***Original Research Article***

# Increased Maize yield in response to applied phosphorus and nitrogen in the Greenbelt zone, in South Sudan


## Abstract

The world needs more food by 2050 especially in the Sub-Saharan Africa where it must be tripled. This study was to evaluate maize (*Zea mays* L) response to nitrogen (N) and phosphorus (P) containing fertilizers in the Greenbelt zone of South Sudan. Triple super phosphate (TSP, 0-46-0) and Urea (46% N) in a factorial experiment was laid in a Randomized Complete Block Design. Maize yield was measured at harvesting stage to evaluate the agronomic and economic effects of N and P fertilizers. Maize yield data were subjected to ANOVA using GenStat 15$^{th}$ Edition and the means were separated using least significant difference and Turkey's Honesty Significance Difference at 95% confidence interval. On average maize yield was 4.7 t ha$^{-1}$) recorded from plots that received a combination of 20 kg P and 120 kg N ha$^{-1}$. The analysis of marginal return confirmed the agronomic recommendation for the fertilizer use. The study recommended further studies to evaluate maize response to several types and rates of fertilizers in multiple seasons and awareness creation among the community on the importance of fertilizer use for sustainable maize production and conduct of farming system research.


**Key words:** *Environmentally friendly fertilizers, shifting cultivation, Sustainable intensification, and marginal rate of return.*



## 1.0 INTRODUCTION

Several studies have shown that global crop production needs to double by 2050 to meet the projected demands from rising population [1,2] while it needs to triple in the Sub-Saharan Africa (SSA) [3] where projected population will hit 1.2 billion [4]. Ray *et al*. suggested that global maize production should be increased by approximately 67 % to be able to meet the demand. According to Smith *et al.* [5], food insecurity is a challenge in the face of changing climate, where majority of people are suffering from malnutrition. There is need to produce surplus nutritious food to enable smallholders sell and earn income, but this requires agricultural intensification with efficient fertilizer use [4,2]. There are serious discussions on going about the role of sustainable intensification (SI) in checking and conserving natural resource base for food production [5,6]. Smith *et al*. [5] defines SI as the process of "producing more food from the same area of land while reducing the environmental impacts". Currently, the increase in food production in sub-Saharan Africa is from the expansion of agricultural land areas, which is not sustainable [7,8] and still the SSA faces chronic food insecurity associated with soil degradation [6].

South Sudan is facing chronic food insecurity as well [9] and yet about 50 % of its total land area (648 000 km$^2$) [10] is suitable for agriculture but still struggling to feed her approximately 13 million people [11,12,13]. Sorghum (*Sorghum bicolor*) is the main cereal crop cultivated in the country in both the smallholder and medium to large scale mechanized farms, comprising about 70 % of the area under cereals [14]. Maize (*Zea mays*) ranks second important cereal crop after sorghum covering an estimated 20 % of the total area under cereal and the remaining 10 % is rice (*Oryza sativa*), bulrush millet (*Pennisetum glaucum*) and finger millet (*Eleusine coracana*) [15]. Preference for maize as staple food increased when South Sudanese returned from exile to South Sudan following the signing of the Comprehensive Peace Agreement (CPA) in 2005. This has resulted into increased demand for maize and gradual expansion of the area under maize production in the country. According to FAO [15], total maize produced in 2020 (131 000 tonnes) was 27.2 % higher compared to maize yields recorded in 2019 in South Sudan. However, for most countries in the East, West and Central Africa including South Sudan the increase in maize yield is mainly from the expansion of areas under maize production thus not sustainable [8]. Shifting cultivation without fertilizer use is a common practice among maize and other crop producers in the Greenbelt zone of South Sudan. Introduction of fertilizers and other improved technologies will intensify maize production and minimize soil degradation effects associated with shifting cultivation. According to Epule *et al.* [8]; agricultural intensification serves as an entry point to combating deforestation and its effects on the environment, enhancing carbon dioxide sequestration, reducing soil erosion, and improving soil organic carbon for sustainable food production.

The Ministry of Agriculture and Food Security (MAFS) in the Republic of South Sudan, is interested in increasing maize yield per unit area of cultivated land [9]; the ministry also acknowledges that poor soil fertility and land degradation are the main contributing factors to low cereal production (0.7 t ha$^{-1}$). However, there are no nationally generated crop-yield forecasts and accurate data existing on cropped land disaggregated by crop [16]. This means that cereal production figures for South Sudan are just the best estimates under the prevailing circumstances, FAO report concluded.

The MAFS' plan to double the 0.7 t ha$^{-1}$ cereal production has not materialized because of civil unrest in 2013 and 2016 [9]. Doubling of cereal production to 1.4 t ha$^{-1}$ in South Sudan would still be far below the current yields recorded in the neighbouring countries of Kenya (1.77 t ha$^{-1}$), Ethiopia (2.9 t ha$^{-1}$) and Uganda (2.2 t ha$^{-1}$) [17,18,19]. The increase would also be below the cereal yield potential of about 5 t ha$^{-1}$ reported for the SSA region [20].

To achieve and sustain the high maize production required to meet current and future food demand, a balanced plant nutrient supply from either organic source or the mineral fertilizers is required [21,22]. Nevertheless, the deficiency of P in highly weathered and degraded soils in SSA decreases the efficiency of other nutrients such as N [23] leading to poor yield and food insecurity. According to IFDC [24], less than 1% of small-scale farmers in South Sudan use inorganic fertilizer; and where the fertilizers are used [20] some smallholders are inappropriately using it. Research aimed at developing area specific fertilizer recommendations is therefore required to guide decision making on the use of fertilizers for sustainable production of maize and other cereals in the country. Therefore, this study aimed to evaluate maize response to N and P different fertilizer application rates and recommend those that would meet the socio-economic conditions of the farmers, because the technology is still new to them, for improved smallholder maize production and food security in the Greenbelt zone, Western Equatoria State, South Sudan. Specifically: to identify the profitable rainfed maize production among alternative treatments and to assess the economic feasibility of N and P fertilizers application on rainfed maize.

## 2.0 MATERIAL AND METHODS

### 2.1 Description of the Study area

The study area is located between 28$^{o}$ 10’ E and 28$^{o}$ 42’ E and between 04$^{o}$ 32’ N and 04$^{o}$ 64’ N covering an area of 47 500 ha. The altitude ranges from 606 – 744 m asl [25]. The International Resource Group (IRG) [26] describes the area as high rainfall woodland savannah that stretches diagonally from northwest of South Sudan along the Central African Republic (CAR), the Democratic Republic of Congo (DRC) and Uganda boarders within the Greenbelt zone. The Greenbelt is one of the six agroecological zones in South Sudan that covers approximately 14 % of the total land (648 000 km$^2$). Maize can be planted and harvested twice a year and the area has great potential to produce a variety of annual and perennial crops [9].

