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Increased Maize Yield in Response to Applied Phosphorus and Nitrogen in the Greenbelt Zone, in South Sudan

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Authors' contributions

This work was carried out in collaboration among all authors. Author IAJB designed the study, performed the statistical analysis, wrote the first draft of the manuscript. All authors reviewed and approved the final manuscript.

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ABSTRACT

Aims: The study focused on assessing the impact of applying phosphorus and nitrogen fertilizers on maize yield in the Greenbelt zone of South Sudan, where nutrient deficiencies often limit crop growth.
Study Design: Field experiments involved a 4 x 4 x 4 factorial experiments in a randomized complete block design. The field experiment was conducted in Sakure and Nginda Payams in Nzara and Yambio Counties respectively, between August 2020 and January 2022.
Methodology: The treatments involved Triple Super Phosphate (TSP, 0-46-0) applied at 20, 40 and 60 kg P ha $^{-1}$ without N, Urea (46% N) applied at 40, 80 and 120 kg N ha^{-1} without P,

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combinations of each level of P with varying levels of N and an absolute control (P_0N_0). Maize variety was an open pollinated called NARD 1. Plot size was 16 m^2, all maize plant above ground was harvested in a net plot (8.5 m^2) after 120 days.
Results: The average maize yield in response to applied fertilizer P and N in the three sites was 4.7 t ha^{-1} an increase of about 62 % over the control (2.9 t ha^{-1}), and was statistically significantly at P = .05
Conclusion: 20 kg P ha^{-1} and 120 kg N ha^{-1} rates were profitable and therefore were recommended as optimum application rates that can contribute to food security and economic progress in the area. However, more research is recommended to establish long-term fertilizer effects on maize performance, optimal application rates, and environmental considerations. The study stressed the need for diversified fertilizer research across seasons and emphasized community awareness about fertilizer benefits for sustainable maize production and farming system research.

Keywords: Environmentally friendly fertilizers; shifting cultivation; sustainable intensification; partial budget analysis; and marginal rate of return.

1. INTRODUCTION

South Sudan is grappling with persistent food insecurity [1] since independence on 9 July 2011, despite having about 50% of its land (644,000 km2) [2] suitable for agriculture. The country struggles to provide for its approximately 13 million people [3,4]. In 2020, Integrated Food Security Phase Classification (IPC) report [5] stated that only 63 % of the cereal food requirement was met. Sorghum is the primary cereal crop, grown by smallholders and larger mechanized farms, covering around 70% of cereal-growing areas [6]. Maize is the second key cereal, encompassing roughly 20% of total cereal-growing land, with the remainder dedicated to rice, bulrush millet, and finger millet [7].

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 after 21 year's civil war. This has resulted into increased demand for maize and gradual expansion of the area under maize production in the country. According to FAO [6], in 2020, total maize production (131,000 tonnes) was 27.2% higher than 2019. However, South Sudanese reliance on expanding cultivation areas [8] like in other African countries without efficient fertilizer use a practice which is unsustainable and contributes to land degradation [9].

The widespread practice of shifting cultivation without proper fertilizer usage prevails among maize producers in the Greenbelt zone. Introducing fertilizers and other improved technologies is expected to intensify maize production, mitigating soil degradation linked to shifting cultivation. According to Epule et al. [9] intensifying maize production approach aligns with agricultural intensification, which not only improves production but also addresses environmental concerns like deforestation that leads to habitat loss for the wildlife, soil erosion, and carbon sequestration.

Declining soil fertility and land degradation are cited as key contributors to low cereal production in South Sudan (0.7 t ha^{-1}) [1]. However, nationally generated crop-yield forecasts and accurate data on cropped land disaggregation are lacking [10]. Increasing maize production in South Sudan remains a challenge without using fertilizer in comparison to the yields in the neighboring countries such as Kenya (3.9 t ha^{-1}), Tanzania (1.54 t ha^{-1}), Ethiopia (3.9 t ha^{-1}) and Uganda (2.5 t ha^{-1}) [11,12,13,14]. Although the other countries' yields are higher than South Sudan, these are still below cereal yield potential, for on station trials and from commercial farms, of about 8 t ha^{-1} for the Sub-Sahara Africa (SSA) region [15] and maize potential yields for the eastern and southern African counties [12]. However, Wortmann et al. [12] noted that information for maize response to nutrient applications is scarce for many areas in the tropical Africa.

