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Characterization of farmers and the effect of fertilization on maize yields in the Guinea Savannah, Sudan Savannah, and Transitional agroecological zones of Ghana

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A B S T R A C T

The aim of this study was to understand the impact of fertilizer use on maize yields in Ghana based on a survey among 1,363 farmers. Farmers were grouped into four typologies using Principal Component Analysis and stepwise regression to analyze the effects of fertilizer and other factors on yield and nutrient use efficiency (NUE). A partial factor productivity of 9.8–12.1 kg grain/kg fertilizer and an agronomic efficiency of 1.2–3.7 kg grain/kg N were found among the typologies. While use of NPK with sulfur and magnesium, are necessary for yield increase, the low NUE may hamper agricultural intensification. A targeted learning pathway for the farmers with most suitable characteristics for attaining highest maize productivity could serve as an example for less well performing farmers. Policies and programs in Ghana, such as Planting for Food and Jobs program that promote fertilizer application, must be redesigned to include measures that increase NUE.

Introduction

The deadline for the global commitment made by country leaders to achieve food and nutrition security by the end of 2030, as detailed by the United Nations Sustainable Development Goal 2, is fast approaching. Therefore, accelerating measures toward attaining this objective is crucial. Data show that there has been a gradual decline in the global prevalence of undernourishment from 14.8% in 2000 to 10.8% in 2018, suggesting that, a total of 821.6 million people were undernourished in 2018 (Food and Agriculture Organization of the United Nations (FAO), the United Nations Economic Commission for Africa (ECA) or the African Union Commission (AUC), 2020). Despite a global slight decline, the number of undernourished people in sub-Saharan Africa (SSA) has risen from 190 million people in 2000 to more than 239 million people in 2018. Similarly, there was an increase in the prevalence of severe and moderate food insecurity in SSA between 2000 and 2017. These trends raise concerns about achieving Sustainable Development Goal two (SDG2), especially in SSA (FAO, ECA and AUC, 2020). Abdullah et al. (2019) explained that SSA has a large rural population whose livelihoods depend on agriculture, but low productivity and unfavorable agroecological factors prevent the region from achieving food security.

In the 2020 Global Hunger Index, Ghana scored 15.2, indicating that the country is moderately food-secure (von Grebmer et al., 2020). This is similar to the average situation worldwide of a moderate hunger level. The 2012 Comprehensive Food Security and Vulnerability Analysis of northern Ghana showed that 680,000 people were either severely or moderately food-insecure (World Food Program, 2012). Specifically, 28%, 16%, and 10% of the people in Upper East, Upper West, and Northern regions, respectively, were severely or moderately food insecure. The assessment showed that poorer households and those with smaller farms had higher food insecurity. Similarly, Adzawla et al. (2021a) revealed that food security was largely moderate in northern Ghana, as 46.9% of sampled households had moderate dietary diversity and 35% had a moderate score on the Household Food Insecurity Access Scale. Nonetheless, 18.5% households in the region were severely food insecure (Adzawla et al., 2021a). Generally, several factors have led to food insecurity (Abdullah et al., 2019; Drammeh et al., 2019; Smith et al., 2017). These factors feed into the inability to produce enough food, especially through productivity improvement. The gap between potential and actual yields in Ghana remains large for almost all staple crops. This is due to several interrelated factors, including climate change and declining soil fertility. Farmers in northern Ghana have often mentioned low soil fertility as a major drawback for producing cereals in the area (Kanton et al., 2016). Continued cultivation of farmland, especially with same crop over the years, affects the soil's organic matter content. As the

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human population continues to increase, there is a need to provide more food for the rising population. Therefore, the use of inorganic fertilizer and sustainable intensification to improve crop production and ensure food security is crucial. In addition to intensified fertilizer application, improving nutrient use efficiency remains critical for maximizing yield gains. Bashagaluke et al. (2020) explained that the quantities of fertilizer applied by farmers and the associated nutrient losses are fundamental factors influencing crop production in SSA.

Over the past few decades, various interventions by both government and non-governmental organizations have been directed toward improving crop yields. These included programs and policies to address the low use and high cost of production inputs, especially improved seeds and fertilizers. Currently, the Investing for Food and Jobs agenda by the government of Ghana has prioritized addressing these and other challenges to ensure accelerated agricultural modernization and sustainable resource management (Ministry of Food and Agriculture, MoFA, 2018). To increase fertilizer use, the government of Ghana introduced a fertilizer subsidy program in 2008, which was merged into the PFJ program in 2017, which seeks to modernize the agriculture sector of the economy in order to improve food security, create employment opportunities, and reduce poverty. Such subsidy programs are important for addressing market failures in the fertilizer sector, especially those related to the high cost or unavailability of fertilizer in local communities (Alhassan et al., 2020). While fertilizer use is increasing in Ghana (Odionye et al., 2020), the average amount used per hectare of land remains low at around 20 kg ha^{-1}.

Studies have shown that application of inorganic fertilizer improves yields of crops, such as maize, in Ghana (Bua et al., 2020). There is a need to increase productivity in the future in response to the increasing population and expanding urbanization, and to prevent further encroachment into natural ecosystems. Maize is an important crop in Ghana, as it is cultivated and consumed in all agroecological zones of the country (Scheiterle and Birner, 2018). Maize production is also profitable, unless there is a disproportionate increase in input prices relative to output prices (Wongnaa et al., 2019). Yet, there is a wide gap between the actual and potential yields of maize, especially in northern Ghana. The fertilizer subsidy program and other programs implemented in the agriculture sector have not been able to address these persistent yield gaps. Ghana is unlikely to achieve SDG2 if there is a persistent shortage in maize supply. Therefore, the question remains as to what must be done to increase maize productivity. Potentially, the great diversity of farmers suggests that a deeper understanding of the production systems of the various farmer groups is needed. It is crucial to identify and tailor policies to meet the needs of the various sub-groups involved in maize production. The objective of this study is therefore, to analyze the various farmer typologies to identify the efficiency of their fertilizer use, and the effects of fertilization on their crop yields in the Guinea, Sudan, and Transitional agroecological zones of Ghana.

Methodology

Study location

This study was conducted in the Guinea, Sudan, and Transitional agroecological zones of Ghana. These zones are predominantly agrarian, as most people engage in crop production. Typically, there are differences in the climate, soil, and natural vegetation between the three zones. For instance, the average annual rainfall for the Transitional zone is 1300 mm (mm), while that of the Sudan and Guinea savannah zones is 1000 mm and 1100 mm, respectively (MoFA, 2017). Also, while farmers in the Transitional zone can cultivate crops in two seasons (major and minor), those in the Guinea and Sudan Savannah zones can only cultivate crops once a year. These differences are reflected in the production technologies and the associated yields of the farmers. Asravor et al. (2019) estimated that farmers in the forest-savannah transition zone were 45% more productive than those in the Guinea Savannah zone. Similarly, Wongnaa and Awunyo-Vitor (2019) estimated that the average yield of maize farmers in the Guinea Savannah zone was 2.2 metric tons per hectare (t ha^{-1}), while farmers in the Transitional zone averaged 4.2 2 t ha^{-1}.