The textural class of the top and subsoils in the study area is sandy clay loam and is well drained while the most limiting plant nutrients in the study area are phosphorus and nitrogen [25]. Consequently, this study focused on evaluating maize response to different combinations of the two limiting nutrients using maize (NARD 1) as a test crop. NARD1 is an improved variety compared to the ones used by farmers in the study area. To be noted is there are also some rainfed hybrid varieties in the country which has been introduced by the Non-Governmental Organizations (NGOs).

### 2.2 Site selection and soil fertility assessment

Experimental sites were established in three villages on three different types of soils characterized by Bazugba *et al*., [25]: Ferralsol (Nangbangi (NA) village), Acrisol (Bure Maku (BM) village) and Retisols (Ataziri (ATA) village). These villages were selected for this study because they were by the roadside and easily accessible. Composite soil samples were taken from each site before planting to establish the initial soil fertility status. Ten subsoil samples were taken randomly in the designated site, placed on a clean plastic sheet where all crumbs were crushed with a piece of wood, mixed properly, spread evenly on the sheet in a round shape. One quarter measuring about a kg was taken as the composite sample for the site. All sites were in use for two years and the experiment was done in the third year as was estimated by the landowners. Farming system is mix crops: groundnuts, maize, and cassava. After harvesting groundnuts and maize the cassava is left on the farm for another year before it is harvested. It is this type of land that was used for the experiment.

### 2.3 Design of field experiments

There were twelve treatments (Table 1) replicated three times per iste. Field experiments involved a 4 x 4 x 4 factorial experiments in a randomized complete block design (RCBD) [27]. At each site, the treatments evaluated included absolute control ($P_0N_0$) 20, 40 and 60 kg P ha$^{-1}$ applied without N; 40, 80 and 120 kg N ha$^{-1}$ applied without P, and combinations of 20, 40 or 60 Kg P applied with 40, 80 or 120 Kg of N ha$^{-1}$. All treatments were replicated three times at each site.

**Table 1. Summary of treatments* evaluated**

| | | | |
|---|---|---|---|
| T1= $P_0N_0$ | T5 = $P_{20}N_0$ | T9 = $P_{40}$ $N_0$ | T13 = $P_{60}$ $N_0$ |

| | | | |
|---|---|---|---|
| $T2 = P_0 N_{40}$ | $T6 = P_{20} N_{40}$ | $T10 = P_{40} N_{40}$ | $T14 = P_{60}N_{40}$ |
| $T3 = P_0 N_{80}$ | $T7 = P_{20} N_{80}$ | $T11 = P_{40} N_{80}$ | $T15 = P_{60}N_{80}$ |
| $T4 = P_0N_{120}$ | $T8 = P_{20} N_{120}$ | $T12 = P_{40} N_{120}$ | $T16 = P_{60}N_{120}$ |

** Numbers in subscript after P or N stand for evaluated P and N application rates kg ha$^{-1}$ respectively*.

### 2.4 Land Preparation, Planting, crop Management

Land preparation involved slashing, burning and cultivation by hand hoe. Following cultivation, the field was laid out to establish right angles following a Pythagorean theory and experimental plots sized 4 m x 4 m (16 m$^2$) were established. The plots in a block were separated from each other by 1.5 m allay and the blocks were separated by 2 M allay. Maize was planted at 75 cm (inter row) x 30 cm (intra row) spacing. Two maize seeds were sown per hill, thinned to one plant per hill two weeks after germination. Fertilizer (TSP – 0-46-0) was band applied with half of the decided amount of nitrogen (Urea- 46% N) after maize germination at the upper slope to the maize row and the remaining half of N was top dressed 8 weeks from planting maize.

The N & P fertilizers were applied after germination of maize to avoid shortage and cost of labour. To note is that it is usually basal application of P fertilizer at planting to ensure that the emerging root comes in close contact with P fertilizer for plant uptake. However, preplant N application in corn in other places is not recommended to avoid loss because of the length of time from application to when the corn plant will begin significant N uptake (v6 or about 3 weeks) Adotey [28]. Adotey [28] states that banding (surface or subsurface) is the common N placement method for applying N fertilizers in Tennessee and that side dress application can be done any time after planting through tasseling.

The field experiments were run for three consecutive growing seasons beginning in August 2020 to January 2022 at NA site and only two consecutive seasons (April and September 2021) at BM and ATA where host farmers turned the exercise down in the middle of the first season (2020) as they perceived that fertilizers damage the soil or cause cancer. For the research to continue, another land was sought in the neighbourhood and consequently, the trials were only done in two instead of three seasons as originally intended. Since the two sites (original fields and the newly sought fields) were very close and similar in terms of visible feature, preliminary soil analysis results for the two original sites were maintained thus preliminary soil sampling was not repeated at the two new sites.

### 2.5 Maize Harvesting and Yield Determination:

Maize was harvested 120 days after planting when the plant was at harvesting (drying phase). A net plot (8.5 m$^2$) was established in each experimental plot excluding border plants then all the maize plants from a net plot were harvested. All above ground parts were harvested by cutting maize straws just above the soil surface and total biomass (stover, cob and grain) was weighed and recorded. Shelled maize grain was weighed at home and sub samples were sun dried to constant moisture content (13 %) using grain moisture meter and converted to tonnes per hectare using equation (1).

$$\text{Yield in tonnes per ha} = \left(\frac{\text{y kg} \times 10000\,\text{m}^2}{8{\cdot}5\text{m}^2 \times 1000\,\text{kg}}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{[1]}$$

Where: y kg = Adjusted weight of maize in kg) obtained on the net plot (8.5 m$^2$)
10, 000 m$^2$ = Area of one hectare
1000 kg = conversion factor from kg to tonnes

Maize stover yield was determined by weighing air dry stover harvested from a net plot and converted to tonnes per hectare using equation 1 above.