Achieving and sustaining high maize production necessitates a balanced nutrient supply, either from organic sources or mineral fertilizers is needed [13] and good soil nutrient management is emphasized. For good soil fertility management, the existing amount of nutrients in the soil must be determined in the beginning. Consequently, studies by [16,17,18] have found that the soil productivity in the Greenbelt zone of South Sudan is limited by N and P deficiencies among other essential nutrients. Bekele et al. [13] has also reported N and P deficiency in Ethiopia soils. Nitrogen and phosphorus are macronutrients that are required by plants in large quantities but most often deficient [19,20], N is very important for plant photosynthesis [20] while phosphorus is essential for root development, and provision of complex energy pathways to the biochemical processes in the plant [17]. However, explains that about 14 kg to 136 kg per hectare of Nitrogen, Phosphorus, Potassium is lost yearly from crop land in the SSA. Sanginga and Woomer [15] reports that phosphorus deficiency in SSA soils reduces the efficacy of other nutrients such as nitrogen, leading to poor yields and food insecurity. In South Sudan, a minimal percentage of small-scale farmers use inorganic fertilizer [21]. Blanket use of fertilizer is happening because large part of the country lacks or has scarce soil information [18] and there are no recommended fertilizer application rates. Sanginga and Woomer, [15] has reported improper use of fertilizers in the SSA too. Deng and d'Ragga [16] suggested the use of the deficient fertilizers, and Yuga and Wani [17] made fertilizer recommendation (60 kg N and 10 kg P ha^{-1}) on the use of NP for Yambio, Juba and Magwi Counties in greater Equatoria, in South Sudan but no study was reported that support the recommendation.

In Nigeria, Amhakhian et al. [22] recommended the application of 100 and 120kg P ha^{-1} for maize cultivation in two different locations. Interestingly, 100 kg P ha^{-1} grain yield was 5.5 t ha^{-1} on average in two seasons while 120 kg P ha^{-1} yielded 3.9 t ha^{-1} on average. In another part of Nigeria, the combination of 120 kg N ha^{-1} and 26 kg P ha^{-1}, in Nigeria, gave optimum yield of 3.6 t ha^{-1} [23]. While a study by Wortmann et al. [12] revealed a good response of maize to 50 kg N ha^{-1} among some eastern and southern African countries but the response to P levels was negligible except in Rwanda to 15 kg P ha^{-1}. In Ethiopia, application rate of more than 20 kg P ha^{-1}, on both Andosols and Nitisols, decreased the agronomic efficiency of P [13] but the requirement for N was 184 kg N ha^{-1} and 46 kg N ha^{-1}, on Andosols and Nitisols respectively.

This study aimed to develop area specific fertilizer recommendations to guide sustainable maize and cereal production by evaluating maize's response to different N and P fertilizer application rates. The goal is to enhance smallholder maize production and food security in the Greenbelt zone, Western Equatoria State, South Sudan, considering the socio-economic conditions of farmers and the novelty of the technology. The study specifically seeks to identify profitable rainfed maize response to applied N and P among alternative treatments and assess the economic feasibility of applying N and P fertilizers.

