2-2 Economic viability of NPK fertilization using Burkina Faso phosphate rock on sorghum and cowpea

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Abstract

A promising agricultural technology to alleviate food insecurity and poverty among resource-constrained farmers in sub-Saharan Africa involves the strategic application of fertilizers derived from the region's abundant phosphorus resources. While the agronomic performance of this technology has been experimentally assessed with a promising outcome, its economic performance and superiority over low-cost, unfertilized production in actual farmers' fields have not been thoroughly investigated. Through participatory on-farm trials, this study illustrated the relative profitability of alternative NPK fertilization methods utilizing Burkina Faso phosphate rock for sorghum and cowpea production across various fertilizer price scenarios. Additionally, it evaluates the economic feasibility of expanding fertilized production using these alternative fertilization techniques among farmers. This analysis uses a whole-farm economic model based on linear programming, developed from comprehensive data across entire plots—including those using conventional and alternative fertilization methods—and designed to determine optimal combinations and adoption scales for these techniques. On-farm trial results indicate that alternative fertilization modestly improves yields for both sorghum and cowpea, with compound fertilizers containing partially acidulated phosphate rock and organic manure showing relatively high cost-effectiveness. Whole-farm economic analyses demonstrate that the optimal fertilized area using alternative fertilization techniques is similar to the current fertilized area when assuming approximately a 50% markup on the alternative fertilizer's production cost. This finding suggests that farmers are unlikely to gain economically from expanding fertilized production using alternative fertilizers if their prices exceed a 50% increase over base production costs. Therefore, reducing fertilizer manufacturing and transaction costs is essential to keep prices well below this threshold and/or to enhance yield effects through advancements in fertilization techniques and complementary agronomic practices.

1. Introduction

Soil nutrient depletion is a major biophysical factor contributing to the decline in per-capita food production in sub-Saharan Africa (SSA), posing a substantial threat to food security and economic development (Drechsel et al., 2001). Enhancing farmers' effective use of fertilizers is crucial to intensifying crop production and overcoming food insecurity (Sanchez, 2010; Jayne and Rashid, 2013; Holden, 2018). However, fertilizer use remains relatively low and inefficient in SSA compared to other regions of the world (Smale et al., 2011; Abate et al., 2020). Furthermore, access to affordable fertilizers is severely restricted for resource-constrained farmers in SSA. Most countries lack a domestic infrastructure for fertilizer manufacture, with landlocked nations facing fertilizer costs five to ten times as high as those in the Global North (Snapp et al., 2014). Recent disruptions caused by the COVID-19 pandemic and geopolitical conflicts have exacerbated the situation by severely disrupting global fertilizer supply chains, resulting in disproportionate price hikes and shortages in SSA (Njoroge et al., 2023). The limited effectiveness of fertilizers, coupled with rising acquisition costs, results in significantly low returns on investment for farmers, greatly reducing their incentives for fertilizer adoption and expansion. One effective strategy to overcome this challenge is developing more cost-effective fertilizer packages using locally available mineral resources, complemented by enhanced technical interventions to maximize their efficacy. Among these, phosphate rock fertilization holds promise in SSA (Margenot et al., 2016). Given that low soil phosphorous (P) is a major constraint on crop production in this region (Verde and Matusso, 2014), ready access to regionally adapted P fertilization techniques and appropriate guidance may significantly improve farmers' investment incentives and performance, potentially leading to broader fertilizer use.

In Burkina Faso, which is abundant in low-grade phosphate rock deposits, various P fertilization techniques have been proposed, including direct application of phosphate rock, application of calcinated phosphate rock (CPR) or partially acidulated phosphate rock (PAPR), and amendment with phosphate-rock-enriched composts. CPR and PAPR have been developed to increase the P solubility of low-grade phosphate rock and are expected to replace imported P fertilizers. The calcination process at 900 °C uses alkaline additives, resulting in high solubility in 2% citric acid (Nakamura et al., 2019). On the other hand, the acidulation of phosphate rock with sulfuric acid results in high water-soluble P and alkaline ammonium citrate-soluble P (Frederick and Roth, 1986). Different P solubility is a principal factor impacting the fertilization effect in upland crop cultivation in SSA (Iwasaki et al., 2022).