## 2.6 Post-harvest Soil Sampling and analysis

Post-harvest soil sampling and analysis was performed purposely to assess the various rates of P and N fertilizers applied residue and its effect on the environment. At the end of field experiments (after harvesting the maize) in January 2022, a representative composite soil sample was collected from each field plot for laboratory analysis. Each composite sample per plot was made up of five surface (0-20 cm) subsamples thoroughly crashed, thoroughly and reduced to 500 g by quartering procedure.  Collected soil samples were sent to the Sokoine University of Agriculture in Tanzania for further processing and analysis. Total nitrogen was determined by Kjeldahl method [29]. Available P was extracted following the Bray 1 method [29]. A 3.5 g of air-dry soil sample was weighed into an extraction bottle and extracted with an acidified extracting solution containing a mixture of 0.03 M $NH_4F$ and 0.025 M HCL. After shacking for 30 minutes the suspension was filtered through a Whatman Filter paper No.42. Available P in the extract was quantified following the ammonium molybdate – ascorbic acid colorimetric method using a UV Spectrometer set at 884 nm wavelength [29].

## 2.7 Statistical Analysis

Maize yield data was subjected to analysis of variance (ANOVA) using GenStat 15th Edition. Treatment means were separated at 95% confidence using LSD and Turkey's Honesty Significance Difference (THSD). The model used to analyse the yield and the biomass data was as in Equation 2.

$$\boldsymbol{Y_{ijk}} = \boldsymbol{\mu} + \boldsymbol{\beta_i} + \boldsymbol{\alpha_j} + \boldsymbol{\lambda_k} + (\beta\alpha)_{ij} + (\beta\lambda)_{ik} + (\alpha\lambda)_{jk} + (\beta\alpha\lambda)_{ijk} + \boldsymbol{\varepsilon_{ijk}} \qquad (2)$$

*Where*

| | |
|---|---|
| *Yijk* | *response variable Y* |
| *μ* | *general mean effect (or reference value),* |
| $\boldsymbol{\beta_i}$ | *site conditions* |
| $\boldsymbol{\alpha_j}$ | *additional effect due to $j^{th}$ level of season α* |
| $\boldsymbol{\lambda_k}$ | *additional effect due to $k^{th}$ level of fertilizer treatment* |
| $(\boldsymbol{\beta\alpha})_{ij}$ | *interaction between site and season* |
| $(\boldsymbol{\alpha\lambda})_{jk}$ | *interaction between season α and treatment* |
| $(\boldsymbol{\beta\lambda})_{ik}$ | *interaction between site and treatment* |
| $(\boldsymbol{\beta\alpha\lambda})_{ijk}$ | *interaction among the sites, seasons, and treatment* |
| $\boldsymbol{\varepsilon_{ijk}}$ | *random errors associated with level of combinations and replication per site* |

## 2.8 Environmental and Economic Assessment of fertilizers

Several frameworks exist for agricultural sustainability assessments [2], but this discussion will use sustainable intensification assessment framework (SIAF) Stewart *et al.,* [30]. This framework has multiple indicators in each of the domains: productive, economic, environmental, human wellbeing, and social [31]. However, this study will focus only on productive, economic, and environmental.

*Productivity:* is concerned with the goal of increasing output per unit input in each time. Land is the critical input, land degradation, and threatened biodiversity from loss of natural habitat [30].

*Economic analysis:* This domain is concerned with profitability of agricultural activities and returns to factors of production [30]. Some of the production inputs nutrients, water, labour, and capital lead to high yields of quality products and financial gain for the producer if properly applied [32,30]. Economic analysis is conducted to assess the feasibility of the treatments using partial budget, dominance, and marginal analysis of each treatment [33]. Partial budget analysis is recommended to estimate the net benefit and marginal returns that could be obtained from various alternative treatments [34]. Other scholars who have used partial budget analysis include Shaaban and Kisetu [35] William et al. [36] Melese et al. [33] and Quee and Samura [37].

The data collected were: Gross average maize yield (t $ha^{-1}$) (AvY): an average yield of each treatment converted in to tons per hectare, Adjusted yield (AdjY): Average yield adjusted downward by 15% to reflect the difference between the management and plot of experimental yield and yield of farmers thus: AdjY (t $ha^{-1}$) = AvY × (1-0.15), total variable costs (TVC) such as costs of purchasing N and P fertilizers (for each equivalent rate of application), and labour costs for fertilizer application but the assumption was that all other costs of maize production were constant across all levels of N and P application within a season. With this, the prevailing farm gate price of maize grain at harvest was obtained and the gross benefit (GB), average price, maize grain yield (kg $ha^{-1}$), and cost benefit ratio (CBR) calculated as shown in Equations 4-6.

$$\text{Gross Benefit (GB)} = \text{Average price (AvP)} \times \text{AdjYield} \quad (4)$$

$$\text{Net Benefit(NB)} = \text{GB} - \text{TvC} \quad (5)$$

$$\text{CBR} = \text{Cost Benefit Ratio} = \frac{\text{Net Benefit}}{\text{Total Variable Cost (TvC)}} \quad (6)$$

If the CBR < 1 then the costs exceed the benefit, the tested N and/or P were rejected. If the CBR≥ 1 then the benefits exceed the costs the tested N and/or P were accepted.

Furthermore, marginal analysis was computed to compare net benefits with partial budget by considering the magnitude of corresponding variable costs [34]. The Marginal Rate of Return (MRR %) was calculated by dividing change in net benefit by change in TvC [34] and expressed in percentage, the decision to adopt a treatment as profitable was based on the Benefit-Cost equation (Eq. 7) and positive difference indicated the change was profitable [36]. To compare the costs that varied with the net benefits, marginal analysis involving dominance analysis was used. Recommendations were made based on the comparisons of the rates of return between treatments to the minimum rate of return acceptable to farmers that range from 50% to 100% [34]. Hence, any treatment that returns above 100% is considered worthy investment by farmers.

$$MRR = \frac{\Delta NB}{\Delta TvC} \quad (7)$$

Or

$$MRR\ (\%) = \frac{Marginal\ \ benefit}{Marginal\ \ cost}\ x\ 100 \quad (8)$$

*Environmental effect:* The environmental effect is concerned with the natural resource base that supports agriculture as well as the agricultural negative effect on the environment for example shifting cultivation [30]. The negative effects are those that pose great threat to people and their environment [37]. Several scientists have mentioned that if agricultural inputs are not well managed, the effect on the environment will be detrimental. They have highlighted on health issues (e.g., cancer), eutrophication of surface waters and release of greenhouse gases (GHG) such as $CO_2$ leading to global warming [39,38, & 40]

## 3.0 RESULTS AND DISCUSSIONS

### 3.1 Rainfall and temperature in the study area

The rainfall and temperature received at the study area for 2020 and 2021 are indicated in Figure 1 (a and b) downloaded from [41] ArcMap version 10.5. According to FAO/WFP [42] the planting season is about 300 days, the rainfall is bimodal, starts in late March all through June, dry spell in July and heavy rains are experienced in August and September decreasing to November. However, from this extracted rainfall from the website, it shows continuous rainfall from late March to November with the month of July receiving about 180 mm in 2020 more than the same month in 2021 while the highest rainfall (250 mm) was experienced in September 2020 compared to about 160 mm in 2021. In both years it indicates that the rainfall is highest in August, September, and October but October 2021 was just 150 mm even lower than July in the same year. On average the temperature was about 33°C but the months of December, January, February, and March were the hottest. High rainfall coincides with lower temperatures up 30°C.