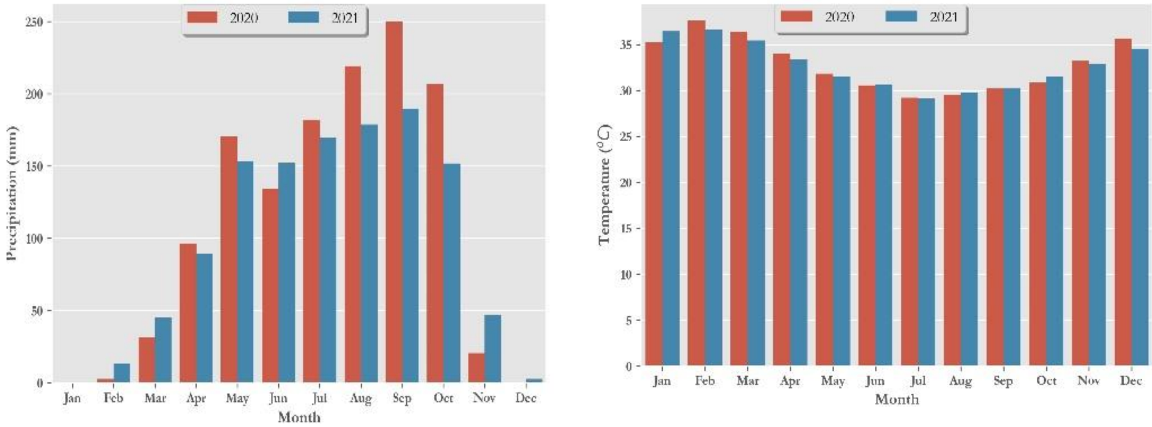
2. MATERIALS AND METHODS

2.1 Description of the Study Area

The study area is located between 28° 10' E and 28° 42' E and between 04° 32' N and 04° 64' N covering an area of 47 500 ha. The altitude ranges from 606 – 744 m asl [18]. The International Resource Group (IRG) [23] 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 (644 000 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 [1].

2.2 Rainfall and Temperature in the Study Area

The rainfall and temperature received at the study area for 2020 and 2021 are indicated in Fig. 1 (a) and (b) downloaded and aggregated from Climate Hazards Group InfraRed Precipitation with Station **data** (**CHIRPS**) [Website:CHIRPS] using ArcMap version 10.5. According to [7] 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.



(a) (b)

Fig. 1. Total annual precipitation (a), and Temperature (b) for 2020 and 2021

2.3 Site Selection and Soil Characteristics of the Study Area

The methodology used to determine the chemical and physical properties are indicated in Table 1. Experimental sites were established in three villages on three different types of soils characterized by [18]. Nangbangi village (Site-1, N 04.59430, E 028.34834), Bure Maku village (Site-2, N 04.47175; E 028.24896) and Ataziri village (Site-3, N 04.543974; E 028.19393). The villages were selected based on proximity to the roadside and accessibility. All three types of soils are problematic, acid soils with low clay activity, low base saturation, parent materials have low nutrient concentration and need careful management for crop production [24]. Ritisols are said not to be good for crop production but most suitable for grazing. Nutrients are concentrated in the soil organic matter and for management purpose, agroforestry has been recommended as soil protecting alternative to shifting cultivation for sustainable yield [24]. The soil is well drained and a variety of crops including pineapples, mangoes, palm oils, cotton, cereals, and many other acid tolerant crops.

Ten sub-samples were taken from dept of 0 – 20 cm per site and quartering procedure was used to obtain 1 kg as the composite soil samples per site. All sites were in use for two years and the experiment was done in the third year as was estimated by the landowners. In the area, the farming system is a mix of 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.

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. 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.

2.4 Design of Field Experiments

Field experiments involved a 4 x 4 x 4 factorial experiments in a randomized complete block design (RCBD) Table 2 [25]. 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 sixteen treatments were replicated three times at each site.

2.5 Land Preparation, Planting, crop Management

Land preparation involved slashing, burning and cultivation by hand hoe, this was done in accordance with the farmers practice in area. 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 P and N fertilizers were applied after germination of maize. 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) [26]. Adotey [26] states that banding (surface or subsurface) is the common N placement methods for applying N fertilizers in Tennessee and that side dress application can be done any time after planting through tasseling. Wortmann et al. [12] reports that in the east and southern Africa studies, all fertilizers were band or broadcasted before planting except for N was split in two halves, one half before planting and the other half six weeks later after planting.