Sampling procedure and data collection

The data for this study were obtained from a broader study that analyzed the crop yields, fertilizer use, and food security of farmers in the Guinea, Sudan, and Transitional zones of Ghana (Adzawla et al., 2021a). The farmers were selected through a multistage sampling procedure. In the first stage, three districts that benefited from the largest amount of fertilizer supplied in a region under the PFJ program in the 2019 cropping seasons were selected to ensure that most of the selected farmers used fertilizer. In the second stage, four communities were chosen from each of the selected districts based on their knowledge of crop production. These communities were selected from different geographical points in relation to the district capital as a way of capturing any diversity in the district. In the final stage, systematic random sampling was used to select about 15 farmers in each community. This gave a total of 1450 farmers. However, this specific study involved only maize-growing farmers which amounted to 1363 farmers. The data were collected using a structured questionnaire. Open data kit was adopted to minimize errors during data collection and entry. With the open data kit method, an application (app) was installed on android tablets and the designed questionnaire migrated unto the app. The app also allowed to collect data offline and migrated online to a central server that is managed by the researchers. Enumerators who assisted in data collection were trained on the app that allowed their effectiveness and efficiency. The coordinates of the location of each farmer were overlaid on the International Soil Reference and Information Center's (ISRIC) soil maps (https://data.isric.org/geonetwork/srv/eng/catalog.search#/home), and soil chemical, physical and biological properties (i.e. edaphic factors) at each point were extracted.

Data analysis

The data for this study were analyzed using PCA and stepwise linear regression. PCA was used to characterize the farmers by the various typologies based on several edaphic, socioeconomic, and production factors, such as fertilizer formulation. The use of PCA also improved the interpretability of the yield-explaining variables. Based on a biplot technique, the farmers were classified under four typologies. To understand the drivers of yield under these different typologies, a linear regression was estimated jointly for the four groups. The estimation was done stepwise to understand the significance of the various factors by their block and the interdependencies among these factors. Thus, a total of four different models were estimated. These involved maize yield as a function of (1) quantity of various fertilizer formulations, (2) edaphic factors, (3) other production inputs, and (4) fertilizer, edaphic factors, and other production inputs. Empirically, the estimated model is given by:

$$Maize\ yield = \beta_0 + \beta_s Fertilizer\ quantity + \varepsilon_1 \tag{1}$$

$$Maize\ yield = \beta_0 + \delta_s Edaphic\ factors + \varepsilon_2 \tag{2}$$

$$Maize\ yield = \beta_0 + \gamma_s Other\ inputs + \varepsilon_3 \tag{3}$$

$$\begin{aligned} Maize\ yield = {} & \beta_0 + \beta_s Fertilizer\ quantity + \delta_s Edaphic\ factors \\ & + \gamma_s\ Other\ inputs + \varepsilon_4 \end{aligned} \tag{4}$$

Table 1
Type and quantity of fertilizer applied by farmers.

Fertilizer type	Users No.	%	Quantity ($kg\ ha^{-1}$) Mean	Standard Deviation
NPK 15-15-15	463	32.8	293.4	189.5
NPK 15-20-20+0.7Zn	299	21.2	191.4	169.1
NPK 23-10-5 + 4MgO+2Zn	208	14.7	163.0	115.3
NPK 20-10-10+3S+2MgO	94	6.7	225.6	61.9
NPK 25-10-10	66	4.7	188.8	118.9
NPK 12-30-17+0.4Zn	39	2.8	138.3	139
NPK 21-10-10+2S	30	2.1	235.4	169.9
NPK 15-15-15+9.6S+1B	8	0.6	124.5	104.8
NPK 4-18-13+3S+3MgO+6CaO+0.1B	7	0.5	220.2	128.3
Ammonium sulfate	318	22.5	143.5	134.8
Urea	296	20.9	113.5	80.1
Users of at least one fertilizer type	1085	80.6	282.1	232.2

where β_s, δ_s, and γ_s are the parameters to estimate. These equations are expanded as:

$$\begin{aligned} Maize\ yield = {} & \beta_0 + \beta_1 NPK + \beta_2 NPKZn + \beta_3 NPKS + \beta_4 NPKZnS \\ & + \beta_5 NPKZnSMg + \beta_6 NPKSMg + \beta_7 NPKZnMg \\ & + \beta_8 NS + \beta_9 N + \delta_1 AWHC + \delta_2 CEC \\ & + \delta_3 Extractable\ calcium + \delta_4 Extractable\ magnesium \\ & + \delta_5 Total\ nitrogen + \delta_6 Extractable\ phosphorus \\ & + \delta_7 Extractable\ potassium + \delta_8 Soil\ pH + \delta_9 SOC \\ & + \delta_{10} Soil\ depth + \delta_{11} Precipitation + \gamma_1 Farm\ size \\ & + \gamma_2 Improved\ seeds + \gamma_3 Local\ seeds + \gamma_4 Herbicides \\ & + \gamma_5 Family\ labor + \gamma_6 Hired\ labor + \varepsilon_5 \end{aligned} \quad (5)$$

Results

Types of Fertilizer Used in Crop Farming, Motivational Factors, and Challenges

Several fertilizer types are found within the Ghanaian fertilizer market, and those used by the farmers during the 2019 cropping season are shown in Table 1. A total of 80.6% of the sampled maize farmers used at least one type of fertilizer. The main fertilizers used were NPK 15-15-15, urea, ammonium sulfate, and NPK 15-20-20 + 0.7 Zn. The first three fertilizer types are widely known and have been used over the years by farmers, while NPK 15-20-20 + 0.7 Zn is a blended fertilizer promoted by the government of Ghana under its PFJ program.

Maize farmers used an average of 282.1 $kg\ ha^{-1}$ of fertilizer. The fertilizer types with the highest application rate were NPK 15–15-15, NPK 20-10-10+3S+2MgO, NPK 21-10-10+2S, and NPK 4-18-13+3S+3MgO+6CaO+0.1B, although the last three fertilizers were used by fewer farmers. Farmers used a particular fertilizer primarily because it produced higher yields, improved crop appearance, was less expensive, and was readily available and because they generally trusted the fertilizer. On the other hand, 19.4% of farmers did not use fertilizer due to a lack of funds, the high cost or unavailability of fertilizer, or their unawareness of fertilizer benefits. Farmers who used fertilizer outlined the constraints to their use. In order of severity, these constraints included a lack of credit, limited reach of subsidized fertilizer in adequate quantities, high cost of unsubsidized fertilizer, inadequate extension service support, a lack of fertilizer at the right time, and a lack of confidence in fertilizer quality. To increase the use of fertilizer, these challenges require maximum attention by various stakeholders, including the MoFA and fertilizer companies and retailers.

Characterization of maize farmers

The estimated Kaiser-Meyer-Olkin measure was 0.75 and this suggests that the sampling is adequate for PCA analysis. To determine the number of relevant components to include in the PCA analysis, the eigenvalues were estimated and plotted (Fig. 1). Forty-two factors were considered in the PCA. However, only 15 components had eigenvalues above 1. Although this suggests 15 components should be retained, there is a structural break in the scree plot after the fourth component. Therefore, only four components were retained. From the results, PC1 explained about 11.4% of the variations in the dataset, and PC2 explained 8.1%. The first four components jointly explained 31.2% of the variations in the dataset, but this increased to about 68% with the 15 components. A benchmark of 0.2 was used in highlighting relevant factors due to the high number of considered factors that led to the low loadings on the retained components. This shows from Table 2 that nine factors contributed highly to PC1, and 21 factors contributed to all four principal components. The results suggest that PC1 explains mostly the edaphic factors, while PC2 and PC3 explain the fertilizer intensity and nutrient use principles.

The positive loadings in Table 2 indicate that these variables correlate positively with the principal component. From PC1, cation exchange capacity (CEC), extractable potassium, extractable nitrogen, extractable phosphorus, soil organic carbon, and soil depth positively correlated with the other factors. The negative loadings indicate a negative correlation between the variable and the component. These included extractable calcium, producer price index (PPI), applied phosphorus, and potassium.