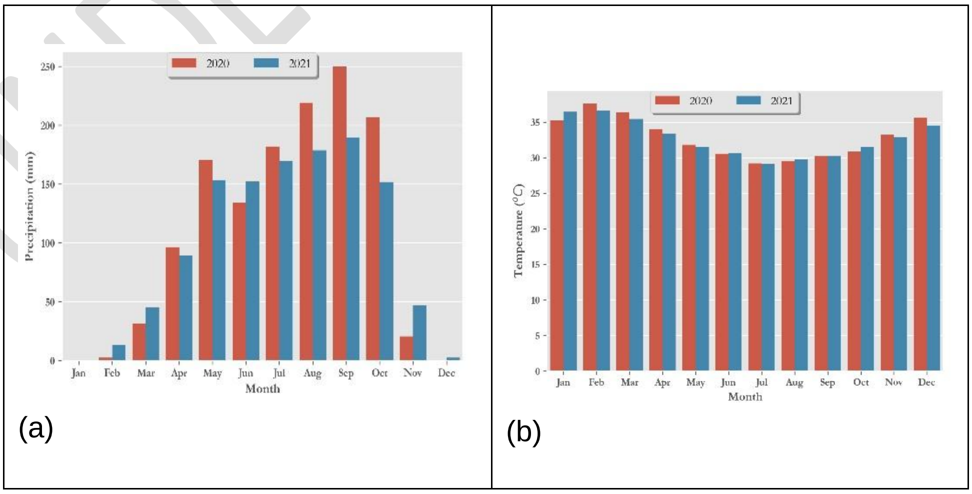


**Figure 1. Total Annual Precipitation (a), and Temperature (b) for 2020 and 2021**

## 3.2. Productive domain

Although there are several indicators, only the grain yield data was used (t $ha^{-1}$) [5].

### 3.2.1 Pre-planting and post-harvest N and P soil fertility status

The experiment in Nangbangi village is in Nginda Payam, Yambio County will be referred to as site-1 for simplicity and both experiments at Bure Maku and Ataziri villages located in Sakure Payam, Nzara County will be called site-2 and site-3 respectively.

The soil fertility status of the experimental sites before the study is presented in Table 2. The most limiting nutrient was phosphorus followed by nitrogen [25] (Bazugba *et al*. 2023). Potassium was marginally available including micronutrient zinc. Based on this results decision was made to only provide NP since the application of fertilizer was a new technology in the area. In the post-harvest soil analysis for available P level increased to an average of 5.28 mg/ kg and TN increased to 0.18 % at site-1; at site-2 available P level was 12.56 mg/ kg and average TN was 0.17 % while at site-3, the average P was 8.78 mg/ kg and TN was 0.17 %. TN does not say much about the availability of the nutrient to crop, in future studies analysis not only for nitrate or ammonium ions should be determined but for all the nutrients as indicated in Table 2 should be considered depending on the availability of resources.

*Table 2 Pre-planting site topsoil characterization (source: Bazugba et al.,* [25])

| ***Soil parameters*** | ***Site-1 (Nangbangi)*** | ***Site-2 (Bure Maku)*** | ***Site-3 (Ataziri)*** |
|---|---|---|---|
| *Texture class* | Sandy clay loam | Sandy clay loam | Silt Loam |
| *pH H2O 1:2.5* | 5.98 | 6.00 | 6.7 |
| *EC 1:2.5 (mS/c* | 0.07 | 0.01 | 0.18 |
| *ESP* | 0.05 | 1.06 | 4.06 |
| *Organic C (%)* | 1.81 | 0.91 | 2.28 |
| *Total N (%)* | **0.13** | **0.07** | **0.13** |
| *Avail. P Bray-1 mg/ kg* | **1.33** | **1.17** | **2.45** |
| *CEC NH4OAc cmol (+)/ kg* | 10.2 | 4 | 8.4 |
| *Exch. Ca (cmol (+)/kg)* | 4.78 | 2.09 | 3.91 |
| *Exch. Mg (cmol (+)/kg)* | 2.13 | 0.82 | 1.45 |
| *Exch. K (cmol (+)/kg)* | 0.3 | 0.24 | 0.37 |
| *Exch. Na (cmol (+)/kg)* | 0.05 | 0.04 | 0.34 |
| *Base saturation (%)* | 71 | 80 | 72 |
| *Sulfur mg/kg* | 26.3 | 36.72 | 38.02 |

*Source: Bazugba et al. 2023*

### *3.2.2 Effect of N and P treatments on maize Yield*

Soil productivity as influenced by fertilizer treatments was measured in terms of all maize above ground parts (biological yield) and weight of grains per unit area of land also referred to as economic yield [5]. Each of the three sites results are summarized and discussed as per the respective site.

### *3.2.3 Nangbangi village (Site-1)*

At Site-1, the control was ($P_0N_0$). Twenty (20), 40 and 60 kg P ha $^{-1}$ was applied without N and 40, 80 and 120 kg N ha$^{-1}$ was applied without P and the yield was also compared in each of the three seasons that are presented in Table 3.

