1.7 Justification

The low yield of maize production in Ghana is a big concern for food security. To address this issue, it is important first to define the opportunity for increasing production. Accordingly, sustainable intensification implies the adoption of more efficient technologies, optimal inputs, and good management practices. This study aims to provide a new useful methodological approach based on systematic and mechanistic modeling of the potential yield and the yield gap of maize in Ghana. This approach is important to support the decisionmaking on strategic investments. In general, this approach will help to identify the main edaphic and ecological problems that inhibit farmers from achieving higher yields.

CHAPTER 2: LITERATURE REVIEW

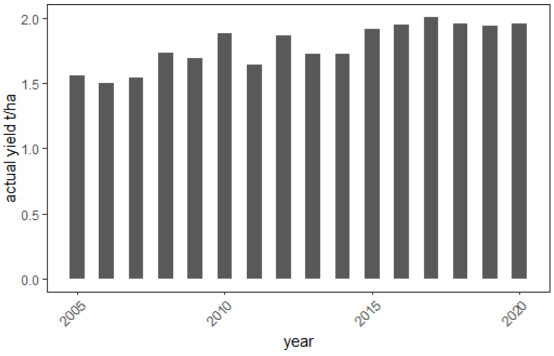
2.1 Maize Production and Consumption in Ghana

Maize is a major food crop in Ghana, accounting for more than half of the country's total cereal output. The Eastern, Ashanti, and Brong-Ahafo regions of Ghana produce approximately 80% of the total maize production. The remainder is supplied by the three northern regions (Northern, Upper East, and Upper West). Maize is cultivated throughout the country (Wongnaa et al., 2019). The high domestic demand for maize, either as food for humans as a source of 25% of calories consumed in the country (MoFA & IFPRI, 2020) or as feed for livestock, make it a valuable source of income for a large number of smallholder farmers in Ghana. The local consumption of maize in Ghana has increased by 14% over the years, from 39.5 kilograms (kg) to 45 kg per person annually (Figure 1). The increased demand for maize has not been matched by an increase in yield. However, a slight increase in yield was observed between 2005 and 2020 from 1 mt/ha to 1.9 mt/ha (Figure 2), which is far below the reported potential yield of 4-6 mt/ha (Ragasa et al., 2014). Importation is the primary option to meet the demand for maize (Figure 3), especially when the production is low due to drought, heat, or the prices of fertilizers (Barimah, 2014). In general, the production area of maize in Ghana has not changed much since 2008 (Figure 4) (https://www.statista.com/). Therefore, the increase in production is mainly dependent on rainfall and input use.



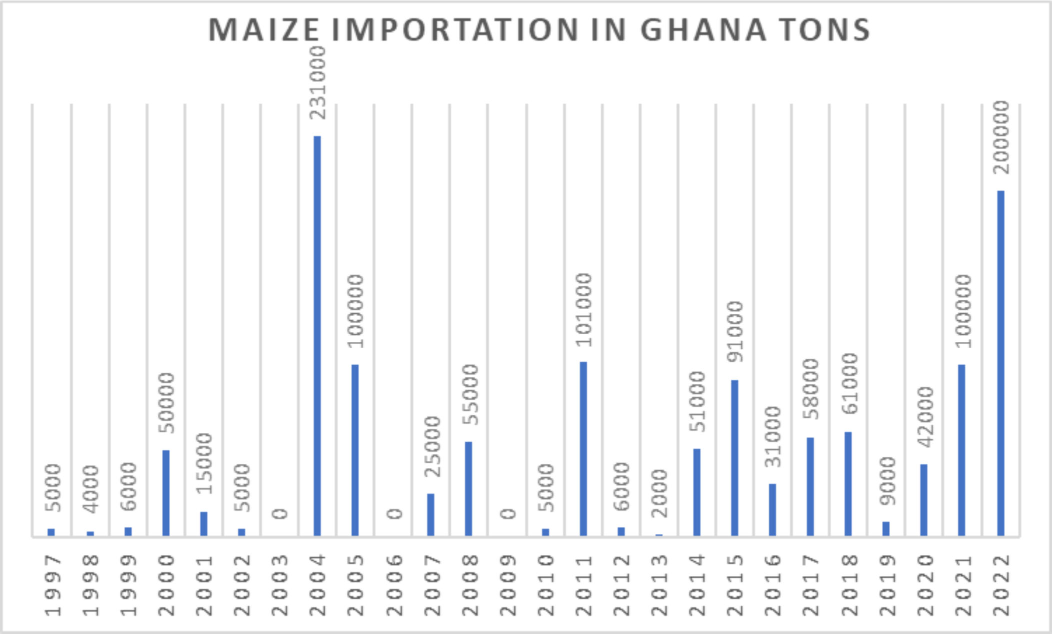
Source: Angelucci et al. (2019).

Figure 1. Increase in Demand for Maize in Ghana for Human Consumption, 1985-2010



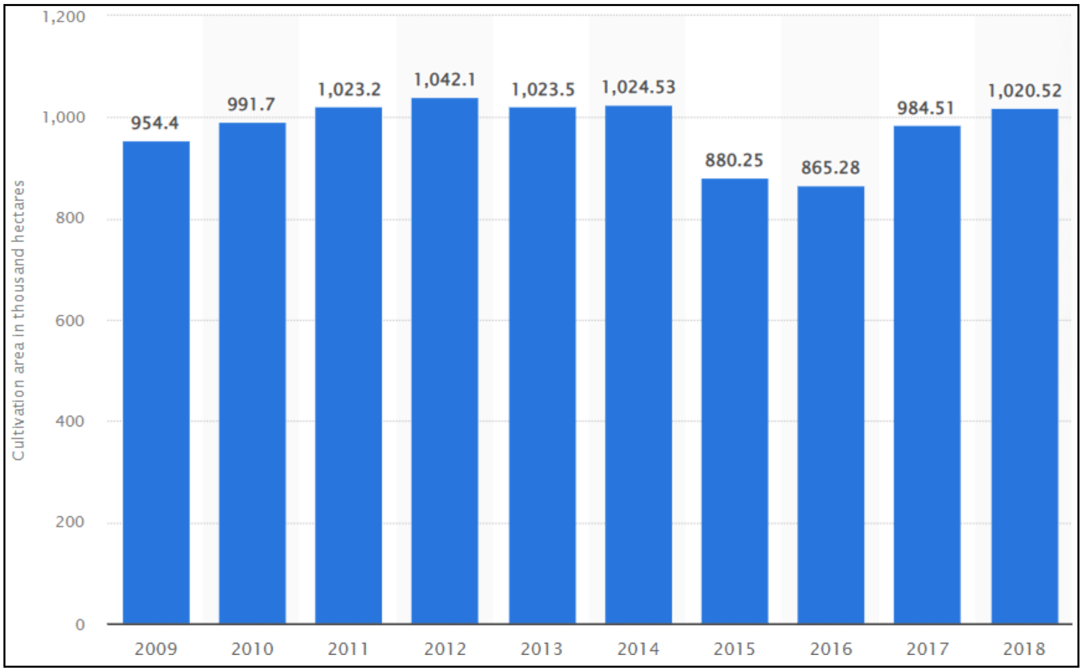
Based on FAOSTAT (2020).

Figure 2. Yield Variability Across the Years in Ghana



Source: https://www.indexmundi.com/.

Figure 3. Quantity of Maize Imported in Ghana per Year, 1997-2022



Source: https://www.statista.com/.

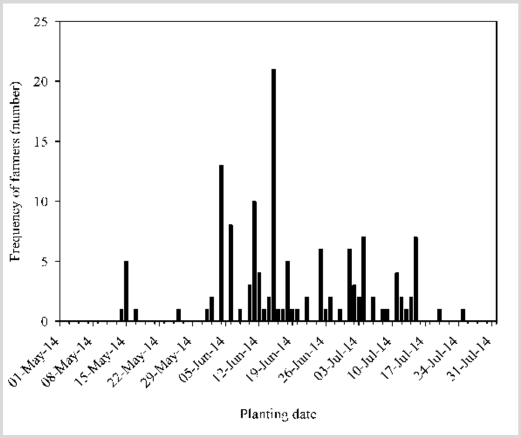
Figure 4. Area Allocated for Maize Production in Ghana

2.2 Maize Cropping System in Ghana

Maize production is dominated by a rainfed system rather than irrigation, which accounts for only 2% of the total arable lands in the country (Worqlul et al., 2019). Several hybrid and open-pollinated varieties have been released to farmers. The Council of Scientific and Industrial Research (CSIR) has released more than 24 maize varieties with different ecologic properties or grain qualities. For example, Wang-dataa is a short-season, drought-tolerant variety, while *Obatanpa* is a long-season variety with a high grain quality (CSIR and MoFA, 2012). Water scarcity is becoming a serious problem in Ghana, especially in the northern regions, affecting the yield and the use efficiency of fertilizer.

The low application of fertilizer by smallholder farmers in Ghana limits production and suppresses the capacity of the land to achieve its potential. Generally, the recommended fertilizer is significantly different among the AEZs, because of the variability in the soil structure and fertility and due to climatic variability. MoFA recommends the application of 76 kg/ha N, 40 kg/ha P_2O_5, and 40 kg/ha K_2O, mainly from 15-20-20 and urea fertilizers, in the Guinea Savannah zone and 91 kg/ha N, 60 kg/ha P_2O_5, and 60 kg/ha K_2O from the same sources in the Forest-Savannah Transitional zone. For the Semi-Deciduous Forest zone, application of 60 kg/ha of N was reported to be efficient for farmers, as it results in the maximum possible net return (Essel et al., 2020).

The planting date of maize in Ghana is governed mostly by rainfall, but the availability of labor is another driver that can delay the planting date. Freduah et al. (2019) conducted a study in Tamale and classified the planting time as early (May), normal (June), and late (July) based on the frequency of farmer practice (Figure 5). Planting in the Savannah area is best done between May 16 and June 15. Early and late planting (April 15-May 15 and June 16-July 15) are preferable over the normal planting time (May 16-June 15) in the Guinea Savannah's Eastern Region. However, the best planting date is also a function of the variety planted. Further, plant density significantly affects the production of biomass (Khalid et al., 2018). In general, the sowing rate and germination percentage determine plant density, which controls establishment success, production, and eventually crop profitability. High plant density can result in more cobs per unit area under ideal water and fertilizer conditions, resulting in an increase in grain output (Al-Naggar et al., 2015). According to Buah et al. (2010), CSIR-Savanna Agricultural Research Institute (SARI) has advised 62,500 plants per hectare for the Guinea Savannah zone. In general, a planting density of 75 cm × 40 cm, equal to 33,300 plants per hectare, is recommended for and commonly used in Ghana (Bawa, 2021).



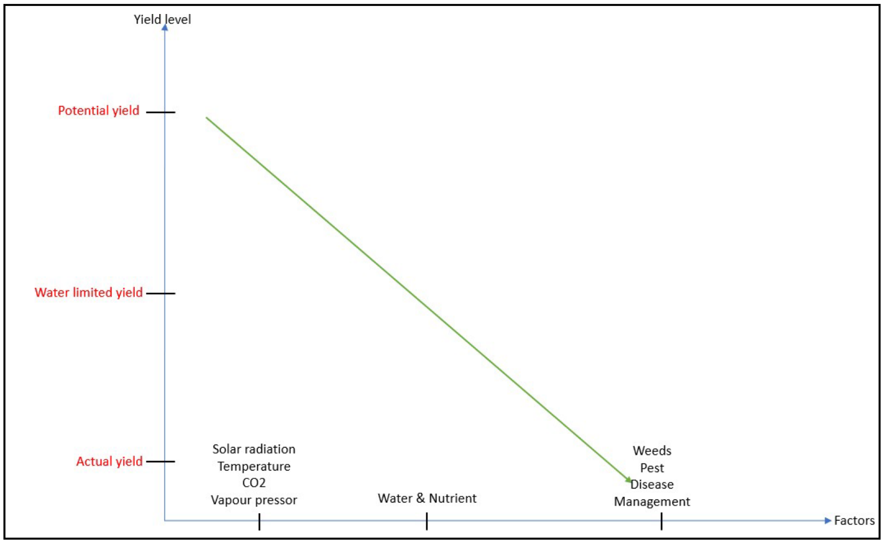
Source: Freduah et al. (2019).