The agronomic effects of these P fertilization techniques have been experimentally evaluated with promising results (Iwasaki et al., 2022; Nakamura et al., 2019; Nakamura et al., 2020; Sagnon et al., 2022). However, their economic viability has not been adequately verified in actual farming. It is imperative to carefully assess whether the promoted P fertilization techniques enable farmers to achieve satisfactory outcomes, potentially through well-designed on-farm experiments. On-farm experimentation has gained renewed prominence in agricultural sciences globally (Lacoste et al., 2021). However, inappropriate design choices may compromise its validation. In fertilizer trials, researchers highlight a critical gap in fertilizer use efficiency between researcher- and farmer-managed fields, attributed to differences in agronomic management, soil resource endowments, and non-random participant selection in most on-farm experiments (Snapp et al., 2014; Tittonell, 2008). Addressing these experimental design issues is critical in validating proposed fertilization techniques in farmers' fields.

Beyond on-farm agronomic experimentation, whole-farm economic evaluation is necessary to thoroughly analyze the viability of farmers' adoption of fertilization techniques and to recommend optimal application strategies. Existing economic assessments of fertilizer use in SSA primarily focus on determining cost-effective application rates for specific crops (e.g., Ouattara et al., 2017; Rurinda et al., 2020) or assessing the crop-specific profitability impact (e.g., Burke et al., 2019; Dabessa Iticha et al., 2021; Kiwia et al., 2022). However, these analyses may inadequately assess whether recommended fertilizer use is beneficial for farmers at the whole-farm level, as optimizing resource use for specific crops could inadvertently compromise resource use for other crops. This suggests that recommended fertilizer applications may not necessarily benefit the overall farm's economic performance, potentially resulting in neutral or adverse effects. The concern is particularly relevant but often overlooked in smallholder production systems in SSA, where limited resources are allocated across diversified crop enterprises to mitigate risks and ensure multiple food and income sources. Therefore, economic analyses addressing tradeoffs in efficiently allocating scarce resources among competing demands are crucial to support smallholder production systems (Williams et al., 2019).

This study examines the profitability of different fertilization techniques utilizing Burkina Faso phosphate rock (BPR) based on participatory on-farm trials and surveys conducted in central Burkina Faso during the 2021 rainy season. Furthermore, the study evaluates the economic viability of scaling up these techniques across farmers' fields.

2. Materials and methods

2.1 On-farm trials

The trial participants consisted of 20 randomly selected smallholder farmers in the Boulkiemde province, Centre-Ouest region of Burkina Faso. These farmers all practice mixed cropping of sorghum and cowpea, the region's primary food and cash crops. Appropriate use of BPR on sorghum and cowpea has been found to increase P use efficiency and grain yield (Iwasaki et al. 2022). Therefore, the on-farm trials focused on the fertilization of these two crops. NPK compound fertilizers were primarily treated as they are the most commonly available in smallholder farmer communities across SSA (Roobroeck et al. 2021), and the study site is no exception. The trial plots were selected based on soil conditions from portions of the participants' sorghum- and cowpea-cultivated fields. The fertilizer application techniques experimented with in the trial combined BPR-derived compound fertilizers (using different P fertilization methods) with the appropriate sowing intervals, amounts, and timing of fertilizer application. The trial also covered conventional practices, including no-fertilizer application (as a negative control) and organic manure application. Specific treatments include: T1) no fertilization (-N-P-K), T2) compound fertilizer application utilizing CPR (+N+P+K), T3) compound fertilizer application utilizing PAPR (+N+P+K), T4) compound fertilizer application utilizing CPR (+N+P+K) and manure, and T5) compound fertilizer application utilizing PAPR (+N+P+K) and manure. Compound fertilizers were applied at 37 kg N ha^{-1}, 45 kg P_2O_5 ha^{-1}, and 14 kg K_2O ha^{-1}. The plot size for each treatment was 50 m² (5 m × 10 m).