The field experiments were run for three consecutive growing seasons beginning in August 2020 to January 2022 at Site-1 and only two consecutive seasons beginning in April 2021 to January 2022 at site-2 and site-3, 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.

2.6 Maize Harvesting and Yield Determination

Maize was harvested after 120 days (drying phase) from 8.5 m^2 net plot, established in each experimental plot excluding border plants. 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 sun dried to a moisture content of 13 %, using grain moisture meter, weighed at home, and converted to tonnes per hectare using equation (1). Maize stover yield was determined by weighing air dry stover harvested from a net plot and converted to tonnes per hectare using equation (1).

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

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 tones.

2.6.1 Statistical analysis

Maize yield data was subjected to 3-way 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.

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

Where,

Y_{ijk} = response variable Y
μ = general mean effect (or reference value),
β_i = site conditions
α_j = additional effect due to j^{th} level of season α
λ_k = additional effect due to k^{th} level of fertilizer treatment
$(\beta\alpha)_{ij}$ = interaction between site and season
$(\alpha\lambda)_{jk}$ = interaction between season α and treatment
$(\beta\lambda)_{ik}$ = interaction between site and treatment
$(\beta\alpha\lambda)_{ijk}$ = interaction among the sites, seasons, and treatment
ε_{ijk} = random errors associated with level of combinations and replication per site

Table 1. Physical and chemical composition of the experimental soil [18]

Soil type	**Feralsols**	**Acrisols**	**Retisols**		
Soil parameters	**Site-1**	**Site-2**	**Site-3**	**Method**	**Reference**
Texture class	Sandy clay loam	Sandy clay loam	Silt Loam	Bouyoucos Hydrometer	[28]
pH H2O 1:2.5	5.98	6.00	6.7	Potentiometrically in distilled water 1:2.5	"
EC 1:2.5 (mS/c	0.07	0.01	0.18	1:1 Soil: Water Extract Method	"
ESP	0.05	1.06	4.06	Calculation	
Organic C (%)	1.81	0.91	2.28	Walkley Black wet combustion	"
Total N (%)	0.13	0.07	0.13	Macro Kjeldahl	"
Avail. P Bray-1 mg/ kg	1.33	1.17	2.45	Bray 1-method	"
CEC NH4OAc cmol (+)/ kg	10.2	4	8.4	1.00 *M* (NH4OAc) extraction method and Kjeldahl distillation	[29]
Exch. Ca (cmol (+)/kg)	4.78	2.09	3.91	Atomic Absorption Spectrometer (AAS)	[28]
Exch. Mg (cmol (+)/kg)	2.13	0.82	1.45	AAS	"
Exch. K (cmol (+)/kg)	0.3	0.24	0.37	Flame photometry	[27]
Exch. Na (cmol (+)/kg)	0.05	0.04	0.34	Flame photometry	[27]
Base saturation (%)	71	80	72	calculation	
Sulfur mg/kg	26.3	36.72	38.02	Turbidimetric	[28]

2.7 Economic Analysis of Fertilizer Use in Maize Production

Partial budget analysis was used to estimate the net benefit and marginal returns that could be obtained from various alternative treatments [30]. The data collected in partial budget analysis were: Gross average maize yield (t ha-1) (AvY) defined as average yield of each treatment converted in to tonnes per hectare; Adjusted yield (AdjY), defined as average yield adjusted downward by 15% to reflect the difference between the experimental plot of yield and yield of farmers (i.e. AdjY (t ha-1) = AvY × (1-0.15); Total variable costs (TVC) i.e. costs of purchasing P and N fertilizers (for each equivalent rate of application), and labour costs for fertilizer application (with an assumption that all other costs of maize production were constant across all levels of P and N application within a season). With this assumption, 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) were calculated as shown in equations 4-6. If the CBR < 1 then the costs exceed the benefit, the tested P and/or N were rejected. If the CBR ≥ 1 then the benefits exceed the costs the tested P and/or N were accepted.