Figure 5. Frequency of the Planting Date of Maize in Tamale

2.3 Yield and the Yield Gap Concept

Yield is defined as the grain weight per unit of land area (usually mt/ha) at the agreed-upon standard of moisture content of the grain, which could vary according to the crop and by country (Fischer, 2015). As consequence, the ideal moisture level is 13% for maize and 12% for rice and soybean, while it should not exceed 13.5% for wheat (https://sesitechnologies.com). Several concepts of yield are used and measured in the literature – potential yield, water-limited yield, experimental achievable yield, actual yield, and others. The actual yield is a result of the interaction of Environment × Genetics × Management and is the achievable yield by farmers (Morell et al., 2016). The theoretical potential yield is the maximum possible yield that could be achieved under optimal growth conditions. The yield is a function of different levels of growth and yield-defining factors, including radiation and temperature, which determine the potential yield. Insufficient availability of water and nutrients limits growth and yield to attainable yield, while pests and diseases may further reduce yields to the actual yield level (Figure 6; van Ittersum et al., 2013). Different levels of yield are important for calculating the yield gap, which is defined as the difference between the actual farmer's yield and the yield achieved in the experimental station where the conditions are mostly controlled (Rong et al., 2021).

The increase in the world population pushes the need for more food and stakes a claim on more resources. Hence, increasing the yield of various crops becomes a necessity in maintaining food security. Thus, yield gap analyses are important to identify the production potential of agricultural lands in the world. Studying the yield gap of various crops in an individual or multi-cropping system serves multiple purposes. First, this provides a framework for identifying the most relevant crop, soil, and management factors that are limiting farm yields as well as better practices that will help close the yield gap. Second, this serves in the prioritization of research, development, and implementation of interventions with effective strategies to address the main issues. Third, the results from such gap analyses are important in developing an economic model that effectively considers the food security and profitability of farmers (van Ittersum et al., 2013).

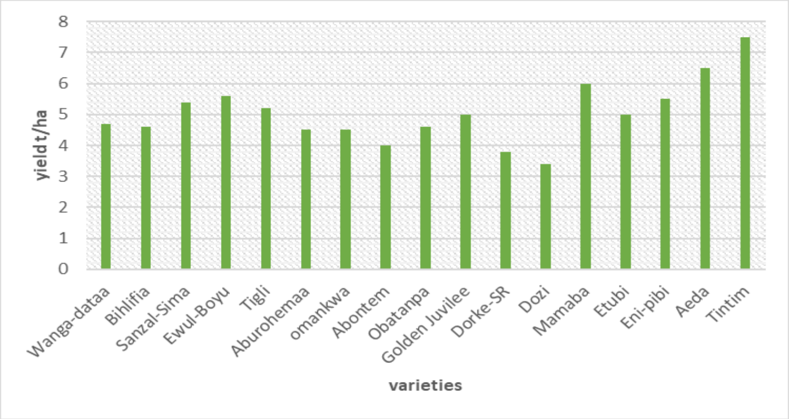


Source: Author's creation.

Figure 6. Various Yield Concepts and Their Driving Factors

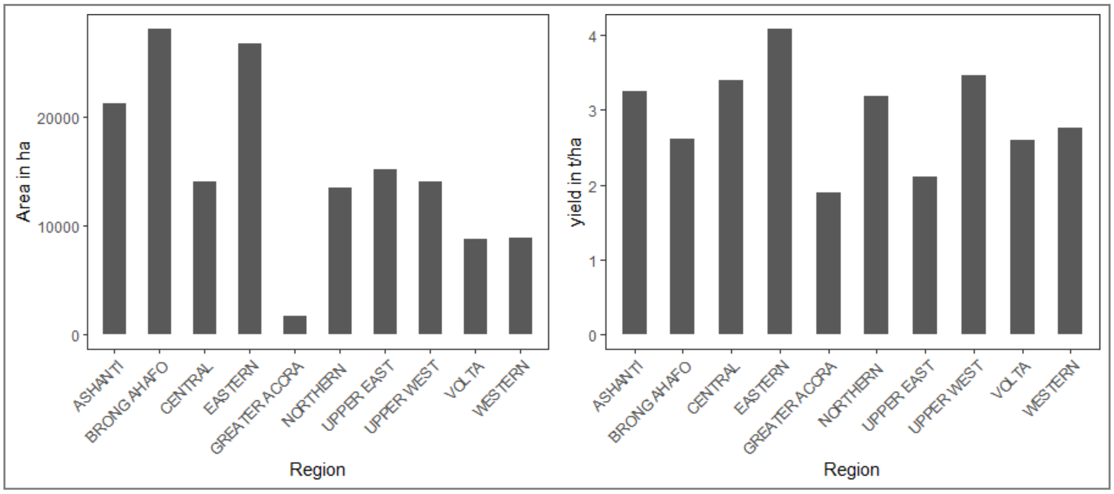
2.4 Yield of Maize in Ghana

Several varieties of maize have been released in Ghana (Figure 7). But *Obatanpa*, a long-season variety, is the most adopted variety by farmers (Scheiterle and Birner, 2018). Early season varieties such as *Dozi* and *Wang-dataa* grow fast, which reduces the risk of loss to the yield due to drought (Sallah et al., 2009), but the fast growth of the crop decreases the physiologic time required to reach maturity, reducing the grain filling duration and, hence, the yield potential. However, the yield achieved by farmers is far below the potential yield. The current yield of maize in the northern regions does not exceed 2 mt/ha (Ifie et al., 2022). The yield is highly variable across Ghana (Figure 8). The low application of fertilizer accompanied by the low soil fertility often explain the yield, but other factors, such as climatic variability, management, and cultivated area, have contributed to the variability of the yield (van Loon et al., 2019).



Source: Author's creation, based on Adu et al. (2014).

Figure 7. Variability of the Potential Yield of Maize among Varieties



Source: Author's creation, based on Ghana open data (https://data.gov.gh/)

Figure 8. Cultivated Area and Actual Yield of Maize in Different Regions of Ghana

2.5 Systematic Modeling and Yield Simulation

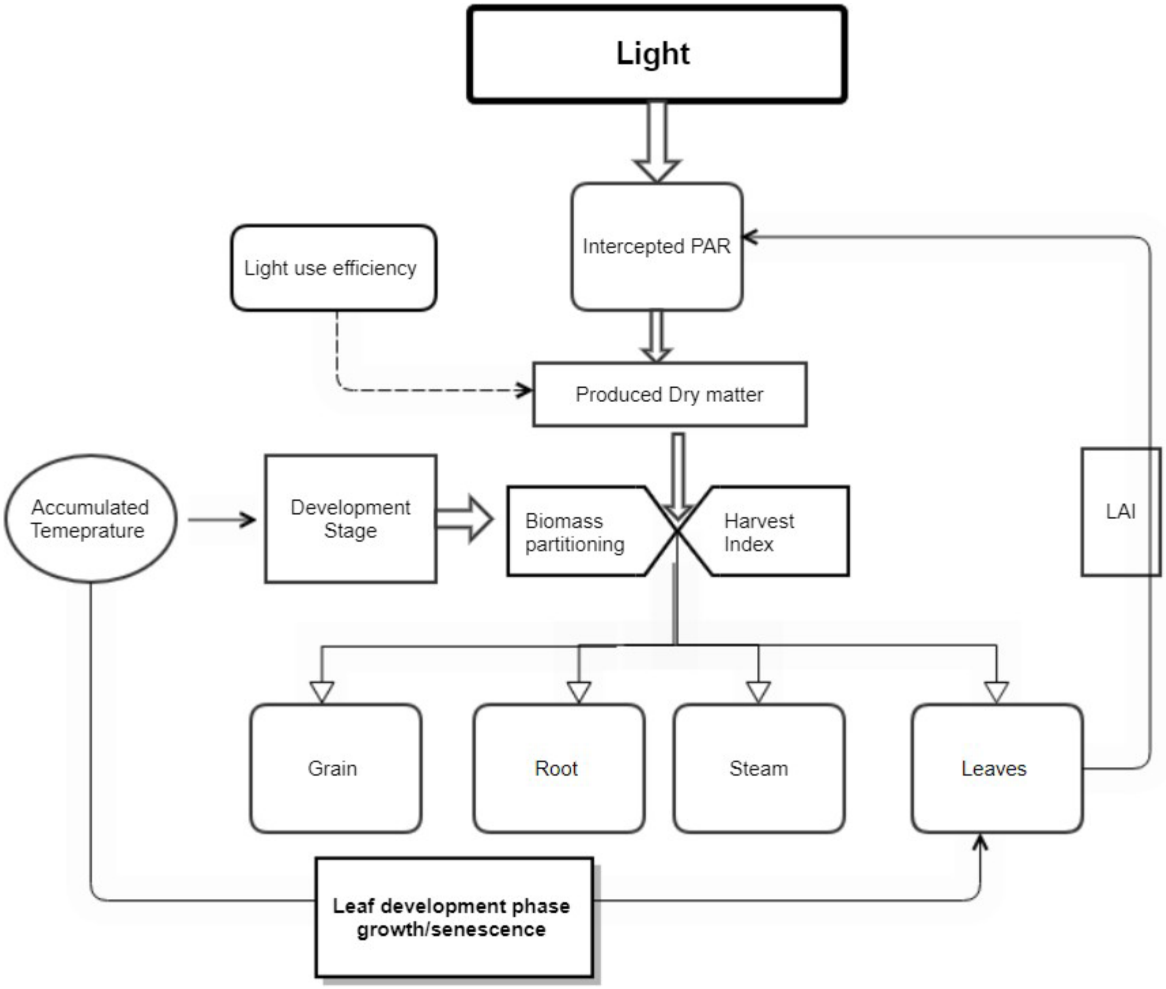
Field experiments require a lot of resources and still do not offer sufficient data to identify the appropriate management practices to achieve sustainable intensification (Jones et al., 2017). Crop models are a collection of mathematical equations that describe how crop genetics, crop management practices, and the environment interact to affect crop yield. It is essentially a mathematical model of a cropping system. Crop models were introduced in the first half of the 20th century by Bavel (1953) and de Wit (1958), establishing the foundation for the use of simulation models for research in plant-soil systems.

The two types of crop models are mechanistic and empirical models. The mechanistic model permits the analysis of the complexities of the ecosystems it describes and provides insights into the system's dynamics in different conditions, as they are based on the basic underlying processes of the phenomenon to be explained (Niarakis and Helikar, 2021). Empirical models, known as correlative or statistical models, are used to describe relationships between variables and observed behavior (crop response) without explicitly considering underlying or interrelated processes. In general, empirical models identify the correlation between several variables and the yield, providing a projection of the future based on the estimation of the predictor's variables (Estes et al., 2013). Crop simulation models are widely used to support decisionmaking, especially under stressed conditions of weather, through rapid, effective, and low-cost evaluation of different management strategies (Murthy, 2004).

2.6 Light Interception and Utilization Crop Model

The Light Interception and Utilization (LINTUL) model was developed by Spitters and Schapendonk (1990). The model utilizes the light use efficiency of the crop to simulate the dry matter and the associated grain yield. However, several versions of the model are now available. LINTUL-1 simulates the potential yield (Spitters, 1990), LINTUL-2 simulates the water limited yield (Gimplinger and Kaul, 2009), and LINTUL-3 simulates the yield under nitrogen limitations (Kooistra et al., 2014). The model is based on a series of equations that interconnect the growth processes based on the intercepted radiation, leaf area index (LAI), specific leaf area, light use efficiency, and dry matter production, while the development of the crop is a function of physiological time or thermal time (Figure 9).

The LINTUL model simulates the production of biomass based on Lambert-Beer's law (Foroutan-pour et al., 2001). The partitioning of dry matter to different organs is a function of physiological development, or growing degree days (GDDs). GDDs are calculated from the summation of the days with an effective daily temperature during the growing season. Light use efficiency is derived from the linear relationship between dry matter production and the accumulated intercepted photosynthetic active radiation (Gimplinger and Kaul, 2009).



Source: Author's creation, based on Spitters and Schapendonk (1990).

