Strategies to increase phosphorus use efficiency with different nitrogen forms in a tropical cropping system

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Abstract

Phosphorus (P) deficiency severely limits crop production in tropical farming systems in Sub-Saharan Africa. Limited information exists on the long-term potential to maximise phosphorus use efficiency (PUE) with different organic and inorganic nitrogen (N) inputs. We investigated the potential for two N management strategies (conservation agriculture and integrated soil fertility management) to increase fertiliser PUE when P fertiliser is applied. The strategies were compared to a monoculture maize control with no N fertiliser using 28 seasons of data from two long-term field trials in Western Kenya, Kenya. Adding farm-yard manure and N within an integrated soil fertility management strategy, improved PUE by 33 - 44 % for a range of rotations. Retaining maize residues and reducing tillage within a conservation agriculture strategy, increased PUE by 20 – 40 % only when N inorganic fertiliser was added. Under conservation agriculture, intercropping with soybean generally increased PUE, presumably by supplying organic N. Further opportunities to increase PUE for intercropping in low inorganic fertiliser systems are promising.

Keywords

conservation agriculture, integrated soil fertility, mass balance, intercropping, maize, legume

Introduction

Soil fertility has steadily declined in tropical farming systems of Sub-Saharan African nations due to continuous cultivation with insufficient input of nutrients. Soils with inherently low native-phosphorus (P) concentrations and high quantities of P-sorbing soil minerals (e.g. iron and aluminium oxides) further compound this issue by reducing P bio-availability. This subsequently reduces fertiliser P use efficiency and crop yield (Sileshi et al. 2010; Kihara and Njoroge 2013; Nziguheba et al. 2016). Specific, sustainable and economically appropriate land management strategies that optimise P use efficiency (PUE) (ratio of P output to input) are needed to closing the yield gap and meeting projected food demands by 2050 (Roser, 2013; Roberts and Johnston, 2015; Nziguheba et al. 2016).

Two farming strategies, conservation agriculture (CA) and integrated soil fertility management (ISFM) have been identified as encouraging sustainable resource management and enhanced food production (Syers, 2008). However, their effect on PUE remains relatively unknown in Sub-Saharan Africa and limited international studies have explored their impact on intercropped systems (Nziguheba et al. 2016; Sommer et al. 2018). We aimed to identify the most efficient crop management strategy to maximise long-term farmer return (in terms of phosphorus input) on P input using the summation of 28 seasons of maize (*Zea mays* L.) crop data under various CA and ISFM practices in the state of Western Kenya, Kenya.

Methods

Two long-term field trials were established in 2003 at Nyabeda (0° 7′46.96″N, 34°24′19.15′E) and Madeya (34° 24′13.7′ E 00° 08′ 38.3″ N) in Western Kenya to employ CA and ISFM practices, respectively. These sites experience a sub-humid tropical climate with approximately 1800 mm of mean annual rainfall (observation period 2003-2016), which precipitates bimodally in long (March to July) and short (August to November) rainfall periods, resulting in two cropping seasons. Soils are classified as Rhodic Kandiudox (USDA) and are explained in detail by Sommer et al. (2018) and Margenot et al. (2017).

Both trials were set out in an incomplete randomised split plot design. CA includes three cropping rotations; (1) monoculture maize (MM), (2) maize-soybean (*Glycine max* L.) rotation (MS) and (3) maize + soybean intercropped in both seasons (M+S), with two management strategies; reduced (conservation) tillage and maize residue application (2 t ha^{-1}). ISFM includes similar crop rotations, except for MS with soybean replaced by tephrosia (*Tephrosia candida* L.) (MT), and management strategies included farm-yard manure (4 t ha^{-1}) and maize residue (2 t ha^{-1}) application (Figure 1).

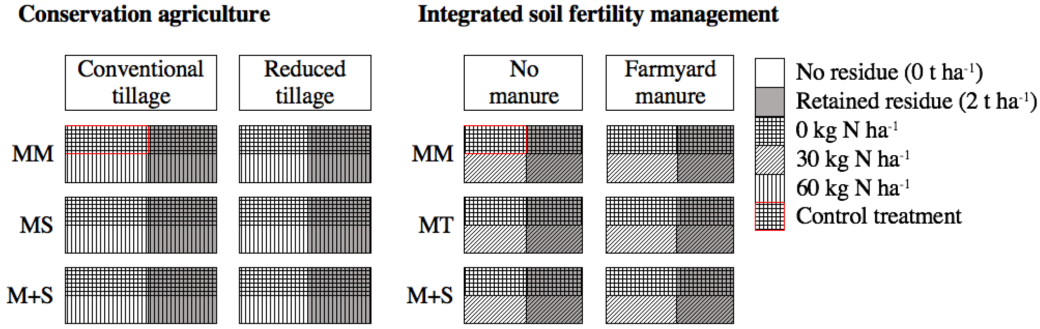

Figure 1. Stylised representation of treatments investigated in both Conservation Agriculture and Integrated Soil Fertility Management trials (i.e. not a depiction of trial design).