2.2 Surveys

We comprehensively surveyed sorghum and cowpea grain yields across all on-farm trial plots for each treatment. Similarly, we visited all other plots cultivated by trial farmers without omission (n=237), directly measuring each plot's size and the harvest quantity of each crop for yield evaluation. Additionally, to gather accurate data on field crop management in both trial and non-trial plots, we provided each farmer with scales and recording materials, along with detailed instructions on their use, to measure and record daily amounts and costs of inputs (seeds, fertilizer, herbicide, and insecticide) and the number of persons, hours, and wages paid for each crop production. Our field staff regularly monitored and assisted in the measurement and recording activities and cross-checked the data before we double-checked it for approval. This data collection and inspection method was adopted to mitigate farmers' recall and measurement errors inherent in agricultural questionnaires and significantly undermine the reliability of agricultural output, input, and productivity variables (Wollburg et al., 2021).

2.3 Analysis

We evaluated the relative profitability of sorghum and cowpea mixed cropping across different treatments. Due to the unavailability of compound fertilizers derived from CRR and PAPR in the market, we established several price scenarios: Scenario 1 represents the baseline production cost of the alternative fertilizer, while Scenarios 2 and 3 represent prices with a 50% and 100% markup on this baseline, respectively. The base production cost was estimated by the fertilizer developers. Additionally, we conducted a whole-farm economic analysis to evaluate the economic viability of expanding alternative fertilization techniques across farmers' fields. The applied analytical model was developed individually for each household and formulated through single-objective linear programming, simultaneously optimizing the allocation of multiple farm resources to maximize system-wide profitability while securing household food security. This model is an application of the African Smallholder Farm Management Model (ASFAM), described in Chapter 1-2.

To identify the optimal choices and adoption scale of alternative NPK fertilization techniques, the cropping options used in the model encompassed not only the conventional cropping systems practiced by each household outside on-farm trials, including both fertilized and non-fertilized crops but also the trial-based cropping systems utilizing new compound fertilizers (i.e., T2, T3, T4, and T5). Since all trial participants were smallholder family farms pursuing income, the model was designed to maximize the total income as the objective function. All parameters for each cropping option, including yield, labor hours, costs, and sale prices, were based on observed values. However, the net income from the trial-based cropping systems was analyzed across varying fertilizer price scenarios. This approach aims to conduct a sensitivity analysis to estimate the price (markup over the base production cost) of the new fertilizer required to achieve an optimal fertilized area comparable to current fertilization levels. The estimated price can be interpreted as the minimum target to be achieved for expanding fertilized crop production using alternative fertilizers. The farm resources considered in the model include available farmland, categorized into upland crops, lowland rice, and vegetable plots, as well as available labor, accounting for the seasonality of both family and hired labor inputs as documented in daily farm operation records. The model was designed to ensure that each household secures sufficient acreage to meet annual consumption requirements for all crops produced based on current yields.