Figure 9. Relational Diagram of LINTUL-1

CHAPTER 3: METHODOLOGY

3.1 Study Area

Ghana is a West African country located on the Gulf of Guinea between latitudes 4°N and 11°N and longitudes 4°W and 2°E, covering 23,884,245 hectares. The country is divided into 10 administrative regions and 216 districts, covering six different AEZs (Coastal Savannah, Evergreen Forest, Deciduous Forest, Transitional, Guinea Savannah, and Sudan Savannah). Generally, the average yearly temperature ranges between 26.1°C in the Western Region and 28.9°C in the northeast of the Upper East Region. Mean annual rainfall varies from about 1,000 millimeters (mm) along the northeast frontier of the Upper East to 2,200 mm along the southwest coast of the Western Region. The coastline barely receives 800 mm of rainfall per year; in general, this part of the country is considered an arid region (MoFA, 2015).

During the 2020 growing season, IFDC's FERARI program conducted several trials on maize. However, this study focuses on only eight stations: Ejura, Mampong, Nyankpala, Wenchi, Kwame Nkrumah University of Science and Technology (KNUST), Sunyani, and two locations in Ashanti – Ashanti Anwomaso and Ashanti Ayeduase) (Figure 8). To map the potential yield in Ghana, we selected 10 points in each district based on the vegetation band on the land use map of the country. However, the density of vegetation in some districts was not high, so only eight points were selected automatically.

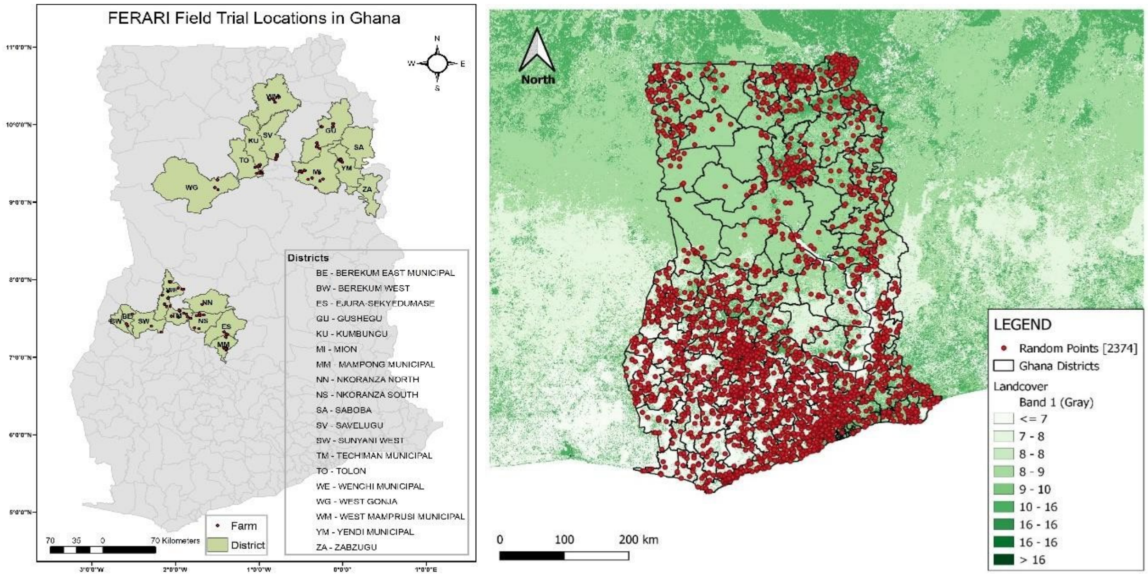


Figure 10. FERARI Experimental Field Locations (left) and Selected Data Points at District Level in Ghana (right)

3.2 Data

The field data from FERARI experiments for 2020 were used to calibrate the LINTUL-1 crop model and determine different factors affecting the yield gap in the experiments. The soil data were obtained from the soil analysis conducted after taking samples at FERARI field stations (Figure 8; Appendix 1). Some general soil data, such as water-holding capacity and root zone depth, were obtained from the ISRIC SoilGrids database Africa soil property map at a spatial resolution of 1 kilometer (km).

The weather data for FERARI trial locations and for the selected locations at the district level in Ghana were downloaded using the Google Earth Engine based on the coordinate system of each point. The Google Earth Engine extracted the weather data from ERA5, developed by ECMWF / Copernicus Climate Change Service ERA5 is an 11 km resolution map, and this is acceptable because the variance of weather data in a small-scale area is not excessive (Muñoz Sabater, 2019).

The data about fertilizer application and different treatment combinations used were obtained from the experimental protocol of FERARI field study of 2020 (Table 1).

Table 1. Treatments Used in FERARI Stations

Treatment	Ashanti Anwomaso	Ashanti Ayeduase	Ejura	KNUST	Mampong	Nyankpala	Sunyani	Wenchi
Control	X	X	X	X	X	X	X	X
NPK	X	X	X	X	X	X	X	X
NPK + S	X	X	X	X	X	X		X
NPS	X	X	X			X		
NKS	X	X	X			X		
PS	X	X	X			X		
PK	X	X	X			X		
N(PR)KS	X	X	X			X		
N(P+PR)KS	X	X	X			X		
PKS	X	X	X			X		
NPK + Zn + S				X	X		X	X
NPK + Zn				X	X			X
NPK + Zn + S + Fe							X	X
NPK + Zn + Fe								X

3.3 LINTUL-1 Crop Model

LINTUL-1 is a mechanistic model that utilizes light interception and light use efficiency to simulate the yield. The intercepted photosynthetic active radiation (IPAR) is a function of daily total radiation, LAI, and the extinction coefficient of light (Spitters and Schapendonk, 1990), modeled using Eq. 1.

$$\boldsymbol{IPAR = RPAR \times (1 - e^{-k \times LAI})} \qquad \textbf{Eq. 1}$$

RPAR is the photosynthetic active radiation part of the daily total radiation in the band from 400 nanometers (nm) to 700 nm, or 0.5 of the total radiation intercepted by the earth, *FPAR*. It is calculated using Eq. 2.

$$\boldsymbol{RPAR = FPAR \times DTR} \qquad \textbf{Eq. 2}$$

LAI is a crop parameter in which its mode of growth over time is a function of crop development stage or of the total thermal time accumulated by the crop. During the juvenile stage, the growth of LAI follows an exponential function in Eq. 3. In general, the juvenile stage in the model is limited by an accumulated thermal time of 330 GDDs or when LAI attains a value of 0.75 m^2 (leaf)/m^2 (soil) (van Oijen and Leffelaar, 2010).

$$\boldsymbol{GLAI = LAI \times \frac{(e^{RGRL \times DTEFF \times DELT}) - 1)}{DELT}} \qquad \textbf{Eq. 3}$$

When the number of GDDs is above 330, the growth of LAI (GLAI) depends on the amount of assimilate partitioned to the leaves multiplied by the specific leaf area (SLA) of the crop. In general, SLA used in the model is constant as long as the implementation of a dynamic model of the change in SLA will not improve the model simulation (Farré et al., 2000).

$$\boldsymbol{GLAI = SLA \times RWLV} \qquad \textbf{Eq. 4}$$

Where the relative weight of the leaves (RWLV) is the change in the weight of the leaves.

Leaf senescence reduces the LAI and the leaf weight and is a function of leaf death due to aging (RDRDV) or shading (RDRSH). Leaf death (RDR) is cited as the maximum between RDRDV and RDRSH. RDRDV is only after anthesis, while the RDRSH is a function of the LAI itself. When the LAI reaches a critical value (LAI_{cr}), the PAR does not reach the leaf in the bottom part of the crop because it is shaded by the upper leaf. RDRSHM is a standard value used to calculate RDRSH.

$$\boldsymbol{RDRSH = RDRSHM \times \frac{(LAI - LAI_{CR})}{LAI_{CR}}} \qquad \textbf{Eq. 5}$$

LAI reduction due to leaf death or senescence (DLAI) is therefore quantified by Eq. 6.

$$\boldsymbol{DLAI = RDR \times LAI}$$

Therefore, the change in LAI becomes RLAI (Eq. 7).

$$\boldsymbol{RLAI = GLAI - DLAI} \qquad \textbf{Eq. 7}$$

RWLV is a function of the partitioning coefficient of dry matter to the leaves multiplied by the total produced biomass. The partitioning coefficient of dry matter to the leaves (FLV), to the stem (FST), to the roots (FRT), and to the storage organs (FSO) follows the development stage of the crop. During the vegetative stage and under the potential conditions, most of the dry matter is allocated to the leaves, then to the roots and the stems. During the reproductive stage, the crop allocates the dry matter more to the storage organs.

$$\left.\begin{array}{ll} \left.\begin{array}{l} RWLV = GTOTAL \times FLV \\ RWLVG = GTOTAL \times FLV - RWLVD \end{array}\right\} & \textit{Leaf growth rate} \\ RWST = GTOTAL \times FST & \textit{Steam growth rate} \\ RWRT = GTOTAL \times FRT & \textit{Root growth rate} \\ RWSO = GTOTAL \times FSO & \textit{Storage Organ growth rate} \end{array}\right\} \quad \textbf{\textit{Eq. 8}}$$

GTOTAL is the total dry matter produced by the process of photosynthesis. As already explained, the model is a summary of interconnected equations and the GTOTAL is a function of IPAR (Eq. 1) and the radiation use efficiency (RUE) of the crop. RUE is measured from the field experiment as the slope of the linear regression line between the dry matter produced and IPAR.

$$GTOTAL = \frac{dw}{dt} = RUE \times IPAR \qquad \textbf{Eq. 9}$$

$$W = RUE \times \int_0^T IPAR \qquad \textbf{Eq. 10}$$

The model considers the RUE as a constant during the crop cycle, assuming a linear relationship between the intercepted radiation and the dry matter assimilation.

3.4 Calibration and Validation of the LINTUL-1 Crop Model

To calibrate the LINTUL-1 crop model, we selected the treatment within one of the stations in which the yield was the highest (Section 4.1). In general, the higher yield was considered where the crop grew close to its optimal conditions. The selected station was used to calibrate the LINTUL-1 crop model by calculating the accumulated temperature to anthesis and to maturity. In addition, the partitioning coefficients were proportionally adjusted based on the difference of the temperature required to reach maturity in the original version of the model (Farré et al., 2000) and the temperature needed to reach maturity in the study area.

Calibration of radiation use efficiency, relative growth of the leaves, and the specific leaf area was based on data from a literature review. The sowing date and the harvest date used in the simulation were matched with the sowing date from the field experiment.

3.5 Potential Yield Simulation and Yield Gap Measurement

3.5.1 Potential Yield Simulations

The potential yield at FERARI field experimental sites was simulated using the LINTUL-1 model, calibrated for Ghana, with temperature and solar radiation as inputs. The simulation date in the model was the same as the growing season of maize in each location (Appendix 2). A non-parametric Kruskal-Wallis test was used to study the variability of the temperature recorded in different field experiment locations. The Kruskal-Wallis test is based on ranking observations and does not require the assumption of normality. It compares the medians of three or more unpaired groups. Values are sorted from low to high, and analyses are based on how those rankings are distributed. Ranks are summed for each group, and disparities between sums are merged in a statistic that follows an x^2 distribution (Simoni et al., 2011). The same test was used to study the variability of the intercepted solar radiation at different locations. The simulated potential yield was used to measure the yield gap based on the observed yield in FERARI experimental stations.

3.5.2 Yield Gap Analysis

Multiple linear regression (MLR) was used to identify the factors contributing to and explaining the yield gap in the FERARI experimental dataset, using yield gap as a dependent variable (y) and other covariate as independent variables ($X1, X2, X3, X4, X5, Xn$), where β is the regression coefficient of each covariate (Eq. 11). The dataset, including the yield gap and all the covariates (soil data, fertilizer application rates, and rainfall), was split into two parts: 70% of the dataset was used for training and building the regression model and 30% was used to test the model.

The MLR was built using a stepwise approach, based on a bidirectional elimination method. The stepAIC function was called from MASS package (https://cran.r-project.org/package=MASS) in RStudio. Overall, the AIC method selects the best model over several possible models based on the stepAIC value, the model with the minimal value selected. AIC uses the highest likelihood estimate (L) and the number of independent variables (K) in the model to calculate the relative information value of the model (Eq. 12; Lord et al., 2021).