*Table 3. The impact of P, N, and season on the response of maize grain yield*

| **Phosphorus level (kg/ha)** | **Mean grain yield (t/ha)** | **Nitrogen level (kg/ha)** | **Mean grain yield (t/ha)** | **Season** | **Mean grain yield (t/ha)** |
|---|---|---|---|---|---|
| 20 | 4.1 a | 120 | 4.1 a | 1 | 4.7 a |
| 60 | 4.0 ab | 40 | 3.9 ab | 3 | 3.5 b |
| 40 | 3.7 ab | 80 | 3.9 ab | 2 | 3.4 b |
| 0 | 3.6 b | 0 | 3.5 b | | |

*Same letters in the same column means there is no significance ($p<0.05$)*

The results indicate that 20 kg P ha$^{-1}$ was significantly different from the control and 120 kg N ha$^{-1}$ followed the same trend and both gave a yield of 4.1 t ha$^{-1}$. The biomass is presented in Table 4, and it follows the same trend as the grain. There is a correlation between the grain yield and biomass. The interaction between P and N and the grain and biomass yields are presented in Table 4 and 20 kg P ha$^{-1}$ combined with 120 kg N ha$^{-1}$ gave highest grain (4.8 t ha$^{-1}$) and biomass (16.9 t ha$^{-1}$) significantly different yields.

Seasons also played important roles in increasing the grain and biomass yields. Season 1 and 3 produced 4.7 t ha$^{-1}$ and 3.5 t ha$^{-1}$ respectively (Table 2). In season 1 (2020) and season 3 (2021) that falls within the second half of the year coincided with the peak rainfall in August, September, and October (Fig. 1), the yields were significantly different at $p < 0.05$. Although season 3 gave high yield but was not significantly different from the yield in season 2 (3.4 t ha$^{-1}$). This means at the beginning of the year 2021 (season 2) there was water stress at some point. The interaction between each individual nutrient and season is indicated in Table 5 and in season 1, 60 and 20 kg P ha$^{-1}$, produced the grain yield 5.0 t ha$^{-1}$ and 4.7 t ha$^{-1}$ respectively; 80 and 120 kg N ha$^{-1}$ gave a grain yield of (5.1 and 4.7) t ha$^{-1}$ respectively.

*Table 4. The impact of season on and the response of maize biomass to applied N and P*

| **Phosphorus level (kg/ha)** | **Mean Biomass yield (t/ha)** | **Nitrogen level (kg/ha)** | **Mean Biomass yield (t/ha)** | **Season** | **Mean Biomass yield (t/ha)** |
|---|---|---|---|---|---|
| 20 | 14.9 a | 120 | 14.6 a | 1 | 14.9 a |
| 60 | 13.8 ab | 80 | 13.7 a | 3 | 14.4 ab |
| 40 | 13.6 ab | 40 | 13.3 a | 2 | 11.5 b |
| 0 | 12.2 b | 0 | 12.9 a | | |

*Same letters in the same column means there is no significance ($p<0.05$)*

*Table 5. Interactions of P with N on maize grain and biomass yield*

| **P x N (kg/ha)** | **Mean grain yield (t/ha)** | **Mean biomass yield (t/ha)** |
|---|---|---|
| 20 120 | 4.8 a | 16.9 a |
| 60 80 | 4.7 ab | 15.5 ab |
| 0 0 | 3.3 b | 11.1 b |

*Same letters in the same column means there is no significance ($p<0.05$)*

The effect of combined P and N and season on yield is presented in Table 5. In season 1, (60 P 80 N) kg ha$^{-1}$ produced 6.6 t ha$^{-1}$; season 1 also with another combination (20 P 120 N) kg ha$^{-1}$ gave 5.2 t ha$^{-1}$ and was not significantly different from the former (6.6 t ha$^{-1}$). In season 3, (20 P 120 N) kg ha$^{-1}$ yielded 5.1 t ha$^{-1}$. In season 2, the yield was 4.1 t ha$^{-1}$ for the combination of (20 P 120 N) kg ha$^{-1}$. Statistically, season was significantly at $p < 0.05$. There is consistence in the three seasons but yield variation between seasons, the second half of the season (1 and 3) that coincided with peak rainfall. This implies that there was probably shortage of moisture in the soil in the first half of the year 2021 although the months of April, May and June received about 100 mm of rainfall in that year, the rains might have been erratic.

These agronomic results have shown that 20 kg P ha$^{-1}$ produced (high yield when applied without N, in the season and in the combination with N; on the other hand, 120 kg N also produced high yield when applied without P, in the season and in combination with 20 kg P. The yields were significantly higher than the control at ($P < 0.05$). Another thing to note is although there was increase in yield in the first season but there was a gradual decrease in yield on the same piece of land in the other two seasons in 2021. The biomass yield followed the same trend as the grain yield. The drop in yield could be attributed to the decrease of some nutrients in the soil [43]. Another reason for drop in yield is due to low moisture in the root zone. Water and temperature are the most important determining factors in crop yield. According to Singh [44], even in humid parts of the world there are times of insufficient rainfall leading to water stress. The soil of the study area is sandy clay loam, there is possibility of high-water infiltration rate passing the root zone since the soil is in advance stage of weathering [25].



*Table 6. Interactions of Season x P and Season x N*

| **Season (4 months)** | **P level (kg/ha)** | **Mean grain yield (t/ha)** | **Season (4 months)** | **N level (kg/ha)** | **Mean grain yield (t/ha)** |
|---|---|---|---|---|---|
| 1 | 60 | 5.0 a | 1 | 80 | 5.1 a |
| 1 | 20 | 4.7 ab | 1 | 120 | 4.7 ab |
| 1 | 0 | 4.6 ab | 1 | 0 | 4.2 abc |
| 3 | 20 | 3.8 abcd | 3 | 120 | 4.0 abc |
| 2 | 20 | 3.7 bcd | 2 | 120 | 3.6 bc |
| 3 | 0 | 3.4 cd | 2 | 0 | 3.3 c |
| 3 | 40 | 3.3 d | 3 | 0 | 3.2 c |
| 2 | 0 | 2.7 d | 3 | 80 | 3.2 c |

*Season: 1 = August 2020, 2 = April 2021 & 3 = August 2021; 0 = no fertilizer added; P = phosphorus; N = nitrogen*
*Same letters in the same column means there is no significance (p<0.05)*

*Table 7 Interaction of Seasons x Phosphorus x Nitrogen and maize yield*

| **Season (months)** | **P x N (kg/ha)** | **Mean grain yield (t/ha)** |
|---|---|---|
| 1 | 60 80 | 6.6 a |
| 1 | 20 120 | 5.2 ab |
| 3 | 20 120 | 5.1 ab |
| 2 | 20 120 | 4.1 ab |
| Pooled mean of control | 0 0 | 3.2 b |
| | | **Mean biomass yield (t/ha)** |

| | | |
|---|---|---|
| 1 | 60 80 | 21.8 a |
| 3 | 20 120 | 21.8 a |
| 2 | 20 0 | 14.4 abcd |
| Pooled means of control | 0 0 | 11.1 bcd |