A biplot was estimated to visualize the distribution of the sampled farmers and the variables considered (Fig. 2). The vector of variables indicates how an increase in these variables influences the positioning of a farmer in the space. The biplot shows that the regions sort differently with regard to the variables considered. Four typologies of farmers were identified from the biplot, and the characteristics of each are shown in Table 3.

Factors influencing the yields of each farmer typology

The farmers were characterized into four typologies, and the mean or percentage values of each variable in bold type in Table 3 based on the typology in which they are found in Fig. 3. The effects of specific factors on the yields of farmers in each typology are provided in Tables 4–7. In order to avoid crowding of the effects of fertilizer and their indirect effects on yield, the socioeconomic variables included in the farmer characterization were dropped from the regression analysis.

Typology 1

Typology 1 are characterized by farmers in the quadrant with a positive loading in both PC1 and PC2. Eleven factors were found in this typology (Table 3). These include applied nutrients, local seed, soil type, and some socioeconomic characteristics. The seed application rate was higher for improved seed than local seed; nonetheless, the average seeding rate for farmers in this typology was 32.3 $kg\ ha^{-1}$, which is lower

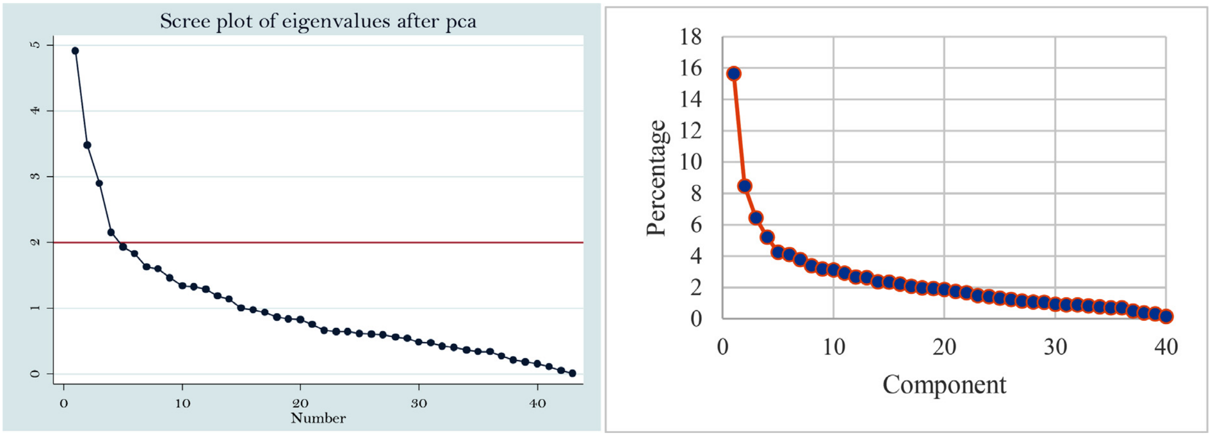

Fig. 1. Scree plot of eigenvalues and percentages after PCA.

Table 2
PCA loading.

Variable	Comp1	Comp2	Comp3	Comp4
Nitrogen fertilizer (kg ha^{-1})	−0.0727	**0.2975**	**0.2261**	−0.0420
Phosphorus fertilizer (kg ha^{-1})	**−0.2068**	**0.2003**	**0.3496**	0.1151
Potassium fertilizer (kg ha^{-1})	**−0.207**	0.1921	**0.3291**	0.1434
zinc fertilizer (kg ha^{-1})	−0.1116	0.0059	**0.3117**	**−0.2232**
sulfur fertilizer (kg ha^{-1})	−0.0073	0.1990	−0.0598	0.0918
Magnesium fertilizer (kg ha^{-1})	0.0204	0.0506	0.1727	**−0.2637**
Farm area (ha)	0.1061	0.1976	−0.1703	0.0248
Improved seed (kg ha^{-1})	0.0663	0.0246	0.0716	0.099
Local seed (kg ha^{-1})	−0.0004	0.0561	0.0041	0.0402
Herbicide use (L)	0.1670	0.0557	0.1043	−0.0626
Labor-family (number ha^{-1})	−0.1258	−0.125	0.088	0.0397
Labor-hired (number ha^{-1})	−0.0318	−0.0949	**0.2488**	−0.0212
Youth (1 if <25years)	−0.0412	0.1209	0.0162	**0.2127**
Gender (1 if male)	0.0651	0.0501	−0.0194	0.0484
Education (years)	0.1257	0.1527	0.1294	0.0418
Farmer Based Organization (1 if a member)	−0.0403	0.0189	0.0109	−0.1071
Experience (years)	0.0391	−0.1039	−0.0411	−0.1968
Smallholder (1 if farm size <2 ha)	0.106	0.1579	−0.183	0.0382
Extension (1 if accessed)	0.1058	0.1123	−0.0685	0.1298
Credit access (1 if accessed)	−0.0303	0.0443	0.0082	0.1143
Mixed cropping (1 if yes)	0.0033	−0.1204	0.1463	−0.0825
PPI (%)	**−0.2292**	−0.1620	−0.1877	0.1461
Very fertile soil (1 if soil is perceived as very fertile)	0.0428	0.0353	0.0087	0.0323
Fertile soil (1 if soil is perceived as fertile)	0.0295	0.0061	−0.168	−0.0113
Distance to input shop (km)	−0.0262	−0.176	−0.0601	0.0464
Acrisols (1 if soil is Acrisols)	0.1314	−0.1051	−0.0122	0.0357
Lixisols (1 if soil is Lixisols)	−0.0138	0.1368	−0.0547	0.045
Available Water Holding Capacity (AWHC) (v%)	0.1224	0.0888	**−0.2844**	0.0312
Soil CEC	**0.2818**	−0.1772	0.1706	**0.346**
Soil Ca content (mg kg^{-1})	**−0.2360**	**−0.2560**	0.0589	0.0267
Soil Mg content (mg kg^{-1})	−0.1662	**−0.2263**	0.198	−0.0373
Soil K content (mg kg^{-1})	**0.2686**	−0.1751	−0.0424	−0.0796
Soil N content (mg kg^{-1})	**0.3414**	−0.1301	0.1775	**0.2575**
Soil pH	−0.1368	−0.1473	0.0726	**0.5110**
Soil OC (ppm)	**0.3566**	−0.1023	0.1753	**0.2574**
Soil P content (mg kg^{-1})	**0.2332**	−0.0605	0.1290	**−0.2232**
Precipitation (mm)	−0.0500	**0.3513**	−0.1520	0.1826
Soil depth	**0.3151**	0.0126	0.1186	−0.1617
Recommended fertilizer type (1 if yes)	0.0726	0.1883	0.0972	0.0023
Right time application (1 if yes)	0.0611	**0.2129**	0.1576	−0.0235
No broadcasting (1 if yes)	−0.1403	−0.0459	−0.0179	0.1261
Right application rate (1 if yes)	0.1287	**0.2513**	0.1103	−0.0052
Subsidy (1 if accessed)	0.0218	−0.137	0.0378	−0.0663
Proportion	**11.4%**	**8.1%**	**6.7%**	**5.0%**

than the 50–60 kg ha^{-1} recommendation (IFDC, 2015). These farmers applied more nutrients, except for zinc, on their farms than farmers in other typologies. Similarly, most of the farmers received credit, were members of a farmer-based organization, cultivated maize on Lixisols soil, and were young. The average yield of a farmer in this typology was 1.7 t ha^{-1}, which is higher than that of the other farmer typologies. Many of these farmers are from North East, Upper West, Bono, and Bono East regions of Ghana.