3. Results

3.1 On-farm trials

In the treatments using alternative NPK fertilizers (T2, T3, T4, and T5), grain yields were higher than for unfertilized treatments (T1), as shown in Table 1. However, multiple comparisons revealed no statistically significant differences among the treatments (Tukey, $p<0.05$), likely due to the generally low yields across all treatments and the limited sample size. The net incomes of T2 and T3 were lower than those of T1, even under the production cost-based fertilizer price Scenario 1, primarily due to the higher costs of alternative fertilizers. Notably, net income from CPR-based compound fertilizer usage was negative under price Scenarios 2 and 3. Due to the relatively high yields and low organic manure costs, net income from the combined uses of alternative NPK fertilizers and organic manure (T4, T5) was improved over NPK fertilizers alone. Nonetheless, net income from CPR-based compound fertilizer combined with organic manure (T4) was substantially lower than that with no fertilization (T1), even under fertilizer price Scenario 1. Conversely, net income from PAPR-based compound fertilizer combined with organic manure (T5) slightly exceeded the no-fertilizer case under the same price scenario. Therefore, based on trial results, the combination of PAPR-based compound fertilizer and organic manure appears relatively cost-effective. However, determining whether adopting and expanding alternative fertilization technologies is recommended for farmers requires whole-farm economic analyses.

Table 1. Summary of the on-farm trial results

	T1	T2	T3	T4	T5
Sorghum yield (avg. kg/ha)	156	203	212	305	339
Cowpea yield (avg. kg/ha)	382	458	515	684	638
Net income (avg. FCFA/ha)					
Price Scenario 1	159,155	8,703	118,933	108,031	169,380
Price Scenario 2	159,155	-89,147	60,747	10,181	111,195
Price Scenario 3	159,155	-186,998	2,562	-87,669	53,010

T1: No fertilization (-N-P-K), T2: NPK (CPR), T3: NPK (PAPR), T4: NPK (CPR) +Manure, T5: NPK (PAPR) +Manure, Net income: Gross income − Paid-out costs, FCFA: Franc of the Communauté Financière Africaine (1 FCFA= 0.016 USD as of October 30, 2024)

The price scenarios of the alternative fertilizer determine the net incomes for T2, T3, T4, and T5. Price Scenario 1 reflects the base production cost of the alternative fertilizer, whereas Scenarios 2 and 3 represent prices with a 50% and 100% markup on the production cost, respectively.

3.2 Whole-farm economic evaluation

Most farmers' crop fields are occupied by production without fertilizer, with the share of the production with conventional fertilizer being only 7%. Based on the linear programming model described above, sensitivity analysis indicated that the price of the alternative NPK fertilizer requires an optimal fertilized area comparable to current levels with approximately a 50% markup over its production cost (Table 2). This finding suggests that expanding fertilized crop production through alternative fertilization methods would not be economically feasible unless the price markup is kept below 50%. Under this fertilizer price scenario, the economically optimized adoption scale of fertilized crop production consists of 4.3% sorghum and cowpea production using alternative fertilizers and 2.2% of other crops with conventional fertilizers.

Although not indicated in Table 2, the number of farmers adopting new sorghum and cowpea cropping systems using alternative NPK fertilizers represents only about one-fourth under a 50% markup. The optimal choices of alternative NPK fertilizers (and their adoption scales) vary among farmers, consisting of PAPR-based fertilizers and CPR-based and PAPR-based fertilizers combined with organic manure.

When the markup on the production cost of the alternative fertilizer exceeds 50%, the optimal adoption scales of new cropping systems diminish, encompassing only those utilizing PAPR-based fertilizer (combined with organic manure). This reduced fertilized area is subsequently replaced by an unfertilized production area. The primary reason for this is the lower profitability of crop production using alternative fertilizers compared to conventional, low-cost, unfertilized crop production. In sorghum and cowpea mixed production, the net incomes of alternative fertilization techniques in trial fields do not significantly exceed those of conventional unfertilized techniques in non-trial fields. Therefore, most crop production without fertilizer application, predominantly sorghum and cowpea mixed cropping, has not transitioned to production with alternative fertilizers in the optimal solution.