*Same letters in the same column means there is no significance (p<0.05)*

### 3.2.4 Bure Maku village (Site- 2)

Experiment at Site-2 was conducted for only two seasons all in 2021 (i.e., season 2 and 3); season 1 (2020) was lost because the farmer suddenly changed his mind in the middle of the season and did not want fertilizer to be used on his land. The ANOVA show season was significant at $p < 0.018$ and phosphorus significant at $p < 0.027$. The results show that 20 kg P ha$^{-1}$ gave 3.917 t ha$^{-1}$ and 120 kg N ha$^{-1}$ produced 3.662 t ha$^{-1}$ only P and Season were significant ($P < 0.05$), yields from application of N alone was not significant. Combination of fertilizer (20 kg P and 120 kg) ha$^{-1}$ produced 4.4 t ha$^{-1}$ the highest in the interaction.

Phosphorus at 20 kg P ha$^{-1}$ in season 2 and 3 produced 4.1 t ha$^{-1}$ and 3.7 t ha$^{-1}$, while 120 kg N ha$^{-1}$ in season 2 and 3 produced 3.8 t ha$^{-1}$ and 3.5 t ha$^{-1}$ respectively. In the overall seasons, P and N interactions in season 2, (20 kg P 120 kg N) ha$^{-1}$ gave grain yield of 4.627 t ha$^{-1}$ over the control (3.0 t ha$^{-1}$) and in season 3, (20 kg P 120 kg N) ha$^{-1}$ produced 4.235 t ha$^{-1}$. Biomass followed the same trend, but it was 40 kg P and 120 kg N that made the difference giving 15.3 t ha$^{-1}$ in season 2 and 13.7 t ha$^{-1}$ in season 3 but was not significant. Except for biomass, the result is consistent site-1.

### 3.2.5 Ataziri village (Site- 3)

Experiment at Site-3 was conducted for only two seasons all in 2021 (i.e., season 2 and 3); season 1 was lost because the farmer suddenly changed his mind in the middle of the season and did not want fertilizer to be used on his land. ANOVA analysis shows there was no statistical significance at $p < 0.05$. The results show that 20 kg P ha$^{-1}$ gave 3.118 t ha$^{-1}$ and 120 kg N ha$^{-1}$ produced 3.176 t ha$^{-1}$. The combination of (20 kg P and 120 kg) ha$^{-1}$ produced 3.765 t ha$^{-1}$.

Phosphorus at 20 kg P ha$^{-1}$ in season 2 produced 3.3 t ha$^{-1}$ and 40 kg P ha$^{-1}$ produced 3.0 t ha$^{-1}$, in season 3 while 120 kg N ha$^{-1}$ in season 2 and 3 produced 3.235 t ha$^{-1}$ and 3.118 t ha$^{-1}$ respectively. The overall season, P and N interactions in season 2, (20 kg P 120 kg N) ha$^{-1}$ gave grain yield of (4.392 t ha$^{-1}$) over control (2.4 t ha$^{-1}$) and in season 3, (20 kg P 40 kg N) ha$^{-1}$ produced 4.0 t ha$^{-1}$. Biomass followed the same trend. The results at site-3 are also consistent with those at site-1.

## 3.3 Economic domain

The net income from agriculture produces after subtracting the total variable cost is the economic profitability [5]. Black [32], emphasized the importance to compute the magnitude of economic returns. Therefore, partial budget analysis manual has been provided by [34]. The manual guided how to estimate the net benefit (NB), benefit cost ratio (BCR) and marginal rate of return (MRR) that could be obtained from various alternative treatments as well as dominance of each treatment. The dominance analysis carried out by first listing the treatments in order of increasing costs that vary (TVC). Any treatment that has net benefits that are less than or equal to those of a treatment with lower costs that vary is dominated [34].

The average and adjusted yield of 16 treatments replicated three times, TVC, GB, NB and BCR are presented in Table 8. The NB with letter 'D' attached to it means it is dominated, implying that this rate of fertilization application was not profitable (Melese *et al.* 2018). The application of 20 kg P ha$^{-1}$ + 120 kg N ha$^{-1}$ had the highest NB (834 334 SSP ha$^{-1}$), followed by the application of 40 kg N ha$^{-1}$ alone (773 992 SSP ha$^{-1}$) and total net benefit of 740 135 SSP ha$^{-1}$ at the rate of 20 kg P ha$^{-1}$ alone while the lowest net benefit was 659 980 SSP ha$^{-1}$ at the rate of (60 kg P + 40 kg N) ha$^{-1}$.

*Table 8 Partial budget and Dominance analysis of the combined application of N & P fertilizers on rainfed maize at Site-1 in 2020/ 2021*.

| *Treatment (N x P)* | *AvY (t/ha)* | *AdjY (SSP/ha)* | *GB (SSP/ha)* | *TVC (SSP/ha* | *NB* | *B:C ratio* |
|---|---|---|---|---|---|---|
| *0 0* | 3.255 b | 2.767 | 680,621 | - | 680,621 | 0 |
| *20 0* | 3.817 b | 3.244 | 798,135 | 58,000 | 740,135 | 12.76094 |
| *40 0* | 3.425 ab | 2.911 | 716,168 | 76,000 | 640167.5 D | 8.423257 |
| *0 40* | 4.065 ab | 3.455 | 849,992 | 76,000 | 773,992 | 10.1841 |
| *60 0* | 3.647 ab | 3.100 | 762,588 | 94,000 | 668587.7 D | 7.112635 |
| *20 40* | 3.843 ab | 3.267 | 803,571 | 94,000 | 709,571 | 7.548631 |
| *40 40* | 3.843 ab | 3.267 | 803,571 | 112,000 | 691571 D | 6.174744 |
| *0 80* | 3.32 ab | 2.822 | 694,212 | 112,000 | 582212 D | 5.198321 |
| *60 40* | 3.778 b | 3.211 | 789,980 | 130,000 | 659,980 | 5.076768 |
| *20 80* | 3.83 ab | 3.256 | 800,853 | 130,000 | 670,853 | 5.160408 |
| *40 80* | 3.595 ab | 3.056 | 751,715 | 148,000 | 603715 D | 4.079152 |
| *0 120* | 3.595 ab | 3.056 | 751,715 | 148,000 | 603715 D | 4.079152 |
| *20 120* | 4.784 a | 4.066 | 1,000,334 | 166,000 | 834,334 | 5.026111 |
| *60 80* | 4.667 ab | 3.967 | 975,870 | 166,000 | 809870 D | 4.878733 |
| *40 120* | 4.026 ab | 3.422 | 841,837 | 184,000 | 657837 D | 3.575199 |
| *60 120* | 4.000 ab | 3.400 | 836,400 | 202,000 | 634400 D | 3.140594 |