However, to improve the accuracy and reduce the standard error, the model selected by stepAIC was checked for multicollinearity using the variance inflation factor (VIF) method in R, which determines how much the variance of a regression coefficient is inflated because of model multicollinearity. The VIF function in R programming was installed from the CAR package (https://cran.r-project.org/package=car). Accordingly, the highly correlated variables were dropped from the dataset, and the process was repeated until stepAIC selected the best model with non-multicollinearity at a VIF < 10, which is considered a tolerant level of multicollinearity according to Kim (2019).

The selected regression model was tested using 30% of the dataset randomly selected for this purpose. The root mean square error (RMSE) and the coefficient of determination (R^2) were used to test the accuracy of the model. The RMSE, which is the square root of the mean of the square of all of the error between the predicted yield gap (Pg) and the observed gap (Og; Eq. 13), and the R^2 show the fraction of variance in the dependent variable that the independent variable can explain; it is measured as ratio between the sum of squares due to regression (SSregression) and the total sum of squares (SStotal; Eq. 14).

$$y = \beta 0 + \beta 1xi1 + \beta 2xi2 + \cdots + \beta pxipn + \in \qquad \textbf{Eq. 11}$$

$$AIC = 2K - 2\ln(L) \qquad \textbf{Eq. 12}$$

$$RMSE = \frac{1}{n}\sum_{g=0}^{n}(Og - Pg)^2 \qquad \textbf{Eq. 13}$$

$$R^2 = \frac{SSregression}{SStotal} \qquad \textbf{Eq. 14}$$

3.6 Potential Yield Map of Maize in Ghana

Based on the selected points at the district level (Section 3.1), the weather data was extracted from ERA5, based on Google Earth Engine. To simulate the potential yield at each point, the LINTUL-

1, calibrated based on FERARI experiments, was applied. Since June 1 is widely regarded as the ideal planting date in nearly all of Ghana (Adu et al., 2014), the sowing date in the model was set to that day to simulate the possible yield for each location. The simulated potential yield at each point was used to calculate the average potential yield at each district in the country, and after that, the average potential yield was mapped using software (package and function). To explain the large variability in the potential yield, a second map of intercepted photosynthetic active radiation was created using the QGIS geographic information software.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Observed Yield in FERARI Field Experiments

The observed yield was significantly different among the study sites. However, the observed yield in Ashanti Ayeduase (0.8 mt/ha) was not significantly different from the observed yield in Nyankpala (0.9 mt/ha), and the observed yields in Mampong (0.2 mt/ha) and Sunyani (0.3 mt/ha) were not significantly different (Figure 11). The yield obtained in Ejura ($p < 0.01$) was significantly the highest among all the study sites. Looking more closely at Ejura (Figure 11), we found that the application of NPS fertilizer gave the highest yield (6 mt/ha). The purpose of this comparison is to take the highest yield among stations and among fertilizer treatments and to consider it as the closest to the potential yield. Therefore, the fact that the difference in yields is not significant between the fertilizer treatments means our choice to use NPS fertilizer for LINTUL-1 calibration will not be a factor in the results.

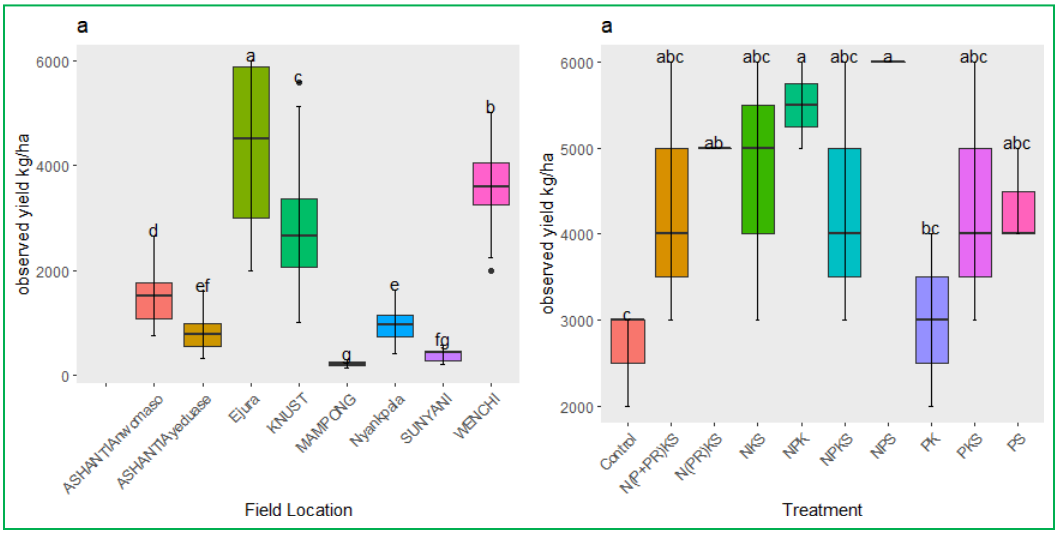


Figure 11. Observed Maize Yield in FERARI Field Experiments, 2020

4.2 LINTUL-1 Maize Calibration

Maturity of maize in the field experiment occurred on average 95 days after planting, while anthesis occurred 55-57 days after planting. This has been confirmed by SARI for the *Omankwa* variety used in Ejura. Accordingly, using the crop data and the weather data of the Ejura station, the temperature sum (Tsum) from emergence to maturity was adjusted from an original value of 1750 GDDs to a calculated value of 1796 GDDs, while the Tsum from emergence to anthesis was adjusted from 970 GDDs to 1027 GDDs. In addition, the partitioning coefficients were adjusted based on the Tsum from plantation to maturity calculated from the field (Table 2; Figure 12). The recalibrated LINTUL-1 model was able to simulate 6.9 mt/ha as the potential yield of maize in Ejura station, while the observed yield was 6 mt/ha. In addition, the model was able to simulate a maximum LAI of 5.1 m^2/m^2 (Figure 13).

Table 2. Calibrated LINTUL-Maize Parameters to Simulate the Potential Yield of Maize in Ghana

Parameters	Original Value	Source	Recalibrated Value	Source
Tsum Maturity	1750 GDD	Farré et al. (2000)	1796 GDD	Calculated
Tsum Anthesis	970 GDD	Farré et al. (2000)	1027 GDD	Calculated
SLA	0.016 m^2 g^{-1}	Farré et al. (2000)	0.032 m^2 g^{-1}	Srivastava et al. (2020)
Relative Growth Rate of Leaf Area	0.009 1/(deg. C d)	Farré et al. (2000)	0.02 1/(deg. C d)	Srivastava et al. (2020)

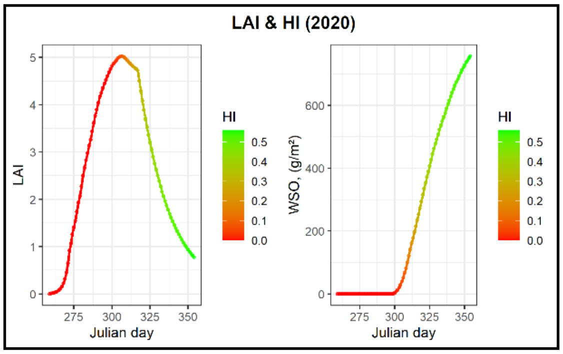


Figure 12. Simulated LAI and Storage Organ Weight at Ejura Station

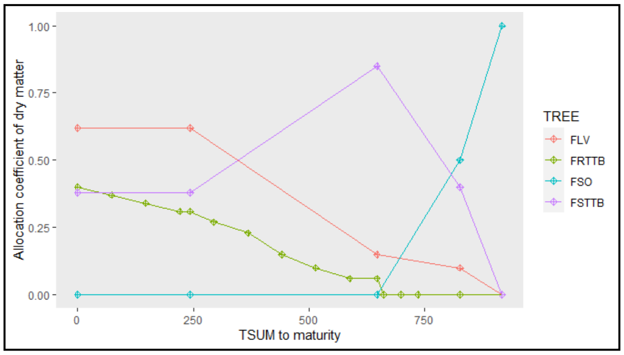


Figure 13. Adjusted Partitioning Coefficient of Dry Matter

4.3 Simulated Potential Maize Yield in the FERARI Study Locations Using LINTUL-1

The simulated potential yield of maize in on-station FERARI trials ranges between 5.5 mt/ha and 6.9 mt/ha (Figure 14). Overall, the maximum potential yield for maize was simulated in Ejura (6.9 mt/ha), followed by Wenchi (6.4 mt/ha), while the lowest potential yield was simulated at Ashanti (5.5 mt/ha).

The maximum LAI, which occurs at the end of the vegetative stage and by the beginning of anthesis, was simulated in Mampong (5.3 m^2/m^2), while the lowest was simulated in Ashanti (4.2 m^2/m^2) (Figure 14). LAI, intercepted solar radiation, and temperature are the major factors driving the simulation of the assimilation of carbon dioxide and production of dry matter. The highest intercepted solar radiation was recorded in Ejura and Wenchi at 389.3 Mj/m^2 and 393.7 Mj/m^2, respectively, while the lowest IPAR was recorded in Ashanti (Figure 15). The difference in IPAR led to different levels of photosynthetic activity of maize in different stations, which impacted the assimilation level on the model equations and finally on the simulated potential yield. The Wilcoxon test shows that the daily variability of temperature (Figure 17) and intercepted radiation (Figure 16) were significantly different among stations (Tables 3 and 4). Temperature particularly drives crop development in the model by governing the partitioning coefficient of dry matter and through its effect on the occurrence of the development stage in the model. In general, temperature fluctuation affects the duration of the maize development stage between locations. However, the development stage occurrence of maize from the observed data and from the simulated data was not significantly different with the change in the temperature between different experimental locations; anthesis basically occurred 60-64 days after planting, except in Mampong, where anthesis occurred 67 days after planting. Maturity in the study location occurred mainly 96 days after planting.

However, the temperature difference between the period of development before anthesis and after anthesis affected the simulated harvest index, which altered the simulated shoot biomass and grain yield (Figure 18). For example, the daily average temperature in Mampong before anthesis (15.59°C) was lower than in Wenchi (16.59°C), which caused the vegetative growth to take 67 days in Mampong and only 62 days in Wenchi. But the average daily temperature after anthesis in Mampong (20.27°C) was higher than in Wenchi (19.79°C), which reduced the grain-filling period and yield. On the other hand, the temperature in Ejura was higher than in Wenchi in both cases, before (17°C) and after anthesis (20.58°C). However, the simulated shoot biomass and the simulated grain yield was higher in Ejura, which is explained by the high IPAR in Ejura compared to Wenchi. In addition, the high grain yield simulated in Ejura was associated with the high IPAR after the anthesis period. In general, the IPAR in Mampong was high during vegetative growth (before anthesis) compared to Ejura, resulting in a high simulated shoot biomass at that station (Figure 14).

Both the intercepted photosynthetic active radiation and temperature variability among locations and between the crop growth stages cause different simulated yields of maize. However, its appears that the amount of intercepted solar radiation has more effect on the harvest index simulated by the LINTUL-1 model.