The factors that influenced maize yield among farmers in this typology are shown in Table 4. Models 1 and 4 included fertilizer variables,

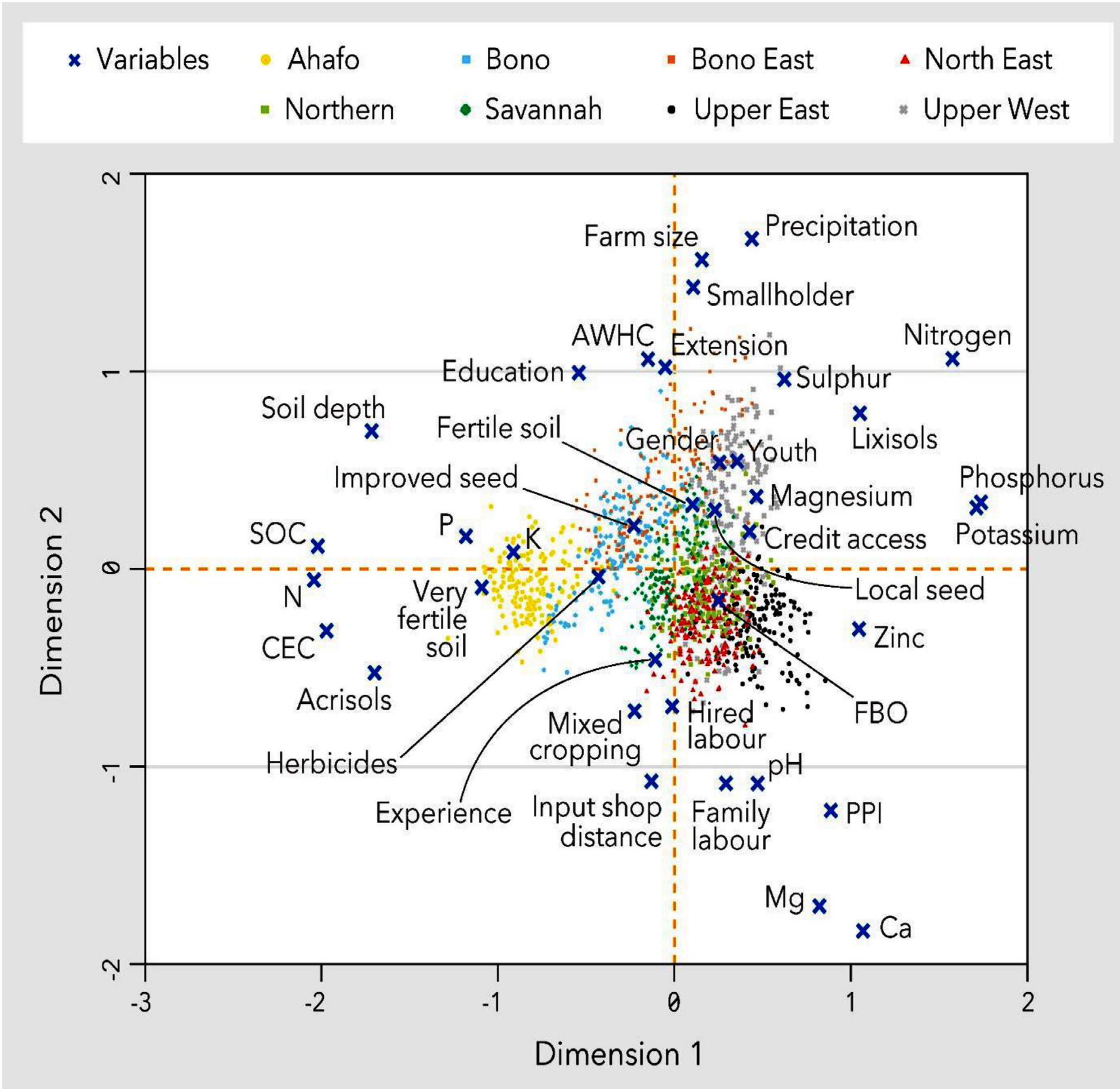

Fig. 2. Biplot of PC1 and PC2 sorted by region.

and their effects were statistically significant and positive. This implies that increasing the use of fertilizers would lead to higher yields. Generally, when only fertilizer variables were considered (Model 1), yield response was favorable for sole NPK, NPK combined with S and Mg, or NPK with S only. Among the edaphic factors, CEC, extractable calcium, extractable phosphorus, total nitrogen, soil pH, soil depth, and precipitation had a significant effect on maize yield. For other production inputs, improved seed and herbicide were significant.

Typology 2

Farmers in Typology 2 are those with factors that had negative loadings in PC1 but positive loadings in PC2. The factors found in this typology are highlighted in Table 3. The average farm size for these farmers was not different from that observed in other typologies. The farmers in this typology used less improved seed and more local seed; the average seeding rate for this group was 36.1 kg ha^{-1}, again lower than the recommended rate (IFDC, 2015). This typology was also dominated by farmers who were male, received extension services, and cultivated less than 2 ha of land. Fewer farmers in this group perceived their soils to be very fertile or fertile. Of farmers who used fertilizer, fewer applied the recommended types, at the right rate, and at the right time. This means that majority of the farmers in this typology do not use fertilizers appropriately for higher yields. Average yield of farmers in this typology was about 1.3 t ha^{-1}.

As shown in Table 5, only herbicides, AWHC, and fertilizer types had a significant effect on the maize yield of farmers in this typology. All fertilizer types had a positive effect on maize yield, with a high impact from NPK+S+Mg and less of an impact from NPK+Zn+S+Mg. The effect of AWHC was negative, implying that the higher the water-holding capacity, the lower the yield. Also, more herbicide was necessary for improving maize yields among farmers in this typology.

Typology 3

The factors in this typology had positive loading in PC1 and negative loading in PC2. These included labor, soil characteristics, distance to input shops, poverty, and fertilizer application method. Most of the farmers cultivated crops in Acrisol soil and practiced fertilizer placement (placing fertilizers on the soil surface close to the plant) rather

Table 3
Characteristics of farmers in each typology.