*AvY = average yield, AdjY= adjusted yield, D= Dominated, GB= gross benefit, TVC= total variable cost, NB= net benefit, B:C ration= benefit cost ration, SSP=South Sudanese Pounds, farm gate price =SSP 246 kg$^{-1}$ (1$=1 000SSP)*

Table 9 was generated after eliminating dominated treatments in Table 8. The % marginal rate of return (MRR %) was calculated by dividing the marginal benefit by marginal cost multiplied by 100 %. The marginal rate of return ratio showed that for every SSP, the net benefit was 33 856.8 SSP for 40 kg N ha$^{-1}$ without P, 59 514.2 SSP at 20 kg P ha-1, and 163 481.4 SSP for combined P and N (20 kg P + 120 kg N) ha$^{-1}$, these are the undominated treatments Table 8.

The profitability study showed that application of 20 kg P ha$^{-1}$ in combination with 120 kg ha$^{-1}$ provided the highest net benefit (834 334 SSP ha$^{-1}$). However, as the total variable costs over the optimum level (Table 8), the net benefit obtained reduced because of higher variable costs associated with lower earnings.

**Table 9 Marginal rate of return of combined N & P fertilizers application on rainfed maize production in Site-1 in 2020/ 2021**

| TREATM. P & N | TVC (SSP/HA) | MC (SSP/HA) | NB (SSP/HA) | MB (SSP/HA) | MRR % |
|---|---|---|---|---|---|
| **0 0** | 0 | | 680620.5 | | |
| **20 0** | 58000 | 58000 | 740,134.70 | 59,514.20 | 103 |
| **0 40** | 76000 | 18000 | 773,991.50 | 33,856.80 | 188 |
| **20 40** | 94000 | 18000 | 709,571.30 | - 64,420.20 | -358 |
| **60 40** | 130000 | 36000 | 659,979.80 | - 49,591.50 | -138 |
| **20 80** | 130000 | 0 | 670,853.00 | 10,873.20 | - |
| **20 120** | 166000 | 36000 | 834,334.40 | 163,481.40 | 454 |

*TVC = total variable cost, MC= marginal cost, NB= net benefit, MB= marginal benefit, MRR = marginal rate of return, SSP=South Sudanese Pounds*

### 3.4 Environment domain

Virgin land is constantly being brought under agriculture to achieve high yields in the study area because the inherent soil fertility is poor [25]. The purpose of this study was to find solution to minimize the current destruction to forest biodiversity in the study area by increasing soil productivity for higher crop yield per unity area through sustainable agriculture intensification [30]. According to Smith *et al*. [5], some of the indicators that are used to assess sustainable intensification are biodiversity, presence of plant materials on the field, measurement of erosion etc. Only the most relevant ones are selected for a particular study [31]. Smith *et al.* [5], have reported that several scientists advocate for keeping plant materials on the fields such as below ground for annual crops and both below and above ground level for the perennials allow for carbon sequestration and nutrient recycling. Presence of this plant materials signifies carbon capture and nutrient cycling within an agricultural system, and it is an indicator of both productivity and environmental sustainability in SI system [5]. A soil with no organic matter or SOC will fail to regulate water dynamics, stabilize the soil structure, exchange nutrients for plants and will greatly impair the activity of soil microorganisms [45,46] and consequently plant performance will decline leading to poor yield and food insecurity. In the study area, the practice is farmers remove every piece of vegetation after cultivation and burn. Several scholars including Lal [47,46] have emphasized the importance of maintaining plant materials on the farms. These activities constitute environmental services that enhance agricultural productivity [30]. To note is clearing forest for the purpose of agriculture destroys the natural habitat of the wildlife too [5].

## 4.0 Discussion

### *4.1 Maize yield in response to NP treatments and the season*

Generally, the yield increased at all sites, in all the plots that received NP treatments over the control. The effect of season was significant at site 1 and 2, the interaction of season and NP at site-1 gave higher yield (5.2 t ha$^{-1}$) compared to the individual fertilizers NP and is recorded in Table 4 where the impact of season has been considered. The same trend was seen in site-2 (4.6 t ha$^{-1}$) and site-3. (4.3 t ha$^{-1}$) all at the rate of 20 kg P ha$^{-1}$ and 120 kg N ha$^{-1}$. However, at site-1 in season 1 (2020), 60 kg P and 80 kg N ha$^{-1}$ gave the highest significant yield (6.6 t ha$^{-1}$), this might have happened by chance, so will not be discussed further. The application of 20 kg P ha$^{-1}$ without N was significant at site-1 and site-2 but was not at site-3, on the other hand 120 kg N ha$^{-1}$ without P was only significant at site-1. The overall response of maize to fertilizer

(NP) application in the three sites is (4.7 t $ha^{-1}$) an increase of 62 % over the control (2.9 t $ha^{-1}$). The response of maize yield to either P or N means each of the nutrient contributed to the yield, but the combined NP gave highest yield in the season. Therefore, in the productive domain we recommend the application of 20 kg P $ha^{-1}$ combined with 120 kg N $ha^{-1}$ for optimum rainfed maize yield. According to Dimkpa *et al.* (2023), the rate of 120 kg N $ha^{-1}$ is common in the SSA although there is variation related to the soil type.

The result also indicates that season 1 (second half of 2020) and season 3 (2021) significantly influenced the yield in site-1 but not at sites 2 and 3. Season 2 (first half of 2021) gave high grain yield at site-2 and 3 but was significant only at site-2. This implies that the rainfall was unevenly distributed in the months and seasons in the two years.

To note is the average combined cereal yield for the country has been documented in many reports as 0.7 t $ha^{-1}$) but 2.9 t $ha^{-1}$ result obtained where no fertilizer was used in this study has revealed that South Sudan has not achieved its yield potential and this result also surpasses the average in other neighouring countries. The results can be attributed to good agronomic management in terms of plant population, weeding and good seed. We saw that farmers are planting several crops (ground nuts, cassava, and maize, sometimes they also scatter sesame) on the same piece of land, consequently, the plant population for maize is always very low. Farmers concentrate effort on a piece of land to avoid labour shortages in the season because management of weeds is another greatest challenge compared to nutrient deficiency some farmers reported.