$$\text{GB} = \text{Average price (AV)} \times \text{AdjYield} \quad (4)$$

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

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

Furthermore, marginal analysis was computed to compare net benefits with partial budget by considering the magnitude of corresponding variable costs [30]. The Marginal Rate of Return on fertilizer use (MRR %) was calculated by dividing change in net benefit by change in TVC [30] and expressed in percentage, the decision to adopt a treatment as profitable was based on the Benefit-Cost equation (Eq. 7) where positive difference indicated that the change was profitable (Tigner, 2018). 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 ranging from 50% to 100% [30]. Hence, any treatment giving returns above 100% was considered worthy investment by farmers.

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

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

2.8 Determining the Effect of Fertilizers on the Soil Environment

To determine the effect of fertilizers on environment, representative soil samples were collected from each study site after harvesting the last season crop. The samples were processed and analysed for available P and total N following the methods used to analyse baseline soil samples collected before subjecting experimental plots to fertilizer treatments (Table 1). Soil P and N analysis results obtained at the end of experiments were then compared with base line soil analyses to establish the effect of fertilizer application on soil P and N fertility status if any.

2.9 Presentation of Results According to SIAF Domains

Results obtained in this study were presented and discussed under three domains of the Sustainable Intensification Assessment Framework (SIAF) namely Productivity, Economic and environment domains [31]. According to [32] productivity domain is concerned with increasing output per unit input per unit time (season or year). This study focused on maize grain and biomass productivity (yield per unit area of land cultivated per season) as an indicator of intensification with different fertilizer treatments. Economic domain is concerned with profitability of agricultural activities and returns to factors of production [32]. In this study results on economic analysis conducted to assess the feasibility of the treatments using partial budget, dominance, and marginal analysis of each treatment [33] were covered under the economic domain. Environment domain on the other hand deals with environmental effects on the natural resource base that supports agriculture as well as the negative effect of agricultural activities on the environment [32,34]. Among indicators that are measured include soil condition, health issues (e.g., cancer), eutrophication of surface waters and release of greenhouse gases (GHG) such as CO2 leading to global warming [34,35]. In this study, the effect of applied N and P fertilizers on N and P fertility status of soils at experimental sites were covered under the environment domain.

3. RESULTS AND DISCUSSION

3.1 Results

3.1.1 Productivity domain

Maize yield (productivity) as influenced by fertilizer treatments, growing season and interaction effects of fertilizer and seasons at Nangbangi (site 1) in three seasons are summarized in Tables 3 - 6. No tables have been provided for Bure Maku (site 2) and Ataziri (site 3) but the data have been provided in the text under each site.

3.1.1.1 Effect of Fertilizers on maize yield at Nangbangi village (site1)

Table 3 presents data on maize grain and biomass yield as influenced by different P and N application rates.

Results indicate that when P and N fertilizers were applied separately, 20 kg P ha^{-1} resulted into the highest maize grain and biomass yields which was significantly different from yields obtained from control plots but statistically like the grain yields obtained following application of 40 or 60 kg P ha^{-1}. On the other hand, 120 kg N ha^{-1} resulted into the highest maize grain yield which was significantly different from the control but statistically like the grain yields obtained following application of 40 or 80 kg N ha^{-1}. Results further indicate that mean maize biomass yield were not significantly affected by different N application rates at site 1.

3.1.1.2 Effect of seasons on maize yields at site 1

Maize grain and biomass yields across three different cropping seasons at Nangbangi village (site1) was as summarized in Table 4. The highest and statistically ($p = .05$) different grain yields (4.7 t ha^{-1}) were recorded in the first season at site 1. On the other hand, biomass yields recorded at the same site were similar in season 1 (14.9 t ha $^{-1}$) and season 3 (14.4 t ha^{-1}) but different from season 2 which had the lowest biomass yields (11.5 t ha $^{-1}$).