Variable	Typology 1	Typology 2	Typology 3	Typology 4
Local seed (kg ha^{-1})	**29.7**	35.2	30.4	27.3
Nitrogen fertilizer (kg ha^{-1})	**60.1**	51.6	51.0	50.7
Phosphorus fertilizer (kg ha^{-1})	**26.2**	21.6	22.0	22.0
Potassium fertilizer (kg ha^{-1})	**25.7**	21.2	21.2	21.5
Sulfur fertilizer (kg ha^{-1})	**8.3**	6.9	6.2	5.4
Average monthly precipitation for the cropping season (mm)	**150.1**	148.3	147.7	146.4
Lixisols (%)	**37.2**	17.5	29.1	16.3
Credit received (%)	**37.1**	16.0	32.0	14.9
Youths (%)	**37.7**	12.5	33.3	16.5
Education (years)	4.9	**3.3**	4.7	3.8
Farm size (ha)	2.3	**2.1**	2.1	2.1
Improved seed (kg ha^{-1})	40	**28.5**	19.4	39.2
Herbicide (L)	5.2	**4.2**	7.3	5.6
Magnesium (kg ha^{-1})	0.8	**0.5**	1.0	1.0
Soil depth (cm)	106.7	**85.4**	86.4	84.3
Males (%)	37.0	**15.2**	30.2	17.7
Extension (%)	39.0	**13.6**	29.7	17.6
Smallholders (%)	41.7	**13.8**	28.5	16.0
Very fertile (%)	50.0	**10.7**	24.3	15.0
Fertile (%)	33.1	**16.7**	32.4	17.9
Right application rate (%)	43.8	**12.4**	26.8	17.1
Recommended fertilizer type (%)	40.3	**15.0**	27.1	17.7
Right time of fertilizer application (%)	42.9	**13.5**	27.1	16.5
Farmer-based organization members (%)	36.5	16.5	**30.7**	16.2
Zinc fertilizer (kg ha^{-1})	0.5	0.5	**0.6**	0.6
PPI (index)	50.8	61.5	**57.6**	58.2
Distance to input shop (km)	50.5	66.9	**58.8**	74.6
Family labor (number ha^{-1})	3.4	3.6	**3.7**	3.2
Hired labor (number ha^{-1})	5.5	3.8	**4.0**	3.9
Acrisol (%)	35.0	11.7	**32.5**	20.8
Extractable calcium (ppm)	989.4	1158.7	**1108.6**	1137.8
Extractable magnesium (ppm)	216.0	237.1	**230.1**	239.1
AWHC (v%)	10.1	10.0	**10.1**	9.9
Soil pH	5.6	5.9	**5.7**	5.9
Application method other than broadcasting (%)	38.5	15.2	**29.0**	17.2
Extractable potassium (mg kg^{-1})	104.0	109.1	107.8	**107.7**
Total nitrogen (mg kg^{-1})	22.4	18.3	22.5	**19.4**
SOC (g kg^{-1})	22.5	18.3	21.3	**19.0**
Extractable phosphorus (mg kg^{-1})	669.3	636.6	668.4	**670.7**
CEC (cmol kg^{-1})	14.4	13.6	16.2	**14.4**
Experience (years)	20.4	22.3	21.0	**21.8**
Mixed cropping (%)	41.9	13.4	27.6	**17.1**
Subsidy (%)	41.6	16.0	26.1	**16.3**
Yield (kg ha^{-1})	1676.8	1261.0	1343.1	1249.7

than broadcasting. The amount of hired labor needed by farmers in this group was similar to that of the other groups. Farmers in this typology, mostly from the Northern, Upper East, and Ahafo regions, had an average yield slightly more than 1.3 t ha^{-1} of maize.

The regression result shows that fertilizer types, extractable Mg, total N, soil depth, farm size, local seed, herbicide, and hired labor significantly influenced maize yield (Table 6). Except for farm size, all of the factors had a positive effect on yield. The use of urea fertilizer (N only) had the highest impact on yield for these farmers.

Typology 4

Only eight of the 42 factors examined were found in Typology 4, in which there is a negative loading of the factors in both PC1 and PC2. Most of the edaphic factors, as well as farming experience, farming system, and access to subsidized fertilizer, were included in this typology. The maize yield of the farmers, who were mostly from the Savannah and Upper East regions, averaged 1.3 t ha^{-1}.

The stepwise regression detailing the effects that the various factors had on the yield is shown in Table 7. This reveals that, unlike the other typologies, not all fertilizer types significantly influenced the farmers' yields. Though not statistically significant, increasing the rate of NPK+Zn+S+Mg fertilizer application resulted in a decline in maize yield among these farmers. Extractable P, extractable K, farm size, local seed, and hired labor also had a significant influence on maize yield. An increase in the level of all other factors, except extractable K and farm size, resulted in a higher maize yield for these farmers.

Nutrient use efficiency among typologies

Table 8 shows yield differences between fertilizer users and non-users as well as the nutrient use efficiency for each farmer typology. Overall, the highest and only significant yield gap between fertilizer users and non-users was found among Typology 1 farmers. Unlike in Table 3, the mean nutrients in Table 8 were estimated solely for the fertilizer users in each typology. Also, the nutrient use efficiency was highest for farmers in Typology 1 and lowest for farmers in Typology 4. The analysis of variance statistics showed that there was a significant difference in all parameters among the four typologies. The low nutrient use efficiency among Typology 4 farmers could contribute to the low yields and the small difference in yield between the fertilizer users and non-users in this category.

Discussion

Farmer characterization was used to identify the various components of farming systems and their interactions for policy design, experimental learning, and technology targeting. This approach allowed an un-

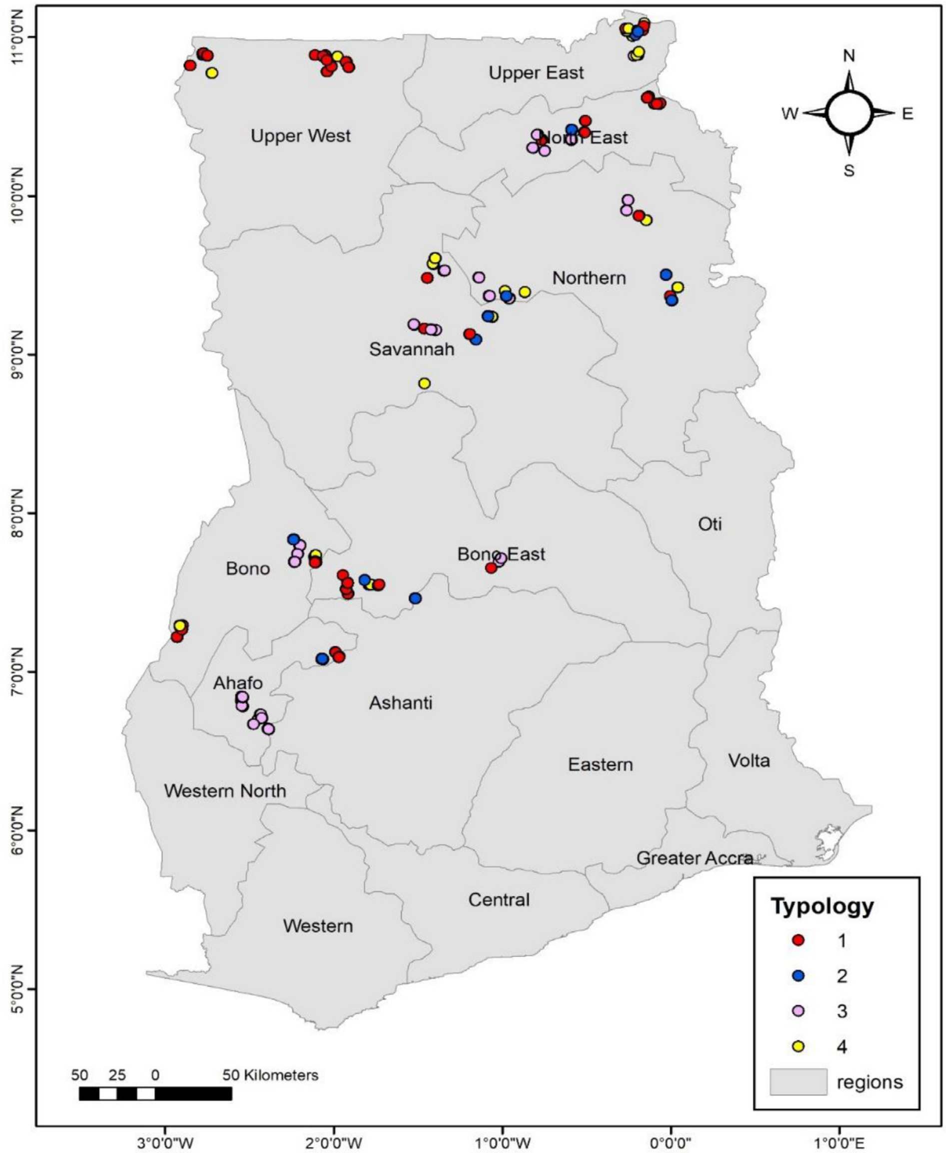

Fig. 3. Location of farms based on their typology.