In the literature search, no published report was found for the recommendation of fertilizer application in the greenbelt or other part of the country. This means the 1 % using fertilizer as report elsewhere in this report are making blanket application that may result in excess use of fertilizer leading to loss of money and pollution of the environment. Therefore, this study will serve as a base line for future research involving inorganic fertilizers and an attempt to recommend fertilizer application in the greenbelt zone. However, the fact that some farmers refused fertilizer experiments to be done on their fields was a short fall in this study; but at the same time, it indicates the level of knowledge gap that needs to be filled with the right information about the use and benefit of fertilizer not only in the study area but in South Sudan in general.

### *4.2 Partial Budgeting and Marginal Analysis*

The benefit-cost ratio equation yielded positive net changes in the treatments Table 5. The positive implies that the incremental benefits in farming with added fertilizers (N & P) exceeded the incremental costs and suggests that using NP is an economically feasible management practice. But at this stage no meaningful recommendations can be made about the technology until the MRR is calculated [34].

The results show that untreated plots (farmer practice) to treatment with NP increased farmers' returns. Both N and P individually and combined NP gave MRR above 100% which was regarded as minimum rate of return acceptable to smallholder farmers to change from one technology to another. This implies that for every South Sudanese Pound (SSP) invested in N or P or combined, farmers will recover their one SSP plus an additional pounds as benefit thus making the application of fertilizer an attractive option. The interested farmers are highly advised to adopt (20 kg P + 120 kg N) ha$^{-1}$ as this gave highest MRR (450 % in Table 9) in the analysis. However, another option is using only 20 kg P ha$^{-1}$ or 120 kg N ha$^{-1}$. Computing MRR was useful because it has indicated the best combination of NP that gave high yield as well as the magnitude of economic returns. The harvested maize was statistically computed, assessed and optimum amount of fertilizer for optimum maize grain yield was recommended for the study area which are 20 kg P+120 kg N ha$^{-1}$. Although only 20 kg P ha$^{-1}$ or only 120 kg N ha$^{-1}$ improved the soil fertility and has given good yield it will not be sustainable in the long run, further studies together with the incorporation of organic matter is required.

### *4.3 Efforts to reduce the detrimental effect of fertilizer on the environment*

Using fertilizer in modern agriculture for crop production enrich soil with nutrients which it lacks [48,49, 40] and fertilizers have transformed the way the world produces food [22]. Fertilizers contribute to increased crop yields per unit area and reduce the need to convert more land to agriculture [39,50] and this means less destructions to the ecosystems. The important thing is nutrient consistency in manufactured fertilizers that allows for efficient production on commercial scale; making food affordable at a reduced cost of production [50].

There is large data gap with respect to knowledge on the impact of fertilizer on the environment and on human health [39,38,40]. Ritchie *et al.* [39] reported that scientists are aware of the adverse effect of fertilizers including greenhouse gas, the loss of half of the applied fertilizer from the fields, lost in runoff water or leaching or is broken down by microbes in the soil releasing potent greenhouse gas, nitrous oxide into the air [39]. Previously, Chen *et al*. [51]) reported that significant fertilizers are lost increasing cost, wasting energy, and polluting the environment, which are challenges for the sustainability of modern agriculture. However, if fertilizer is appropriately applied, so that plants use all the nutrients, and none are lost there will be little chance for pollution [50].

According to Ritchie *et al*. [39] Chen *et a*l. [51] , and Suman *et al*., [52], scientists want to use less fertilizer without sacrificing crop yields and there are several options, and these options are grouped under environmentally friendly fertilizers (EFFs): 1) EFF coatings can prevent urea exposure in water and soil by serving as a physical barrier, thereby reducing the urea hydrolysis rate and decreasing nitrogen oxides and dinitrogen ($N_2$) emissions, 2) EFFs can increase the soil organic matter content, 3) hydrogel/ superabsorbent coated EFFs can buffer soil acidity or alkalinity and lead to an optimal pH for plants, and 4) hydrogel/ superabsorbent coated EFFs can improve water-retention and water-holding capacity of soil. With these scientists believe that EFFs play an important role in enhancing nutrients efficiency and reducing environmental pollution.

## 4.0 CONCLUSION AND RECOMMENDATIONS

Generally, maize grain and biomass yield increased in the plots where fertilizers were applied compared to the control. The yields were significant at site-1 (5.2 t ha$^{-1}$) and site-2 (4.6 t ha$^{-1}$), but site-3 (4.3 t ha$^{-1}$) was not significant although the trend conformed to the other sites. Combined application of NP at the rate of 120 kg N ha$^{-1}$ and 20 kg P ha$^{-1}$ increased maize yield in the study area on average up to 4.7 t ha$^{-1}$ an increase of 62 % over average of the control (2.9 t ha$^{-1}$) in the three sites. The economic analysis revealed that the farmers will make profit at the recommended rate of NP with marginal rate of return of 450 %. This translates to increased maize grain production and hence improved food security. Based on the findings in this study, we therefore recommend the use of 20 kg P $ha^{-1}$ and 120 kg N $ha^{-1}$ for optimum maize production in Sakure and Nginda Payams. Given very low levels of fertilizers use stemming from lack of knowledge and awareness in South Sudan, we also recommend awareness creation and training on the role/ importance of fertilizers in improving maize yield and sustaining soil productivity in the study area and similar agroecological zones.

South Sudanese use the blanket application of fertilizers, there is no known fertilizer rate to be used in any part of the country, this study may serve as the first attempt to make recommendations for fertilizer application. Since this study was done in two seasons in the same year 2021, there is need to conduct multi location and multi – season research in the Greenbelt to test several sources of fertilizer for proper recommendations.

Besides soil fertility, it was also evident from this study that the plots where no fertilizer was used gave a yield of 2.2 t $ha^{-1}$ higher than the national average for cereals of 0.7 t $ha^{-1}$ reported in the country. The reason for this was attributed to the very low plant population planted per unit of land because the farmers plant more than one crop in a season per unit of land. Further studies of the farming systems to establish the actual plant population and yield in a mixed cropping system is recommended.

**DATA AVAILABILITY STATEMENT:**

The data used to generate the results is available with the corresponding author and can be made available once requested.



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