Table 3. Wilcoxon Rank Sum Test With Continuity Correction for Temperature Variability

	Ashanti	Ejura	Mampong	Nyankpala	Sunyani
Ejura	***				
Mampong	***	***			
Nyankpala	***	***	***		
Sunyani	***	***	***	***	
Wenchi	***	***	***	*	*

***: $p = 0$, *: $p < 0.01$.

Table 4. Wilcoxon Rank Sum Test With Continuity Correction for Solar Radiation

	Ashanti	Ejura	Mampong	Nyankpala	Sunyani
Ejura	***		-	-	-
Mampong	***	no-sig		-	-
Nyankpala	***	***	***	-	-
Sunyani	***	*	***	***	
Wenchi	***	***	***	*	no-sig

***: $p = 0$, *: $p < 0.01$

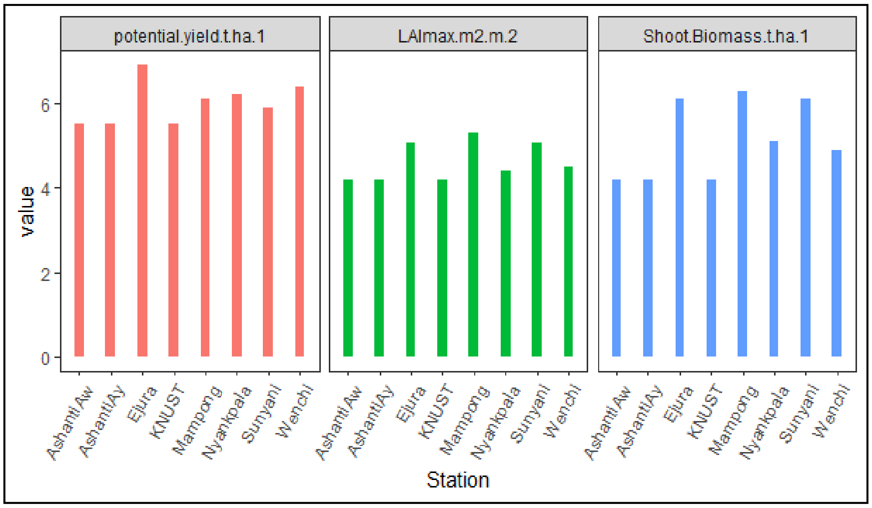


Figure 14. Simulated Potential Yield, Maximum LAI, and Shoot Biomass in FERARI Field Stations

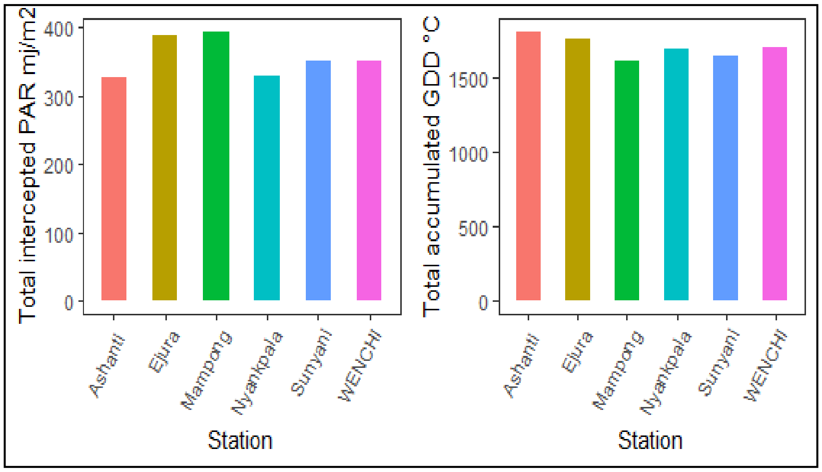


Figure 15. Accumulated Temperature and Intercepted Photosynthetic Active Radiation in FERARI Experiments

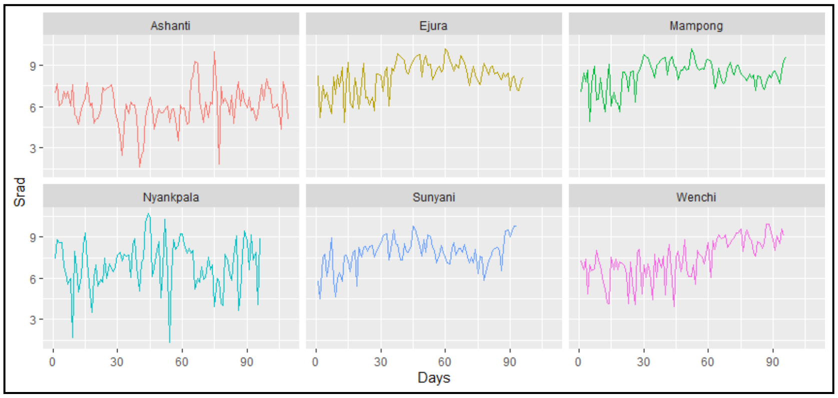


Figure 16. Intercepted Solar Radiation in the Field Experiments (Mj/m^2)

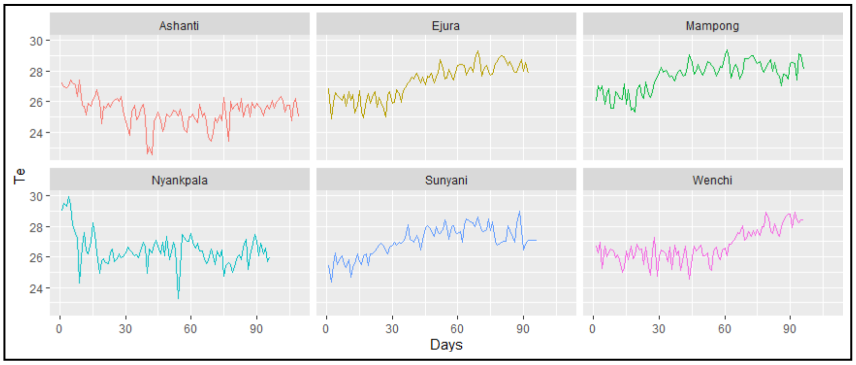


Figure 17. Temperature in the Field Experiments (°C)

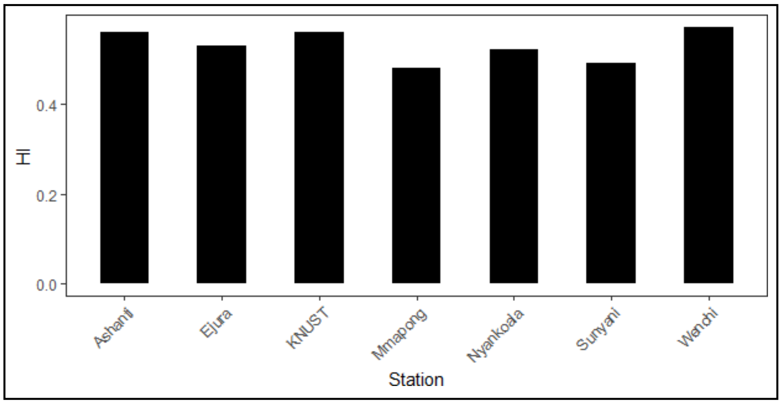


Figure 18. Harvest Index Simulated by LINTUL-1

4.4 Maize Yield Gap Quantification in FERARI Locations

The yield gap is significantly different between the study areas. The highest yield gap (96.4%) was measured in Mampong, while the lowest yield gap (14%) was measured in Ejura with the application of NPS fertilizer at rate of 18-20-0+10S (Figure 19). Within the same station, the yield gap differed due to the application of different fertilizers. For example, in Wenchi station, with the application of NPKS at rate of 120-40-40+15S, a yield gap of 39% was measured, which is significantly ($p \approx 0$) lower compared to all the other treatments. Similarly, in Ashanti Anwomaso and Ashanti Ayeduase, the lowest yield gap was measured with the NPKS treatment at rate of 120-40-40+15S at an average of 72% and 85%, respectively (Appendix 3; Figure 20). Additionally, in Ashanti Ayeduase, the only yield gap significantly different from the control was with the application of NPK and NPKS (Figure 20). Furthermore, the lowest yield gap (14%) was with NPS at a rate of 18-20-0+10S. Even so, it was not significantly different from the yield gap (21%) in the NPK fertilizer treatment at rate of 18-20-25. However, the yield gap decreased more with the application of NPS than with the application of NPK (Figure 21). In general, this finding shows the positive effect of the application of sulfur fertilizer to increase the yield and reduce the yield gap compared to the application of only NPK. More results regarding the treatments in different study areas are presented in the Appendices 4, 5, and 6.

In Wenchi, the application of NPK plus zinc (Zn) at a rate of 120-40-40+2.5Zn had no considerable influence on the yield gap when compared to the application of NPK alone at a rate of 120-40-40

(Figure 22). Similar results were obtained in Mampong, where the difference in the yield gap between NPK and NPK+Zn was not significant (Figure 23). We also found that the application of iron (Fe) has no effect on the yield gap in this study. Furthermore, the yield gap in the treatment with NPK+Zn+Fe at rate of 120-40-40-2.5Zn in Wenchi is significantly higher than the yield gap in the treatment where only NPK+Zn at rate of 120-40-40-2.5Zn was applied. Further, when comparing the control and NPK+Zn+Fe treatment, the yield gap is not significantly different (Figure 22).

The yield gap in Mampong (Figure 23) is very high, and that is because of the low achieved yield with the application of different fertilizer or without fertilizer in this station. In general, the reason behind these unexpected results needs more investigation.