derstanding of the variability in the local farms. Specifically, the characterization of the smallholder farmers through the PCA method led to the identification of four farmer typologies. The study established that the majority of the farmers are grouped in Typology 1, followed by Typology 3. Farmers in Typology 1 appeared to exhibit characteristics favorable for improving farm yields. For instance, in addition to the high use of fertilizers and improved seed varieties, these farmers practiced various integrated agricultural practices, particularly cover cropping, mulching, and combined use of agrochemicals. Similarly, the quantity of maize output sold by these farmers was generally greater than those in the other typologies, which suggests high commercialization among these farmers. The average yield for the farmers in Typology 1 was consistently the highest. From Fig. 3, farmers in typology 1 are located in the Sissala West and Sissala East districts of Upper West region, Wenchi district of Bono East region and Bunkpurugu-Nyankpanduri district of North East region. Clearly, Sissala West and Sissala East districts respectively recorded the highest yields of 2.9 and 2.8 8 t ha^{-1}.

Even among farmers in this study who were from districts with a large supply of subsidized fertilizers in the 2019 production season, the level of fertilizer use was below the recommended application rate under the PFJ program (300 kg ha^{-1} NPK plus 100 kg ha^{-1} urea) (MoFA, 2019). The fertilizer use can be attributed to a number of factors including availability and financial constraints. Even with the subsidy on fertilizers and the awareness on the benefits of fertilizer use, the smallholder farmers are unable to afford the required fertilizer quantities. As a result, these farmers tend to apply the little they afford on their farms without adhering to the recommended application rates. The net effect is the inability of the farmers to obtain their potential yields. This is consistent with Awunyo-Vitor et al. (2016), who indicated that Ghanaian farmers generally underutilize fertilizer resources. Tetteh et al. (2018) also acknowledged that the major reasons for the low maize yields in Ghana are low soil fertility and less application of external inputs. The results also established that although the effect of fertilizer use on yield was positive for all farmer typologies, the extent of the effect differed. The effect was generally highest for Typology 1 farmers. Compared to farmers in other typologies, most farmers in typology 1 adopts the 4R nutrient stewardships that ensures higher yield returns from fertilizer. The implication is that beyond simply using fertilizers, adhering to the principles of their use is important to obtain the desired yields. Also, the favorable socioeconomic characteristics such as the access to extension service and farmer group membership by farmers in typology 1 means that they are able to obtain appropriate production information and access to support from colleague farmers that enhances the adoption of good agronomic practices (GAP). Ragasa and

Table 4
Determinants of maize yield among farmers in typology 1.

Variable	Model 1	Model 2	Model 3	Model 4
NPK	0.422***			0.231***
NPKZn	0.358***			0.241***
NPKS	0.428***			0.242***
NPK+Zn+S	0.380***			0.271***
NPK+Zn+S+Mg	0.344***			0.206***
NPK+S+Mg	0.445***			0.261***
NPK+Zn+Mg	0.362***			0.233***
NS	0.361***			0.233***
N	0.452***			0.307***
AWHC (v%)		0.008		0.022
CEC (cmol kg^{-1})		−0.110***		−0.094***
Extractable calcium (mg kg^{-1})		0.0003**		0.0003**
Extractable magnesium (mg kg^{-1})		−0.002*		−0.002
Total nitrogen (g kg^{-1})		0.027***		0.022**
Extractable phosphorus (mg kg^{-1})		0.001***		0.001**
Extractable potassium (mg kg^{-1})		−0.001		−0.001
Soil pH		0.087***		0.088***
SOC (g kg^{-1})		0.022*		0.015
Soil depth (cm)		−0.003***		−0.002**
Precipitation (mm)		0.010***		0.009***
Farm size (ha)			0.027	−0.002
Improved seed (kg ha^{-1})			0.011	0.036*
Local seed (kg ha^{-1})			−0.003	0.018
Herbicide (L)			0.184***	0.061*
Family labor (number ha^{-1})			−0.024	−0.036
Hired labor (number ha^{-1})			0.064**	0.028
Constant	5.444	6.267	7.184	4.941
Adjusted R-Squared	0.312	0.519	0.057	0.597

***, **, and * indicate significance at 1%, 5%, and 10%, respectively.

Table 5
Determinants of maize yield among farmers in typology 2.

Variable	Coef.	Coef.	Coef.	Coef.
NPK	0.090***			0.095***
NPKZn	0.094***			0.111***
NPKS	0.089***			0.085***
NPK+Zn+S	0.131**			0.122**
NPK+Zn+S+Mg	0.060***			0.070***
NPK+S+Mg	0.130***			0.149***
NPK+Zn+Mg	0.092***			0.091***
NS	0.096***			0.098***
N	0.109***			0.110***
AWHC (v%)		−0.108**		−0.110***
CEC (cmol kg^{-1})		−0.005		0.008
Extractable calcium (mg kg^{-1})		0.000		0.000
Extractable magnesium (mg kg^{-1})		0.001		−0.001
Total nitrogen (g kg^{-1})		−0.011**		−0.007
Extractable phosphorus (mg kg^{-1})		0.000		0.000
Extractable potassium (mg kg^{-1})		0.003		0.000
Soil pH		0.040		0.013
SOC (g kg^{-1})		0.006		−0.002
Soil depth (cm)				0.000
Precipitation (mm)				0.002
Farm size (ha)			−0.032	−0.082
Improved seed (kg ha^{-1})			0.023	0.024
Local seed (kg ha^{-1})			0.024	0.012
Herbicide (L)			0.131***	0.085**
Family labor (number ha^{-1})			0.015	0.013
Hired labor (number ha^{-1})			0.030	0.012
Constant	6.850	7.513	6.890	7.725
R-Squared	0.184	0.123	0.273	0.277

*** and ** indicate significance at 1% and 5%, respectively.

Chapoto (2017) explained that beyond fertilizer use, other factors such as improved seeds, availability of labor and labor-saving technologies are important for improving agricultural productivity and development of Ghana. This result also suggests that policies to promote fertilizer use must be accompanied by associated policies that would enhance other characteristics such as access to information, institutional support and farmers' adoption of GAPs. For Typology 4 farmers, not all fertilizer types had a significant influence on their maize yield. Although this study is unable to explain the underlying reasons why some fertilizer types had no significant effect on these farmers' yields, it thus hint that increasing agricultural productivity require the use of integrated practices appropriately. Previous studies (Andani et al., 2020; Asravor et al., 2019; Awunyo-Vitor et al., 2016) also have found a positive effect of fertilizer application on maize yield among Ghanaian farmers. Similarly,

Table 6
Determinants of maize yield among farmers in Typology 3.