Table 2. Share of the optimal adoption area for various fertilization cropping systems to the total farmland area (as determined by the linear programming model under a 50% markup to the production cost)

	Share (%)
Sorghum + cowpea mixed cropping (+N+P+K: CPR)	0
Sorghum + cowpea mixed cropping (+N+P+K: PAPR)	3.8
Sorghum + cowpea mixed cropping (+N+P+K: CPR with manure)	0
Sorghum + cowpea mixed cropping (+N+P+K: PAPR with manure)	0.5
Other cropping systems with conventional fertilizer application	2.2
Total	6.5

4. Conclusion

Through participatory on-farm trials and surveys, this paper highlights the profitability of alternative BPR-based NPK fertilization techniques for sorghum and cowpea production under various fertilizer price scenarios. Furthermore, it estimates the impact of these techniques on expanding fertilized crop production among farmers. On-farm trial results underscore that alternative fertilization techniques slightly enhance yields for both sorghum and cowpea, particularly the combined application of PAPR-derived compound fertilizers and organic manure, which show relatively high cost-effectiveness. Whole-farm economic analyses demonstrate that the optimal fertilized area using alternative fertilization techniques is similar to the current fertilized area when assuming approximately a 50% markup on the alternative fertilizer's production cost. This finding suggests that farmers are unlikely to gain economically from expanding fertilized production using alternative fertilizers if their prices exceed a 50% increase over base production costs. Therefore, reducing fertilizer manufacturing and transaction costs is essential to keep prices well below this threshold and/or to enhance yield effects through advancements in fertilization techniques and complementary agronomic practices. If these efforts yield positive results and demonstrate to farmers superior economic advantages over the prevailing unfertilized cropping systems at the whole-farm level, it could potentially stimulate broader adoption of fertilized production.

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References

Abate, G. T., Abay, K. A., & Spielman, D. (2020). Fertilizer policies and implications for African agriculture. *ReSAKSS Annual Trends and Outlook Report*.

Burke, W. J., Frossard, E., Kabwe, S., & Jayne, T. S. (2019). Understanding fertilizer adoption and effectiveness on maize in Zambia. *Food Policy*, 86, 101721.

Dabessa Iticha, M., Jaleta, M., & Mitiku, F. (2021). Determinants and profitability of inorganic fertilizer use in smallholder maize production in Ethiopia. *Cogent Food & Agriculture*, 7(1), 1911046.

Drechsel, P., Gyiele, L., Kunze, D., & Cofie, O. (2001). Population density, soil nutrient depletion, and economic growth in sub-Saharan Africa. *Ecological Economics*, 38(2), 251–258.

Frederick, E. D. & Roth, E. N. (Eds.) (1986): *Sulfuric Acid-based Partially Acidulated Phosphate Rock: Its Production, Cost, and Use, Technical bulletin/IFDC*. International Fertilizer Development Center, Muscle Shoals, Ala., U.S.A.

Holden, S. T. (2018). Fertilizer and sustainable intensification in sub-Saharan Africa. *Global Food Security*, 18, 20–26. https://doi.org/10.1016/j.gfs.2018.07.001.

Iwasaki, S., Ikazaki, K., Bougma, A., & Nagumo, F. (2022). Appropriate use of local phosphate rock increases phosphorus use efficiency and grain yield of sorghum and cowpea in the Sudan Savanna. *Frontiers in Soil Science*, 1, 709507.

Jayne, T. S. & Rashid, S. (2013). Input subsidy programs in sub-Saharan Africa: A synthesis of recent evidence. *Agricultural Economics*, 44(6), 547–562.

Kiwia, A., Kimani, D., Harawa, R., Jama, B., & Sileshi, G. W. (2022). Fertiliser use efficiency, production risks and profitability of maize on smallholder farms in East Africa. *Experimental Agriculture*, 58.

Lacoste, M., Cook, S., McNee, M., et al. (2021). On-farm experimentation to transform global agriculture. *Nature Food*, 1-8. https://doi.org/10.1038/s43016-021-00424-4.

Margenot, A. J., Singh, B. R., Rao, I. M., & Sommer, R. (2016). Phosphorus fertilization and management in soils of sub-Saharan Africa. In *Soil phosphorus* (pp. 151–208). CRC Press.