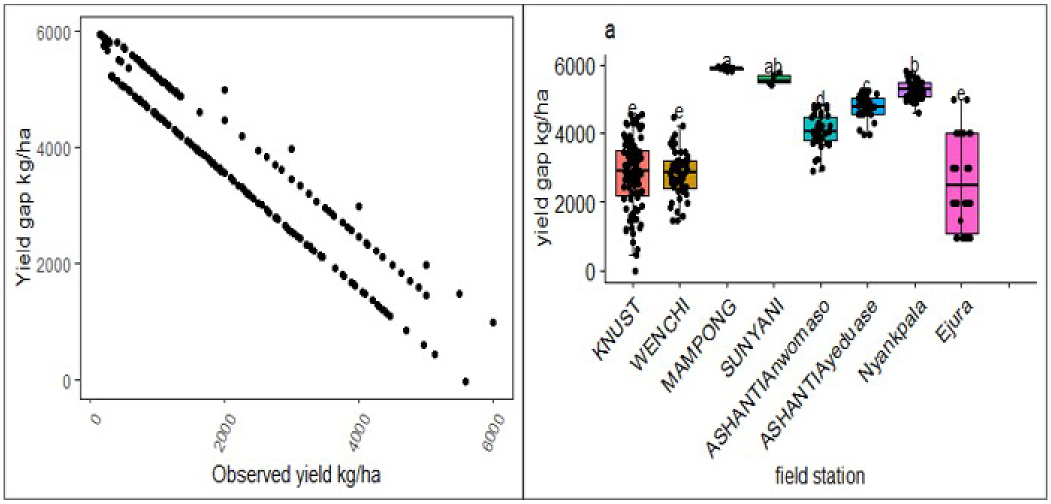


Figure 19. Yield Gap in FERARI Stations

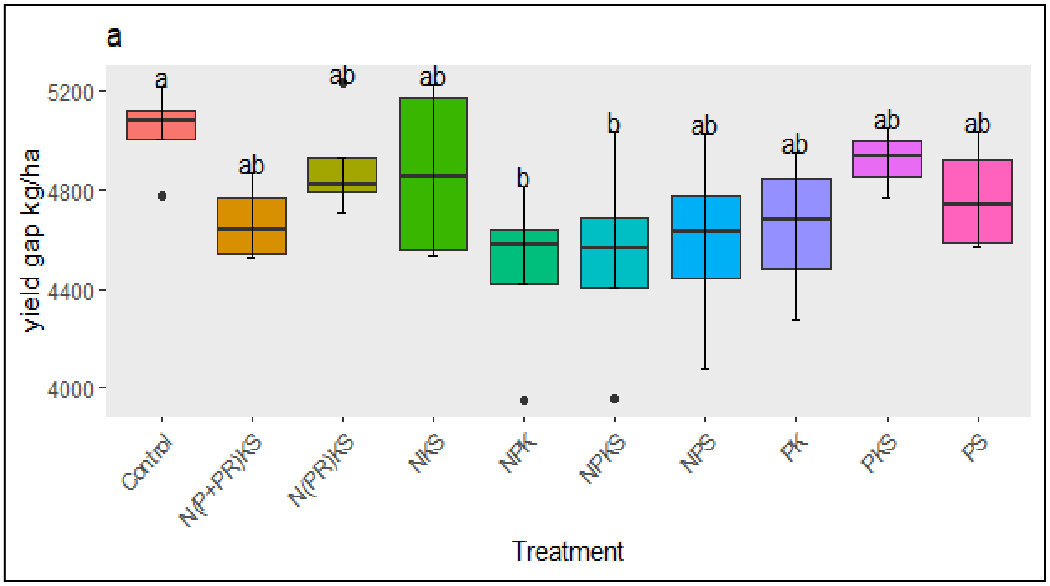


Figure 20. Yield Gap Variability Among Treatments in Ashanti Ayeduase Station

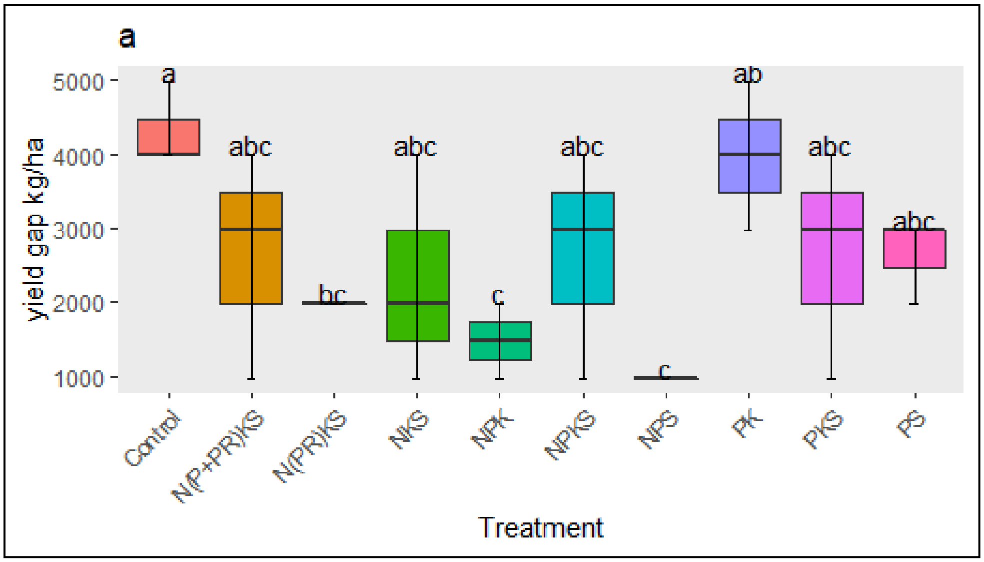


Figure 21. Yield Gap Variability Among Treatments in Ejura Station

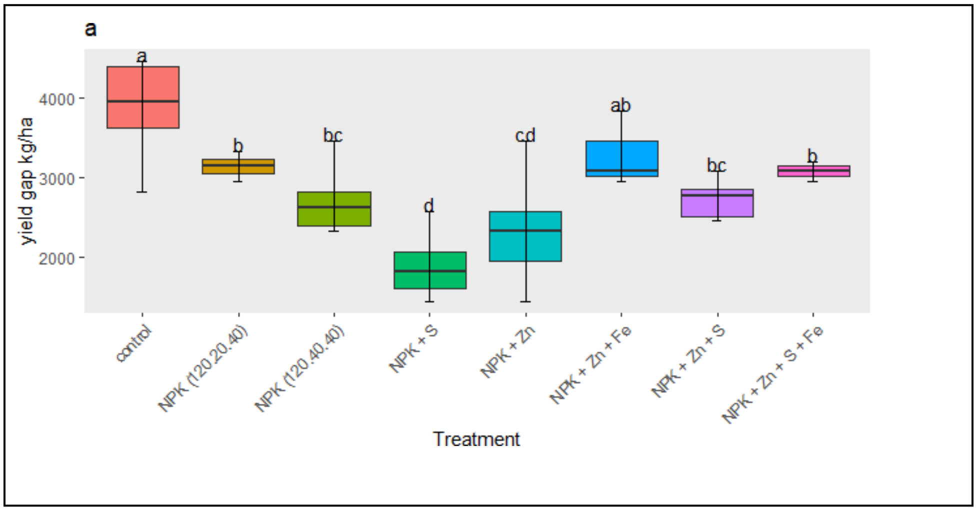


Figure 22. Yield Gap Variability Among Treatments in Wenchi Station

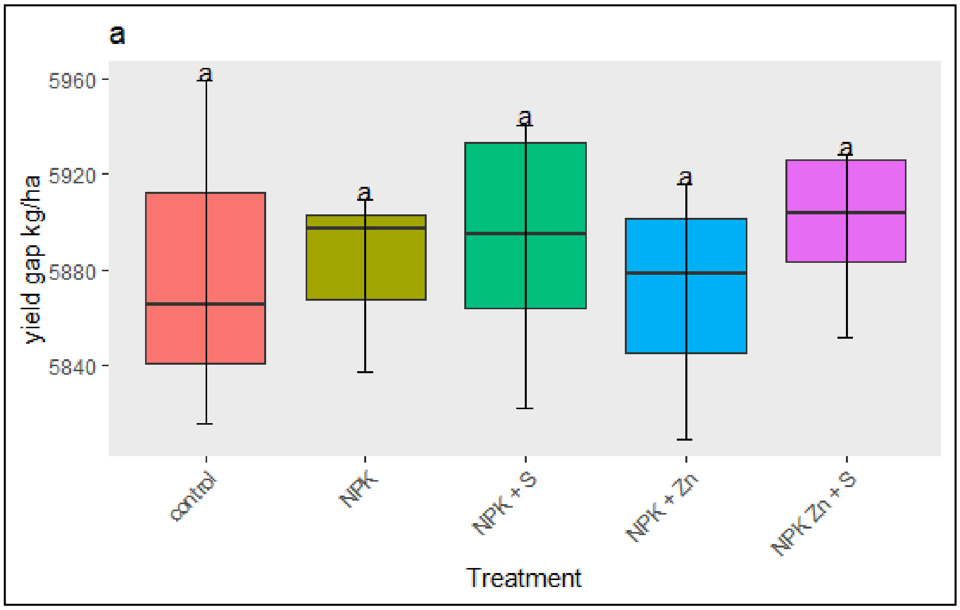


Figure 23. Yield Gap Variability Among Treatments in Mampong Station

4.5 Maize Yield Gap Explanation

To explain the yield gap variability and to explore the main factors driving the gap other than fertilizer, regression analysis was performed. The AIC stepwise statistical methodology identifies the most relevant variables among all the possible linear models that could explain the yield gap. The model selected by AIC was tested for multicollinearity, and the highly correlated variables were dropped in further analyses (Appendix 6). In general, multicollinearity existed between pH, cation exchange capacity (CEC), base saturation of the soil, concentration of micronutrients in the soil, and soil texture. Among the highly correlated variables, we kept only the pH as an explanative variable because its VIF value (3.66) was in the tolerance level of multicollinearity (VIF < 10) after the other correlated variables were dropped from the model. Indeed, removing those variables did not affect the explanatory power (R^2) of the outcome.

Accordingly, the best model identified by AIC explained the yield gap by soil organic matter content, amount of rainfall, root zone depth, amount of fertilizer applied, soil texture, soil pH, and available phosphorus in the soil solution (Table 5). This model was able to explain 68.9% of the variability, with an RMSE of 774.3 kg/ha (Figure 24).

Soil organic matter content has a highly significant ($p \approx 0$) effect on the yield gap of maize. Increasing organic matter by one unit reduced the yield gap by 1,364 kg/ha. The water-holding capacity of the root zone also significantly contributed to the yield gap ($p < 0.01$). The correlation between the yield gap and soil water-holding capacity was negative, which means increasing the ability of the soil to retain water will reduce the yield gap. In general, increasing the water-holding capacity by one unit reduces the yield gap by 302 kg/ha. Furthermore, the root zone depth significantly ($p \approx 0$) explains the gap, with a coefficient equal to -36.8 kg/ha. The AIC model considers only N and S fertilizer application as important variables to explain the yield gap. Application of 1 kg/ha of nitrogen reduced the gap by 12 kg/ha, while 1 kg/ha of sulfur reduced it by 15.5 kg/ha. Even though nitrogen reduced the yield gap, the effect was still very low, which reflects the low N use efficiency in the study areas. The importance of sulfur as a secondary micronutrient is also highlighted by these results. The model selected by AIC does not consider phosphorus and potassium as explanative variables. However, a multilinear model with the covariates selected by AIC with the addition of phosphorus and potassium as explanative variables (Table 5) was tested. This shows that phosphate and potassium fertilizer did not significantly affect the yield gap of maize in the study areas.

These findings identified a contribution of the soil structure and chemical proprieties to the maize yield in the study areas, which reveals that the gap is not solely caused by fertilizer application rate, but also soil organic matter, soil pH, soil water-holding capacity, and root zone depth. Rainfall also contributes to the yield gap, as an increase in the amount of rain reduced the gap by 12 kg/ha. Soil organic matter, soil pH, and water-holding capacity are the factors that contribute most to closing the yield gap.

Table 5. AIC Multiple Linear Regression Model to Explain the Yield Gap of Maize

Covariate	Estimate	Std. Error	T value	Sig
Intercept	16456.649	1434.083	11.475	***
Root zone depth	-36.8347	4.3469	-8.474	***
Rainfall	-12.4368	0.8601	-14.46	***
Nitrogen fertilizer	-12.7335	1.6918	-7.527	***
Sulfur fertilizer	-15.5808	8.3081	-1.875	.
Iron fertilizer	103.6477	39.3137	2.636	**
Phosphate rock	3.5896	1.5716	2.284	*
pH	565.6731	132.5054	4.269	***
Organic matter	-1364.609	154.4637	-8.834	***
Soil phosphorus	-2.9206	0.7118	-4.103	***
Water-holding capacity	-302.0255	119.1135	-2.536	*

***: $p = 0$, *: $p < 0.01$, .: $p < 0.05$

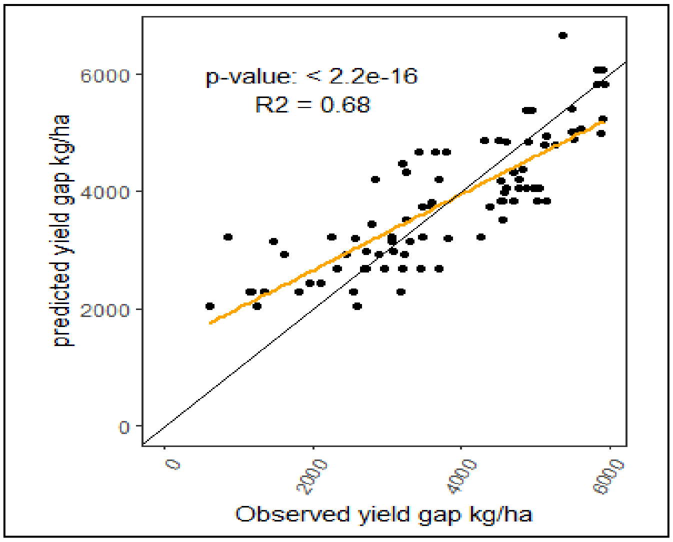


Figure 24. Accuracy of the MLR Model in Explaining the Yield Gap by the Covariates

4.6 Potential Yield Map of Maize

Based on LINTUL-1, the Coastal Savannah and Guinea Savannah AEZs have very high simulated potential yields, ranging from 5.5 mt/ha to 8 mt/ha, while the Semi-Deciduous Forest and Western Region AEZs have relatively low potential yields, in the range of 2-5 mt/ha. In the Transitional AEZ, maize has a potential yield of 5-6 mt/ha (Figure 25a). A map of the total intercepted radiation was created to explain this fluctuation in the potential yield (Figure 25b). The variability in IPAR in Ghana greatly explains the potential yield. For instance, the total IPAR throughout the maize growing season was quite high in the Coastal and Guinea Savannah AEZs; as a result, LINTUL-1 simulated a high potential yield for this region at more than 6.5 mt/ha. Similarly, LINTUL-1 simulated a low potential yield for the Western Region because of the lower IPAR.