Variable	Coef.	Coef.	Coef.	Coef.
NPK	0.076***			0.078***
NPKZn	0.067***			0.060***
NPKS	0.077***			0.066***
NPK+Zn+S	0.062***			0.055***
NPK+Zn+S+Mg	0.068***			0.055***
NPK+S+Mg	0.072***			0.071***
NPK+Zn+Mg	0.064***			0.065***
NS	0.056***			0.051**
N	0.105***			0.103***
AWHC (v%)		−0.039**		−0.018
CEC (cmol kg^{-1})		−0.016*		−0.012
Extractable calcium (mg kg^{-1})		0.000		0.000
Extractable magnesium (mg kg^{-1})		−0.001***		0.000*
Total nitrogen (g kg^{-1})		0.013**		0.011**
Extractable phosphorus (mg kg^{-1})		0.000		0.000
Extractable potassium (mg kg^{-1})		0.000		−0.001
Soil pH		−0.022		−0.036
SOC (g kg^{-1})		0.004		0.000
Soil depth (cm)		0.002***		0.001*
Precipitation (mm)		0.000		−0.002
Farm size (ha)			−0.075*	−0.105**
Improved seed (kg ha^{-1})			0.042**	0.024
Local seed (kg ha^{-1})			0.033***	0.033***
Herbicide (L)			0.061***	0.057***
Family labor (number ha^{-1})			0.036**	0.015
Hired labor (number ha^{-1})			0.055***	0.039***
Constant	6.739	7.455	6.831	7.410
R-Squared	0.281	0.283	0.122	0.243

***, **, and * indicate significance at 1%, 5%, and 10%, respectively.

Table 7
Determinants of maize yield among farmers in Typology 4.

Variable	Coef.	Coef.	Coef.	Coef.
NPK	0.062***			0.069***
NPKZn	0.043			0.084***
NPKS	0.027			0.070**
NPK+Zn+S	0.058			0.132**
NPK+Zn+S+Mg	−0.005			−0.066
NPK+S+Mg	0.030			0.040
NPK+Zn+Mg	0.063			0.035
NS	0.003			0.014
N	0.057			0.077**
AWHC (v%)		0.006		0.017
CEC (cmol kg^{-1})		0.009		0.004
Extractable calcium (mg kg^{-1})		0.000		0.000
Extractable magnesium (mg kg^{-1})		0.001		0.000
Total nitrogen (g kg^{-1})		−0.007		0.002
Extractable phosphorus (mg kg^{-1})		0.001***		0.001***
Extractable potassium (mg kg^{-1})		−0.005*		−0.006**
Soil pH		−0.006		−0.046
SOC (g kg^{-1})		−0.006		−0.008
Soil depth (cm)		0.003**		0.002
Precipitation (mm)		0.001		0.004
Farm size (ha)			−0.253***	−0.141*
Improved seed (kg ha^{-1})			−0.025	−0.021
Local seed (kg ha^{-1})			0.018	0.042*
Herbicide (L)			0.044*	0.026
Family labor (number ha^{-1})			0.005	0.051
Hired labor (number ha^{-1})			0.137***	0.095***
Constant	6.935	6.457	6.968	5.990
R-Squared	0.253	0.191	0.184	0.355

***, **, and * indicate significance at 1%, 5%, and 10%, respectively.

Scheiterle et al. (2019) concluded that, although fertilizer use leads to higher yields, fertilizer prices make their use less profitable for farmers.

Among the fertilizers with added micronutrients, NPK with S and Mg appeared to have a relatively higher impact on maize yield. This corresponds with Andani et al. (2020), who stated that sulfur is becoming the fourth major nutrient after N, P, and K, since it plays vital role in the primary metabolism of taller plants, synthesis of secondary metabolic products, and photosynthetic activities. To improve crop productivity and crop nutrition, S must always be used in the right quantity (Andani et al., 2020). Bua et al. (2020) also revealed that crop yields with NPKS are higher than those with only NPK. Kanton et al. (2016) estimated that the use of NPK 23-10-5 + 2MgO+3S+0.3 Zn and NPK 21-10-10+2S produced higher maize yields, return on investment, and rainfall use efficiency relative to NPK 15-15-15 and organic fertilizers. These

Table 8
Nutrient use efficiency among farmer typologies.

	Typology 1	Typology 2	Typology 3	Typology 4	*F*-value
Yield (kg /ha^{-1})					
Non-fertilizer users	1229.2	973.2	1093.8	1125.2	2.32*
Fertilizer users	1763.0	1330.9	1424.6	1287.7	25.47***
Yield difference	533.8$^{\beta}$	357.7	330.8	162.5	
Nutrient use (kg /ha^{-1})					
Total nutrients	145.1	127.0	135.3	132.0	5.0***
Nitrogen	71.7	64.1	67.7	66.2	3.39**
Phosphorus	31.2	26.8	29.2	28.7	3.02**
Potassium	30.7	26.3	28.1	28.1	3.3**
Nutrient use efficiency [PFP= (Y/F)]					
Total nutrients	12.1	10.5	10.5	9.8	3.09**
Nitrogen	24.6	20.8	21.1	19.5	9.95***
Phosphorus	56.4	49.6	48.7	44.9	12.86***
Potassium	57.4	50.6	50.7	45.9	11.83***
Nutrient use efficiency [AE =(Y-Yo)/F]					
Total nutrients	3.7	2.8	2.4	1.2	15.67***
Nitrogen	7.4	5.6	4.9	2.5	19.53***
Phosphorus	9.5	7.2	6.8	3.6	17.81***
Potassium	9.3	7.1	6.5	3.5	17.55***

***, **, and * indicate significance at 1%, 5%, and 10%, respectively, between the typologies. PFP = Partial Factor Productivity; AE = Agronomic Efficiency; *Y* = average yield (kg/ha) for fertilizer users; Yo = average yield (kg/ha) for non-fertilizer users. $^{\beta}$ = indicated significance between fertilizer users and non-users.

fertilizers produced taller plants, led to early tasseling and silk formation, and increased straw yields, plant height, stem girth, and grain size. Apart from S with accumulating evidence from different sources for its importance in yield increase, the impact of Mg and Zn are confounded in these composite fertilizer products, and their individual and synergistic contributions to yield increase remain elusive from the dataset.

Importantly, nutrient use efficiency was generally low among all farm typologies. The agronomic efficiency and partial factor productivity led to the conclusion that nutrient use efficiency was lowest for Typology 4 and highest for Typology 1 farmers. For instance, the partial factor productivity revealed that, for every 1 kg ha^{-1} fertilizer applied, only 12.1 kg ha^{-1} and 9.9 kg ha^{-1} of maize grain was obtained under the best- and worst-performing farmer typologies (Typologies 1 and 4, respectively). Adu-Gyamfi et al. (2019) also estimated that nutrient (N, P, and K) uptake and nutrient recovery for maize is generally low on farmer practice fields. With continually declining soil fertility and harsh climatic conditions, achieving food security will be hampered if measures to raise the nutrient use efficiency are not promoted and adopted. It will hamper agricultural intensification and sustainability if farmers will not achieve the expected results from fertilization. Although, Adzawla et al. (2021a) ranked limited credit, limited supply of subsidized fertilizers and high cost of commercial fertilizers as the major three challenges hindering fertilizer use, beyond these financial challenges low fertilizer use efficiency can explain the reason why farmers continue to use lower amounts of fertilizers on their farms than recommended. The implication is that policy efforts should target measures to improving nutrient use efficiency in addition to promoting use of fertilizers. Agronomic nitrogen use efficiency in northern Ghana under controlled on-station conditions have been found to reach 30–50 kg grain per kg N applied with subsurface placement of NPK (Adu-Gyamfi et al., 2019). These efficiencies are more in line with globally expected yield responses to fertilizer application in maize. However, Adu-Gyamfi et al. (2019) reported nitrogen use efficiency of only 7 to 19 for broadcasted NPK on the soil surface. These findings reveal the importance of appropriate application of fertilizers, suggesting that nutrient use efficiency under current farm practices is only about 15% of attainable. Similar values hold for P and K based on data from Adu-Gyamfi et al. (2019) and our findings (Table 8).