Nakamura, S., Kanda, T., Imai, T., Sawadogo, J., & Nagumo, F. (2019). Solubility and application effects of African low-grade phosphate rock calcinated with potassium carbonate. *Soil Science and Plant Nutrition*, 65(3), 267–273.

Nakamura, S., Saidou, S., Barro, A., Jonas, D., Fukuda, M., Kanda, T., & Nagumo, F. (2020). Kodjari phosphate rock for rainfed lowland rice production in the Sudan Savanna, Burkina Faso. *Tropical Agriculture and Development*, 64(2), 97–106.

Njoroge, S., Mugi-Ngenga, E., Chivenge, P., Boulal, H., Zingore, S., & Majumdar, K. (2023). The impact of the global fertilizer crisis in Africa. *Growing Africa*, 2(1), 3–8. https://doi.org/10.55693/ga21.XZVK8042.

Ouattara, K., Serme, I., Bandaogo, A. A., Ouedraogo, S., Sohoro, A., Gnankambary, Z., Youl, S., Yaka, P., & Pare, T. (2017). Optimizing fertilizer use within an integrated soil fertility management framework in Burkina Faso. In Wortmann, C. S., & Sones, K. R. (Eds.), *Fertilizer use optimization in sub-Saharan Africa*. CABI.

Roobroeck, D., Palm, C. A., Nziguheba, G., Weil, R., & Vanlauwe, B. (2021). Assessing and understanding non-responsiveness of maize and soybean to fertilizer applications in African smallholder farms. *Agriculture, Ecosystems & Environment*, 305, 107165.

Rurinda, J., Zingore, S., Jibrin, J. M., Balemi, T., Masuki, K., Andersson, J. A., Pampolino, M. F., Mohammed, I., Mutegi, J., Kamara, A. Y., & Craufurd, P. Q. (2020). Science-based decision support for formulating crop fertilizer recommendations in sub-Saharan Africa. *Agricultural Systems*, 180, 102790.

Sagnon, A., Iwasaki, S., Tibiri, E. B., Zongo, N. A., Compaore, E., Bonkoungou, I. J. O., Nakamura, S., Traore, N., Barro, N., Tiendrebeogo, F., & Sarr, P. S. (2022). Amendment with Burkina Faso phosphate rock-enriched composts alters soil chemical properties and microbial structure, and enhances sorghum agronomic performance. *Scientific Reports*, 12(1), 13945.

Sánchez, P. A. (2010). Tripling crop yields in tropical Africa. *Nature Geoscience*, 3(5), 299–300.

Smale, M., Byerlee, D., & Jayne, T. (2013). *Maize revolutions in sub-Saharan Africa* (pp. 165–195). Springer Netherlands.

Snapp, S., Jayne, T. S., Mhango, W., & Ricker-Gilbert, J. (2014). Maize yield response to nitrogen in Malawi's smallholder production systems. *Working Paper No. 9*, Malawi Strategy Support Program. International Food Policy Research Institute, Washington, DC.

Tittonell, P., Vanlauwe, B., Corbeels, M., & Giller, K. E. (2008). Yield gaps, nutrient use efficiencies and response to fertilisers by maize across heterogeneous smallholder farms of western Kenya. *Plant and Soil*, 313, 19–37.

Verde, B. & Matusso, J. (2014). Phosphorus in sub-Sahara African soils—strategies and options for improving available soil phosphorus in smallholder farming systems: A review. *Academic Research Journal of Agricultural Science and Research*, 2(1), 1–5.

Williams, P. A., Crespo, O., & Abu, M. (2019). Adapting to changing climate through improving adaptive capacity at the local level–the case of smallholder horticultural producers in Ghana. *Climate Risk Management*, 23, 124–135. https://doi.org/10.1016/j.crm.2018.12.004.

Wollburg, P., Tiberti, M., & Zezza, A. (2021). Recall length and measurement error in agricultural surveys. *Food Policy*, 100, 102003.