3.1.1.3 Interaction of individual fertilizer x seasons on maize yields at site 1

Results in Table 5 indicate the interaction effect between each individual fertilizer nutrient and season on maize grain and biomass yields recorded at site 1. 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. The results indicate that each of the individual nutrients at the applied levels increased maize yield; and the seasons also had significant impact on maize yield.

3.1.1.4 Interaction effect of season and fertilizer combinations on maize yields

The effect of combined P and N and season on yield is presented in Table 6 at site 1. 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}). The 5.2 t ha^{-1} is about 62.5 % increase over the control. There is yield increase Statistically, season was significantly at p = .05. There is consistency in the three seasons for 20 P and 120 N kg ha^{-1}, giving higher yields but not withstanding the seasonal yield variations in the second half of the seasons (1 and 3) that coincided with peak rainfall.

3.1.1.5 Effect of Fertilizers on maize yield at Bure Maku village (Site- 2)

Tables are not presented for this site; however, data have been presented in the text. 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 = .018, phosphorus significant at p = .027 and N was significant at p = .054. 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} all P, N and Season were significant (P = .05). 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}. This means an increase of 53.3 % over the control. 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 with site-1.

3.1.1.6 Effect of Fertilizers on maize yield at Ataziri village (Site- 3)

Tables are not presented for this site either; however, data have been presented in the text 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 showed there was no statistical significance at p = .05. (N was p = .153; P was p = .514 and season was p = .984).

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. In 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}) an increase of 83.3 % over the control. Biomass followed the same trend. The results at site-3 are also consistent with those at site-1.

3.1.2 Economic domain

The net income from agricultural produce after subtracting the total variable cost is the economic profitability [36]. Black [37], emphasized the importance of computing the magnitude of economic returns. Therefore, partial budget analysis manual has been provided by [30]. The manual guided how the net benefit (NB) was estimated, 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 total variable cost (TVC). Any treatment that had net benefits that were less than or equal to those of a treatment with lower TVC was dominated [30].

The average and adjusted yield of 16 treatments replicated three times, TVC, GB, NB and BCR are presented in Table 7. The NB with letter 'D' attached to it means it is dominated, implying that this rate of fertilization application was not profitable [33]. The application of 20 kg P ha^{-1} and 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 was generated after eliminating dominated treatments in Table 7. 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 South Sudanese Pounds (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. 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 are over the optimum level (Table 7), the net benefit obtained reduced because of higher variable costs associated with lower earnings.

Table 2. 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.*

Table 3. The effect of P and N fertilizers on maize grain and biomass yields

Phosphorus level (kg/ha)	Mean grain yield (t/ha)	Nitrogen level (kg/ha)	Mean grain yield (t/ha)
20	4.1 a	120	4.1 a
60	4.0 ab	40	3.9 ab
40	3.7 ab	80	3.9 ab
0	3.6 b	0	3.5 b
Phosphorus level (kg/ha)	**Mean Biomass yield (t/ha)**	**Nitrogen level (kg/ha)**	**Mean Biomass yield (t/ha)**
20	14.9 a	120	14.6 a
60	13.8 ab	80	13.7 a
40	13.6 ab	40	13.3 a
0	12.2 b	0	12.9 a

Same letters in the same column means there is no significance (p = .05)

Table 4. The impact of season on maize grain and biomass yield

Season	Mean grain yield (t/ha)	Mean Biomass yield (t/ha)
1	4.7 a	14.9 a
3	3.5 b	14.4 ab
2	3.4 b	11.5 b

Table 5. 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 = .05)

Table 6. Interaction of seasons x phosphorus x Nitrogen and maize yield

Season (months)	P x N (kg ha^{-1})	Mean grain yield (t ha^{-1})
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 t ha^{-1}
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 = .05)

Table 7. 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^{-1})	AdjY (SSP ha^{-1})	GB (SSP/ha)	TVC (SSP ha^{-1}	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 8. Marginal rate of return of combined N & P fertilizers application on rainfed maize production in Site-1 in 2020/ 2021