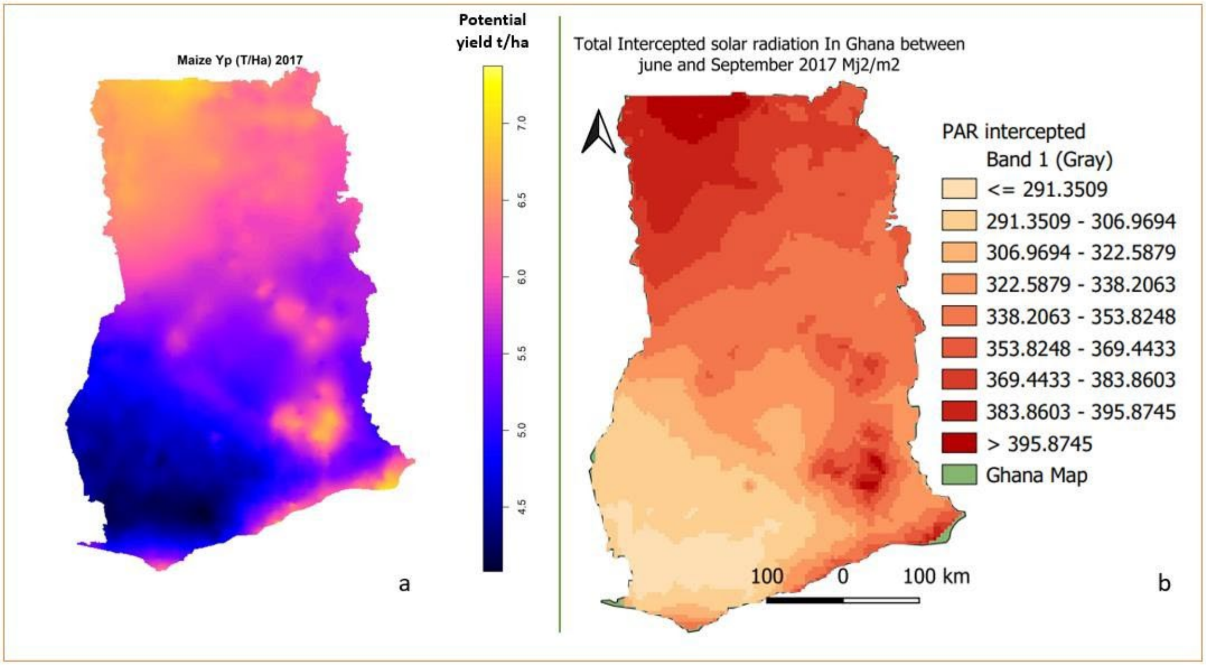


Figure 25. (a) Potential Maize Yield in Ghana in 2017; (b) Intercepted Photosynthetic Active Radiation in June-September 2017

4.7 Discussion

4.7.1 LINTUL-1 Validation

Using a light use efficiency crop model, this study was done to calculate the potential yield and yield gap of maize in Ghana. The stations where the field experiments were conducted had a fluctuating simulated potential yield between 5.5 mt/ha and 6.9 mt/ha. Similar results were reported by MacCarthy et al. (2018). In addition, LINTUL-1 simulated a potential yield of 6.2 mt/ha for the Nyankpala Region, which is about 10 miles away from Tamale, where MacCarthy et al. (2018) reported a potential yield of 6.4 mt/ha using the DSSAT crop model. The potential yield simulated in this study in the northern regions of Ghana ranged between 6 mt/ha and 8 mt/ha. Previously, Abdulai et al. (2015) reported 6 mt/ha as the potential yield in northern Ghana, which is in agreement with our findings in this study. Furthermore, the potential yield of several maize varieties in Ghana was reported to be in the range of 4-6 mt/ha (IFDC and USAID, 2016), which is lower than what was simulated in this study. This would be expected because the value assigned to each variety was based on the highest yield achieved in a farm experiment in which the stressors are not completely managed.

4.7.2 Potential Maize Yield in Ghana

In this study, the potential maize yield was higher in the northern regions compared to the southwestern region of Ghana. Interestingly, the IPAR in each region basically followed the same trend as the potential yield. According to Yang et al. (2021), one of the major causes of the variability in the yield potential between various regions of the world is the unequal distribution of solar radiation, as different solar radiation levels are caused by variability in the cloud cover index between different regions. In Ghana, the cloud cover index is high in the Rainforest zone, where less solar radiation reaches the ground level compared to the Savannah, where the cloud cover index is lower (Tanu et al., 2021) (Appendix 7). This phenomenon is reflected in our finding for the IPAR and the potential yield variability in Ghana. This study sets a strong basis for analyzing yield potential, but further improvement may be needed to quantify the potential maize yield more accurately in Ghana through improved calibration and with experimental data throughout the entire country.

4.7.3 Maize Yield Gap in Ghana

The yield gap in this study was measured as the difference between the theorical potential yield simulated by LINTUL-1 and the yield attained in the experimental sites. This approach has been used in several studies to quantify the yield gap (van Ittersum and Cassman, 2013; Boling et al., 2021). The yield gap quantified in the study location was between 14% and 96.4%. Similar values for the maize yield gap were reported by van Loon et al. (2019), ranging from 67% to 87%, but for water-limited yield. In general, the yield gap of maize in Ghana is very high compared to the average gap in West Africa of 20-36% (Danquah et al., 2020).

4.7.4 Fertilizer Application and Yield Gap

The findings of this study clearly demonstrate that combining sulfur with NPK fertilizer reduces the yield gap. In Wenchi, for example, the yield gap in the NPKS treatment was lower than the yield gap in the NPK treatment. Sulfur’s usefulness in increasing maize production has already been reported by Sutar (2017), who argued that increased sulfur content in the soil leads to increased nitrogen uptake. Similarly, Kugbe et al. (2019) found that the application of 11.3 kg of sulfur, 1.3 kg of zinc, and 1.3 kg of boron with NPK increased maize yield by 26%. Sulfur plays a key role in maize metabolism, as it is required for the synthesis of essential amino acids, such as cysteine, cystine, and methionine. As a result of its relationship with the protein structure, sulfur has an effect on crop quality (Sutar et al., 2018).

Zinc had a non-significant effect on the yield gap in this study. This may indicate that the soil has sufficient Zn in the solution. A soil analysis for Wenchi and Mampong shows a Zn level of 3.8 mg/kg and 4.9 mg/kg, respectively, which is above the required threshold (0.90-1.65 mg/kg) for maize to show a significant response (Eteng and Asawalam, 2017). In addition, the application of iron did not contribute to decreasing the yield gap. In general, the yield gap in the treatment NPK+Zn+S+Fe was higher than the yield gap in the treatment NPK+ZN+S. Similarly, the gap observed in the NPK+Zn+Fe treatment was higher than the gap in the NPK+Zn treatment. The decreased yield with application of iron could be due to a toxicity effect of this element. Toxicity has been confirmed by Chérif et al. (2009), who found that around 50% of lowlands in West Africa are under iron toxicity stress, which has a significant negative effect on the crop yield. In addition, Annan et al. (2010) found the iron concentration to be high in some crops cultivated in Ghana, such as *Ocimum canum (8), Clausena anisate,* and *Rauwolfia vomitoria*. Further studies and analysis are needed to explore why iron application decreased the yield of maize.

4.7.5 Yield Gap Analysis

Closing the yield gap in maize production in Ghana has so far been associated with increased fertilizer use, as well as increased use of improved seeds, herbicides, and mechanization (Wahab et al., 2022). However, in this study, we explored the effects of several factors on the yield gap, including fertilizer application, soil chemical proprieties, and weather conditions. The application of fertilizer, especially NPKS, increased the yield of maize and reduced the yield gap in Ghana. However, a wide gap still exists between the observed yield and the potential yield. This was also observed by Adzawla et al. (2021a). In general, the yield gap of maize in Ghana is the result of genetic-environmental-management interactions factors. Instead of fertilizer application, several studies have indicated that interactions among three biophysical constraints – poor soil fertility, low plant water availability, and climate variability – are the main causes for the low maize yield (Danquah et al., 2020).

4.7.5.1 Soil Organic Matter

The results of this study show that low soil organic matter was the major factor driving the yield gap. Increasing the organic matter content in the soil by 1% will reduce the yield gap by 1.3 mt/ha. These findings are comparable to those of Kane et al. (2021), who found that increasing the organic matter content in the soil by 1% enhanced maize production by 2.2 mt/ha under dry conditions. Soil organic matter in the study locations ranged from 0.89% to 3.30%, which is on the lower end; a fertile soil should contain at least 4% organic matter (Logah et al., 2011). Soil organic matter has a major role in the cropping system in Ghana, due to its impact on physical, chemical, and biological factors, such as soil water retention, nutrient cycling, and plant root development. Additionally, Oldfield et al. (2019) mentioned that increasing the soil organic matter in maize production from 0.86% to 3.44% could reduce the need for nitrogen fertilizer by 70%.

4.7.5.2 Soil pH

Soil pH is the second largest contributor to the yield gap in the study locations (Table 5). The yield gap typically increases by 565 kg/ha when the pH increases by one unit. This is contrary to the findings of The et al. (2006), who reported that increasing soil pH improved the yield of maize because it improved the soil CEC and reduced the aluminum and iron oxide in the soil solution, increasing the availability of nutrients.

The soil pH in the study areas ranged from neutral to moderately acidic (4.94-6.67). According to Baquy et al. (2018), this is higher than the desired pH for maize growth, which is between 4.46 and 5.07, depending on the type of soil. The soil pH for the area studied by The et al. (2006) was between 4.67 and 5.10, which is lower than the pH in our study areas. The pH would need to increase by 0.27 to push it to the range in our study. Soil pH has been reported to not be a good indicator for the possible effect of acidity on crop yields compared to the aluminum concentration (Fox, 1979). However, the soil pH in maize production is recommended to be kept above 5.5 to avoid any chemical change in the soil solution and to avoid an interaction with chemical inputs, particularly herbicides, which could injure the crop (Marsh and Lloyd, 1996).

4.7.5.3 Rainfall and Moisture in the Soil

Rainfall, soil water-holding capacity, and root zone depth all significantly explain the yield gap. The low amount of rainfall appeared to increase the yield gap in the study areas. The low water-holding capacity of the soil is accompanied by a low capacity of the soil to support crop growth under severe drought, leading to the loss of the available forms of nutrients and organic matter through erosion and runoff (Amegashie et al., 2012). Several studies support the findings from this study. For example, Yangyuoru et al. (2009) proved that different levels of soil moisture or water-holding capacity result in different grain and dry matter yields in maize production. The importance of soil moisture was also determined by Admasu et al. (2017), who found moisture stress during different growth stages of maize to lead to different levels of yield. This indicates that sufficient moisture in the soil is required during the development and maturity stages of maize.

In this study, an increase in the soil water-holding capacity by one unit decreased the yield gap by 302 kg/ha. A high soil water-holding capacity strongly mediates the effect of low and erratic rainfall through supplying the crop water demand (Williams et al., 2016). Jiao et al. (2017) also observed that a high water-holding capacity stabilizes the yield of maize under variable rainfall.

4.7.5.4 Phosphate and Potassium Fertilizer

In general, the MLR stepwise model indicates that variability in the phosphorus fertilizer application from 20 kg/ha to 40 kg/ha and the variability in potassium application from 25 kg/ha to 40 kg/ha did not significantly explain the yield gap of maize in the study locations. Even so, the increase in phosphate fertilizer by 1 kg reduced the yield gap of maize by 8 kg/ha. This appears contradictory to findings in the literature. For example, Logah et al. (2014) did several experiments in Ejura and Ashanti Anwomaso and found that the application of 60 kg/ha of phosphate fertilizer significantly improved the yield of maize compared with the application of 30 kg/ha. Additionally, 60 kg/ha of phosphate fertilizer was also recommended for maize production by Adu et al. (2014). Moreover, Owusu-Bennoah et al. (1995) reported that the soils in Ghana are highly deficient in phosphorus, which means that the yield should positively respond to the application of phosphorus.

Increasing the potassium fertilizer increased the maize yield gap. However, different results were obtained by Adu et al. (2014), who recommended the application of 60 kg/ha of potassium fertilizer for maize in Ghana. Atakora et al. (2014) reported that increasing potassium fertilizer from 0 to 90 kg/ha increased yield from 2.5 mt/ha to 2.7 mt/ha. The exchangeable potassium in the study areas was between 0.01 mEq/100 g and 0.49 mEq/100 g, which is already less than the critical level of potassium in soil to grow maize of 0.6 mEq/100 g (Adeoye and Agboola, 1985). Basically, this indicates that application of potassium fertilizer should increase the yield of maize and reduce the gap, which did not happen in this case. However, some studies have reported that both deficient and excessive levels of potassium can inhibit the activity of carbon-metabolizing enzymes in leaves and limit photosynthesis through stomatal restrictions (Xu et al., 2020).