Various edaphic factors (soil properties) have a significant effect on maize yields, and may be specific to some farm typologies, but are likely to be generally applicable to all given the low average yield. Overall, soil depth tends to favor yields with farm Typology 1 having the deepest soils with highest yields compared to the other typologies. Within typologies, the impact of soil depth is less pronounced with only slightly negative or positive impacts on yield. Soil water is important for crop growth and for nutrient availability and uptake and, as estimated by Danquah et al. (2020), low plant available water capacity of soils leads to lower yields. While such clear effects do not emerge from our analyses, it is important that further analysis on soil water holding capacity in combination with soil depth and rainfall are done to establish the factors that determine water availability, and with that nutrient availability and uptake, to the plants for yield formation. This is particularly relevant given the erratic nature of rainfall in northern Ghana. Higher mineral content (Ca, P, and N) of soils tend to support higher yields among farmers which is generally valid, certainly so in deficient soils that need more minerals, such as in northern Ghana (AGRA, 2018). Antwi et al. (2016) estimated that only 3%, 28%, and 73% of the soils in Ghana's Northern Region had the desired amount of nitrogen, phosphorus, and potassium, respectively, for maize production. Consistently, Scheiterle et al. (2019) indicated that maize requires a high amount of N and stressed that the N deficiency in most farmlands of northern Ghana contributes to farmers' low yields. While the economic application rate of 90 N kg ha^{-1} is recommended (for Ghana, based on trials done under controlled on-station conditions Tetteh et al., 2018), farmers' reluctance to apply such high amounts could be explained from the low nutrient use efficiencies obtained. Still application rates of around 70 kg N ha^{-1} can be considered very high given these efficiencies. Juxtaposing these identified factors about the aberrant availability of water and nutrients raises the importance of further improving seed varieties to tolerate unpredictable periods of drought and nutrient deficiencies in the regions. The majority of maize farmers indeed indicated insufficient rainfall as the primary reason for the high deviation of their yields from the potential yield (Adzawla et al., 2021b).

Among farmers in Typologies 1 and 3, an increase in the quantity of improved seed led to a significant increase in yields, while local seed had a significant effect on the yield of Typology 4 farmers. The use of improved seed is important, especially with the use of fertilizer. Weed management is essential and the use of herbicides improved crop yield and explains why maize farmers in Adzawla et al. (2021b) did not deem weed infestation as a major reason for their inability to obtain potential yields. Considering that maize farmers invest more labor in weed management than other farm activities (Adzawla et al., 2021b), the use of herbicides can free labor for other activities. Scheiterle et al. (2019) estimated that more herbicides are required to increase maize yields in northern Ghana and further stressed that weed management is a major challenge for maize production, especially for farmers who do not use mechanization. However, it is important to note that the use of herbicides requires more financial investment at one time and technical know-how to effectively apply and prevent health hazards. Therefore, promotion of herbicides should be combined with proper sensitization of farmers on their safe use.

Conclusions and recommendations

Maize is an important staple in Ghanaian households and, as such, a major determinant of the country's food security status. Improving maize yields is crucial for meeting the growing human food and poultry feed demand. Amid the existing yield gaps, fertilization and improvement in the use efficiency of fertilizer and other inputs remain essential. Clustering farmers into groups based on comparable characteristics and understanding their production systems allows policies to be tailored to specific farmers' needs. One significant factor in increasing the maize yield of farmers in all typologies was found to be fertilizer use, suggesting the need to stimulate fertilizer use by smallholder farmers. However, the observed low nutrient use efficiency provides little justification to promote increasing the amounts used. The provision of credit facilities as a stopgap for promoting fertilizer use might, therefore, not be a prudent option under the current returns from the high application rates. Instead, farmers must be trained and educated on GAPs to guarantee higher returns from fertilization. Interacting effects with other production factors, primarily plant-available water and improved seeds, must be further understood to guide farmers to enhance the use efficiency of fertilizers, as obtained in on-station experiments. Preliminarily, MoFA must reexamine and possibly redesign the PFJ program to emphasize policy measures that will ensure higher use efficiency of fertilizers.

The typologies revealed the general heterogeneity among farmers and the underlying more homogenous groups in such broader diversity. Farmers in Typology 1 were generally productive and had relatively high returns from fertilization, though below what is achievable. These farmers use more fertilizer, access extension services, and practice mixed cropping systems, resulting in relatively high yield as compared to other typologies. Adherence to the 4R Nutrient Stewardship principles was low among Typology 2 and Typology 4 farmers. These farmers require more education and training on fertilizer management and the benefits of adherence to GAPs. This study established that the use of herbicides in adequate quantities to control weed infestation is important for improving farmers' yields. Education on safety precautions involved in using these chemicals is required. Whereas a negative correlation between farm size and yield in all typologies suggests the need to reduce current farm sizes for maize intensification, this contradicts the principles of economies of scale. Reducing the cultivated area could reduce the total amount of labor needed and intensify the use of agro-inputs per unit area, resulting in higher yields for the cash-constrained farmers. However, this short-term strategy would counter a more desired medium- to long-term strategy to improve the efficiency of inputs for higher farm incomes and livelihoods. Due to inter-household interaction, production innovations used by some farmer groups may affect other farmers. Therefore, Typology 1 farmers should be targeted first for innovation diffusion and yield improvement, with farmers in other typologies following suit. Given the wide geographical distribution of Typology 1 farmers among other farm typologies, this trickledown effect, possibly through the identification of champion farmers for change, could be effectively pursued. Promotion of effective fertilizer use among farmers must be accompanied by training and sensitization on efficient fertilizer utilization to prevent growth of inefficiencies, enhance income, and stimulate adoption.

This study is important, as it examines the effects of fertilizer on the yields of farmers of different typologies and the nutrient use efficiency of their crops. The study's fundamental findings show that policy reform must be undertaken. Beyond the quantitative analysis of the farmer typologies in this study, a detailed understanding of the characteristics of these farmers will provide a learning pathway for improving maize yields of farmers of the various typologies.

In brief, this study established low nutrient use efficiency among the farmers, with many having negative nutrient use efficiencies. There are observed differences in the socioeconomic and production characteristics, such as yield and fertilizer use, among the farmer typologies. Therefore, the extent to which yield varied depends on the various input and soil variables of each typology. The farmers in Sissala West and Sissala East districts exhibited better maize production outcomes that are suitable for improvement and promotion. The use of NPK fertilizers with S and Mg produced a slightly higher yield than other formulations. Given the generally low yield returns from fertilizer use, fertilizer policies in Ghana should include measures that promote adoption of GAPs.

Declaration of Competing Interest

There is no conflict of interest.

Appendix

Tables 2–7.

CRediT authorship contribution statement

William Adzawla: Formal analysis, Writing – review & editing. **Williams K. Atakora:** Writing – review & editing. **Isaac N. Kissiedu:** Writing – review & editing, Formal analysis. **Edward Martey:** Investigation, Methodology, Data curation, Writing – review & editing. **Prince M. Etwire:** Writing – review & editing, Investigation, Methodology, Data curation. **Amadou Gouzaye:** Investigation, Writing – review & editing. **Prem S. Bindraban:** Investigation, Supervision, Writing – review & editing.

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