Treat. P & N	TVC (SSP ha^{-1})	MC (SSP ha^{-1})	NB (SSP SSP ha^{-1})	MB (SSP SSP ha^{-1})	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

3.1.3 Environment domain

3.1.3.1 Pre-planting and post-harvest N and P soil fertility status

The soil fertility status of the experimental sites before the study is presented in Table 1. The most limiting nutrient was phosphorus followed by nitrogen. Potassium was marginally available including micronutrient zinc. Based on these results, the decision was made to only provide P and N 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^{-1} and TN increased to 0.18 % at site-1; at site-2 available P level was 12.56 mg kg^{-1} and average TN was 0.17 % while at site-3, the average P was 8.78 mg kg^{-1} and TN was 0.17 %. TN does not say much about the availability of nutrients to crop. In future studies, analysis should be done for nitrate or ammonium ions but for all the nutrients as indicated in Table 1 should be considered depending on the availability of resources.

3.2 Discussion

3.2.1 Maize yield in response to P and N treatments and the season

Generally, the yield increased at all sites, in all the plots that received P or N treatments over the control. Phosphorus level at 20 kg P ha^{-1} consistently gave high grain and biomass yields individually at all sites as well as when combined with 120 kg N ha^{-1}. Nitrogen (120 kg N ha^{-1}) individually gave high grain and biomass yield and in combination with P gave significantly high yield. However, rates of more than 20 kg P ha^{-1} did not do any better; implying that higher rates of P were not profitable in the study area. The high grain and biomass yield in plots that received P or/ and N exhibit that the nutrients were deficient in the soils. The combined P and

N treatments produced the highest yield at all sites. This implies that synergistic effect of both nutrient in giving high yield [38]. From this study it is not conclusive to concretely recommend 20 kg P ha^{-1} and 120 kg N ha^{-1} as the best option because perhaps a lower rate of P could be found and a higher rate of N too.

Several studies with low levels of P and high rates of N are needed in the study area for further confirmation and recommendation. Just as variability of soils are in the study area as they are in South Sudan and the SSA. A few studies have come up with different P and N recommendations in different countries. In Ethiopia, [39] recommended 46 kg N ha^{-1}, 40 kg P ha^{-1}, [40] recommended 100 kg P ha^{-} and 120 kg P ha^{-1} without N for good maize yield of above 5 t ha^{-1} in two different locations in Nigeria, [41] came up with use of micro dose use that can be affordable to small scale farmers, recommending (10 kg N and 5 kg P ha^{-1}) and (20 kg N and 20 kg P ha^{-1} for some parts of Tanzania. Wortmann et al. [12] found that maize responded favourably to 50 kg N ha^{-1} in eastern and southern Africa countries, but maize responded to 15 kg P ha^{-1} only in Rwanda. According to Wortmann et al. the resource poor farmers can substantially increase productivity and profitability by applying an affordable amount of fertilizer to larger area and not according to economically optimum requirements. According to [42] the rate of 120 kg N ha^{-1} is common in the SSA although there is variation related to the soil type.

The effect of season was significant at site 1 and 2, though not significant at site-3, season boosted the fertilizer effect at all sites. The overall response of maize to fertilizer (P and N) application in the three sites is (4.7 t ha^{-1}) an increase of about 62 % over the control (2.9 t ha^{-1}). The result also indicates that season 1 (second half of 2020) and season 3 (2021) significantly influenced the yield at site-1 because second half of the year coincided with the peak rainfall in August, September, and October (Fig. 1), the yields were significantly different at p = .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) the crop was affected by moisture stress at some point at site 1. However, sites 2 and 3 received more rains in season 2 (first half of 2021) and not season 3. Because there were no experiments at site-2 and site-3 in season 1, it is difficult to compare. The results implies that the rainfall was unevenly distributed in the months, sites, and seasons in the two years. Fig. 1 shows that there was high rainfall in the second half of 2020. Although in season 3 high yield was received 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) the crop was affected by moisture stress at some point at site 1.