4.8 Conclusion

This study found that the LINTUL-1 model can simulate the potential yield of maize in different AEZs in Ghana. The potential yield map clearly shows a great potential for maize production in the northern regions due the high interception of photosynthetic active radiation. The simulation shows that the effect of temperature on the potential yield of maize is negligible compared to the effect of solar radiation.

Based on the data collected from eight different locations, a multiple linear regression model enhanced by Akaike information criterion explained 68% of the yield gap. Several factors other than fertilizer were found to explain the yield gap of maize. This study shows the importance of soil organic matter, soil water-holding capacity, root zone depth, rainfall, and fertilizer, particularly nitrogen and sulfur, in explaining the yield gap. It also shows that increasing soil organic matter by 1% increases maize yield by 1.3 mt/ha. Given the advantages and significance of soil organic matter, this discovery may help farmers manage their fields and focus their investments. In addition, pH variability can negatively influence the yield of maize, thus increasing the yield gap. However, a new finding is that increasing soil pH to 6 was widely reported to improve the yield of maize and other crops.

This study also highlights that sulfur has already become the fourth major nutrient for the production of maize in Ghana. In general, the application of sulfur shows a higher yield compared to the application of potassium. The recommended application of NPK only may need to be complemented with the addition of sulfur to increase maize yield. This study makes a valuable contribution to help and support decisionmaking in sustainable investments to improve the yield of maize in Ghana, indicating that not only the fertilizer should be considered when producing maize, but also improvement in the soil organic matter content, which will improve the water retention capacity and soil fertility. All of these factors will lead to closing the yield gap of maize in Ghana.

The methodology used in this study was efficient in quantifying and explaining two-thirds of the yield gap of maize in Ghana. Further studies are needed to quantify the water-limited yield in Ghana, which may help to provide a more comprehensive explanation for the yield gap caused by edaphic and management factors rather than radiation and temperature alone. In general, the production system in Ghana is based on rainfall, a main driver for yield, along with soil water-holding capacity and root zone depth, all of which may affect water availability to the plant.

APPENDICES

Appendix 1. Soil Data for the Study Areas

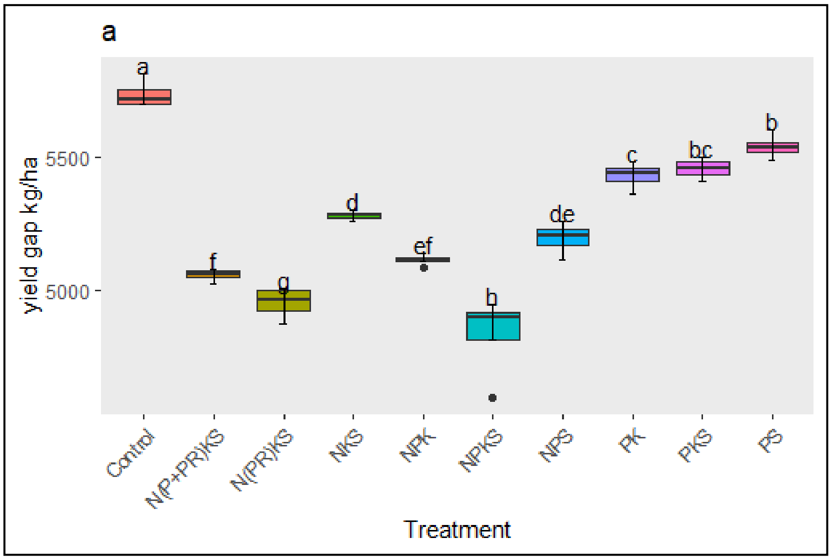
	pH	Exchangeable Acidity	Organic Matter	P Level in the Soil	Root Zone Depth	Water-Holding Capacity
FERARI Locations	4.9-6.67	0.7-0.95 mEq/100 g	0.89-3.3%	1.5-379 mg/kg	75-150 cm	V%

Appendix 2. Sowing Date and Harvest Date of Maize during This Study

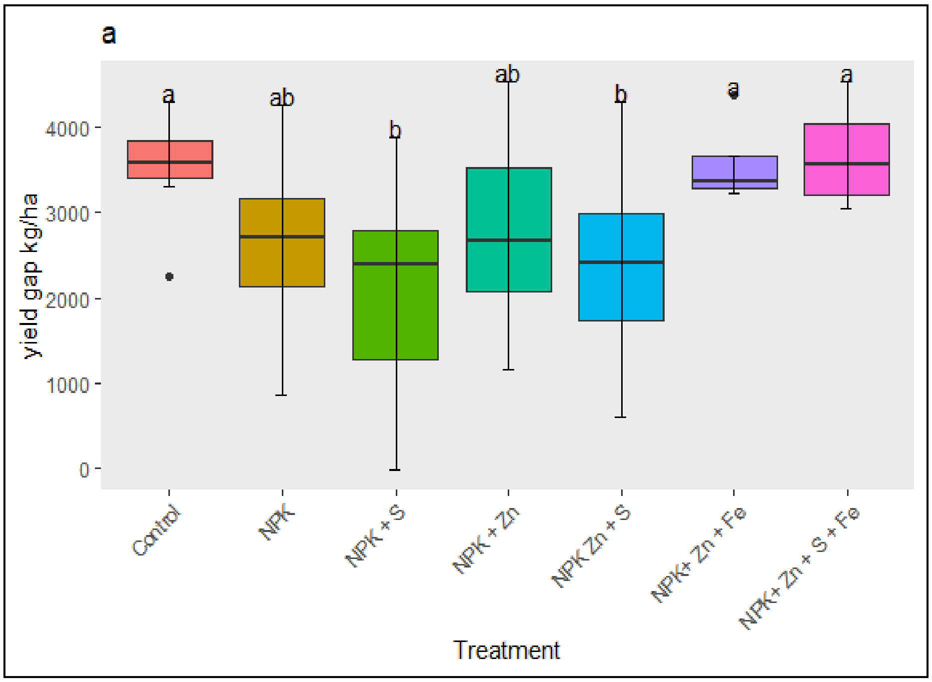
	Ashanti	KNUST	Mampong	Sunyani	Nyankpala	Wenchi	Ejura
Date of Sowing	June 1	May 15	September 24	October 1	June 24	August 19	September 16
Harvest Date	September 17	August 15	December 28	December 30	September 27	November 22	December 20

Appendix 3. Agroecological Zones of Ghana

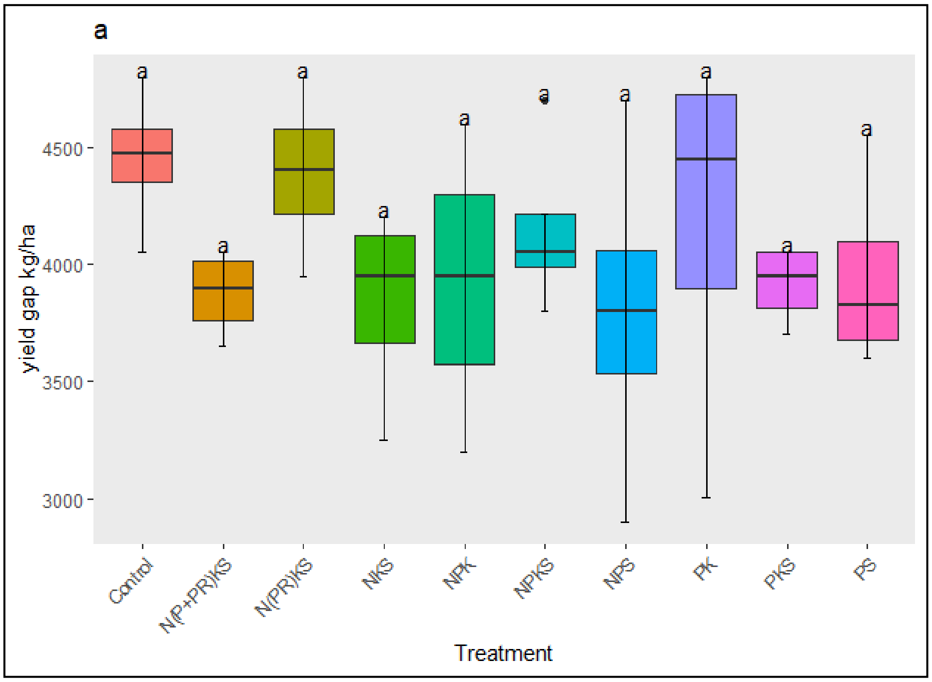
Appendix 4. Yield Gap Variability in Nyankpala Field Station



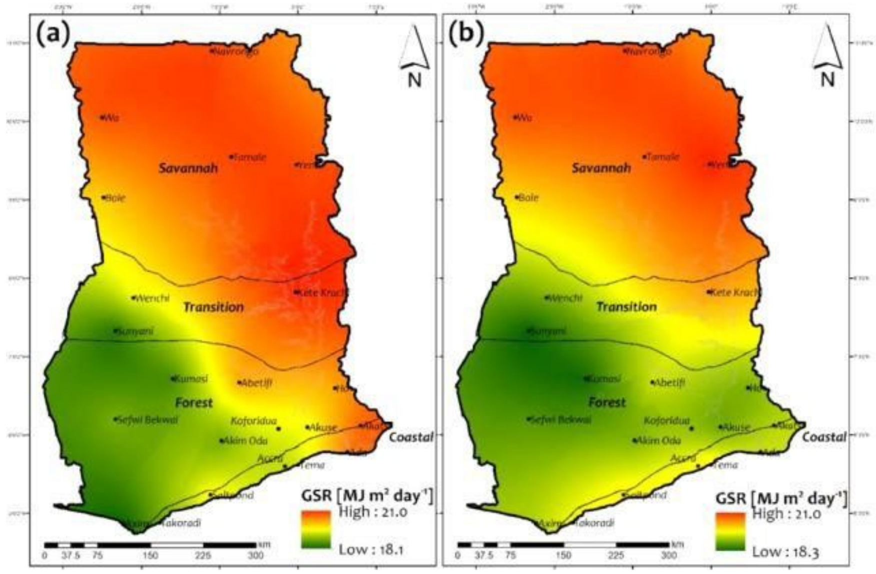
Appendix 5. Yield Gap Variability in KNUST Station



Appendix 6. Yield Gap Variability in Ashanti Anwomaso Station



Appendix 7. Solar Radiation Intercepted in the Ground in Ghana



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FERARI

FERTILIZER RESEARCH & RESPONSIBLE IMPLEMENTATION

FERARI is an international public-private partnership that builds science-based approaches to site-specific fertilization for widespread adoption by farmers in Ghana for improved food and nutrition security. This calls for a transformation of the fertilizer and food systems that must be driven by evidence-based agro-technical perspectives embedded in multi-stakeholder processes.

To support this transformation, the following institutions have partnered to implement the Fertilizer Research and Responsible Implementation (FERARI) program:

- International Fertilizer Development Centre (IFDC)
- Mohammed VI Polytechnic University (UM6P)
- OCP Group
- Wageningen University and Research (WUR)
- University of Liège (ULiège)
- University of Ghana (UG)
- University for Development Studies (UDS)
- Kwame Nkrumah University of Science and Technology in Kumasi (KNUST)
- University of Cape Coast (UCC)
- University of Energy and Natural Resources (UENR)
- Akenten Appiah-Menka University of Skills Training and Entrepreneurial Development (AAMUSTED) College of Agriculture Education
- Council for Scientific and Industrial Research in Kumasi (CSIR-SRI) and in Tamale (CSIR-SARI) and its subsidiary (CSIR-SARI-Wa)

FERARI operates in conjunction with the Planting for Food and Jobs program of the Government of Ghana (GoG) to embed development efforts into national policy priorities to reach impact at scale. It trains five Ph.D. and two post-doctoral candidates and dozens of master's-level students in building the evidence base for its interventions.

FERARI conducts hundreds of fertilizer response trials on maize, rice, and soybean, on-station and also with farmers, and demonstrates them to farmer groups in the northern and middle belt of Ghana. It conducts surveys among farmers and actors in the value chain to understand the drivers for use of fertilizers and other inputs and the marketing of the produce to enhance farm productivity and income. It helps the GoG to establish a Ghana National Fertilizer Platform, developing its soil mapping expertise toward an information platform.

The content of this report is the sole responsibility of the authors of the involved institutions portrayed on the front page.

IFDC

Developing Agriculture from the Ground Up