To note is the average combined cereal yield for the country has been documented in many reports as 0.7 t ha^{-1}) [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 maize yield also surpasses the average in other neighouring countries [12]. The results can be attributed to good agronomic management, mainly in terms of plant population. Also, Slash-and-burn practices result in the significant release of nutrients stored within the aboveground biomass into the soil [43]. 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 there is only blanket use of fertilizer as reported by some scholars [12,39]. Sometimes the blanket application may be too small or result in excess use of fertilizer leading to loss of money and pollution of the environment as reported by [39]. 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.

3.2.2 Partial budgeting and marginal analysis

The benefit-cost ratio equation yielded positive net changes in the treatments Table 7. The positive implies that the incremental benefits in farming with added fertilizers (N & P) exceeded the incremental costs and suggests that using P and N is an economically feasible management practice. But at this stage no meaningful recommendations can be made about the technology until the MRR is calculated [30].

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 pound as benefit thus making the application of fertilizer an attractive option. To improve food production per unity area, interested farmers are highly advised to adopt (20 kg P + 120 kg N) ha^{-1} as this gave highest MRR (450 % in Table 8) 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 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}.

3.2.3 Efforts to improve nutrient availability and reduce the detrimental effect of fertilizer on the environment

The study area soil chemical characteristics indicate that the soil is deficient in P and N. Using fertilizer in modern agriculture for crop production adds the much-needed nutrients to the soil [44,45], and fertilizers have transformed the way the world produces food [34]. Fertilizers contribute to increased crop yields per unit area and reduce the need to convert more land to agriculture [34] and this means less destruction to the ecosystems. The manufactured fertilizers are important because the nutrient consistency in them allows for efficient crop production, making food affordable at a reduced cost of production [34].

Virgin land is constantly being brought under agriculture to achieve high yields in the study area because the characteristic soil fertility is poor [18]. The purpose of this study was to find a 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 [32]. According to [36], 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 [46]. Smith et al. [36], 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. The presence of these 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 [36].

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 [47,48] 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 [49] and [48] have emphasized the importance of maintaining plant materials on the farms. These activities constitute environmental services that enhance agricultural productivity [32]. To note is clearing forest for the purpose of agriculture destroys the natural habitat of the wildlife too [36].

There is large data gap with respect to knowledge on the impact of fertilizer on the environment and on human health [34,35]. Ritchie *et al.* [34] reported that scientists are aware of the adverse effect of fertilizers including greenhouse gas, the loss of half of the applied N fertilizer from the fields, lost in runoff water, leaching or is broken down by microbes in the soil releasing potent greenhouse gas, nitrous oxide into the air [34]. Previously, [50] 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 [34].

According to [34,50,51], 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. CONCLUSION AND RECOMMENDATIONS

Generally, maize grain and biomass yield increased in the plots where fertilizers were applied compared to the control. The average yield was 4.7 t ha^{-1} in the study area, an increase of 62 % over average of the control (2.9 t ha^{-1}) in the three sites. 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. Further studies of the farming systems to establish the actual plant population and yield in a mixed cropping system is recommended.

The economic analysis revealed that the farmers will make profit at the recommended rate of P and N 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.

Considering the minimal use of fertilizers in South Sudan, primarily due to a lack of knowledge and awareness, we strongly advocate for initiatives aimed at raising awareness and providing training regarding the significant impact of fertilizers on enhancing maize yields and preserving soil productivity within the study area and comparable agroecological zones.

This study may serve as the first attempt to make recommendations for fertilizer application in the study area. 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.

Shortcoming of the study. The study was designed to be conducted on farmers' fields in three season and in three locations per the soil types. But some farmers declined to continue with fertilizer application on their farms citing destruction to their land and human health. The fact that some farmers refused fertilizer experiments to be done on their fields was a short fall in this study; nevertheless, 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.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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