Crop management is detailed by Sommer et al. (2018). Briefly, all soybean and tephrosia residue remained on plots after harvest, while maize residue was removed and returned in the applied residue treatments only. Farmyard manure and inorganic fertiliser was broadcast and incorporated at sowing. All cropping systems received seasonal applications of potassium and P at 60 kg ha^{-1}. From 2015, P fertiliser was reduced to 45 kg ha^{-1} for all systems under ISFM. Nitrogen (N) treatments were applied (as granular urea) at 0 and 60 kg ha^{-1} in the CA trial and 0 and 30 kg ha^{-1} in the ISFM trial (Figure 1).

In this study we conducted a mass balance analysis of P as per Equation 1. Total outputs included harvested grain (maize and/or soybean grain) (P_Y) and residue (P_R), and inputs included returned residue (maize only), farmyard manure (P_{FYM}) and inorganic fertiliser (P_F). Runoff or leaching of P was not included as topography at both sites was relatively flat (Sommer et al. 2018). P input of farmyard manure and maize residue were both estimated at 1.9 g kg^{-1} (Margenot et al. 2014, unpublished data; Margenot et al. 2017). P output of grains were estimated from the literature as 1.5 g kg^{-1} for maize (Delve et al. 2009) and 5.4 g kg^{-1} for soybean (GRDC, 2016).

$$PUE = \frac{P_Y + P_R}{P_F + P_{FYM} + P_R} \quad \text{(Equation 1)}$$

Analysis of variance was carried out using RStudio version software 4.1.1. Conservation agriculture treatments were statistically compared to the control using a TukeyHSD post-hoc analysis.
Rudimentary visual analysis of ISFM treatments is presented however further statistical comparison is required. Statistical significance refers to $p \leq 0.05$, unless otherwise indicated.

Results

ISFM and CA strategies were not directly compared because trial-site baseline productivity was significantly different (data not presented). All treatments under CA and most under ISFM had PUE ≤ 0.25, implying an inefficient use of applied P (Roberts and Johnston 2015). MM resulted in the highest PUE compared to all other cropping systems under 30 kg ha^{-1} of seasonal N (Figure 2). It is worth noting however, that under either strategy, M+S resulted in the highest PUE (0.19) in the absence of all N inputs and was found to be significantly different to the control. In addition to inorganic N, manure without maize residue applied under MM achieved the highest PUE (0.26), using P 44 % more efficiently compared to the control (highlighted in red Figure 2). The application of 30 N kg ha^{-1} alone, increased PUE against the control by 39 %. Treatments under MT achieved lowest PUE, irrespective of inputs, and were less than or equal to the control (Figure 2). Treatments with 60 N kg ha^{-1} achieved greater PUE compared to those with no N input, the addition of N alone increased PUE by 67 %, relative to the control treatment. Omission of N, with applied residue and reduced tillage under MM however, resulted in lowest PUE, although this was not significantly different to the control (Figure 2B).

Discussion

Effect of rotation

Under both CA and ISFM, monoculture maize achieved the highest PUE compared to intercropping and maize rotations, but only when inorganic N fertiliser was applied. Under monoculture, increased N resulted in larger maize grain and residue-P annual output compared to other cropping systems, increasing PUE. This indicates that PUE is affected by N nutrition and cropping intensity. Intercropping with legumes generally increased PUE for systems with no input of fertiliser N. The direct benefit derived from sowing legumes without reducing cropping intensity, probably alleviated soil N constraints whilst maintaining average annual maize yields. This provided an opportunity to convert applied P into harvestable outputs, thus increasing PUE. Although intercropping legumes alone did not replace the role of inorganic N at increasing maize yields and maximising PUE, this study suggested that intercropping could be a viable option for farmers who manage low N input CA systems, which has been reported elsewhere (Masvayaa et al. 2017).

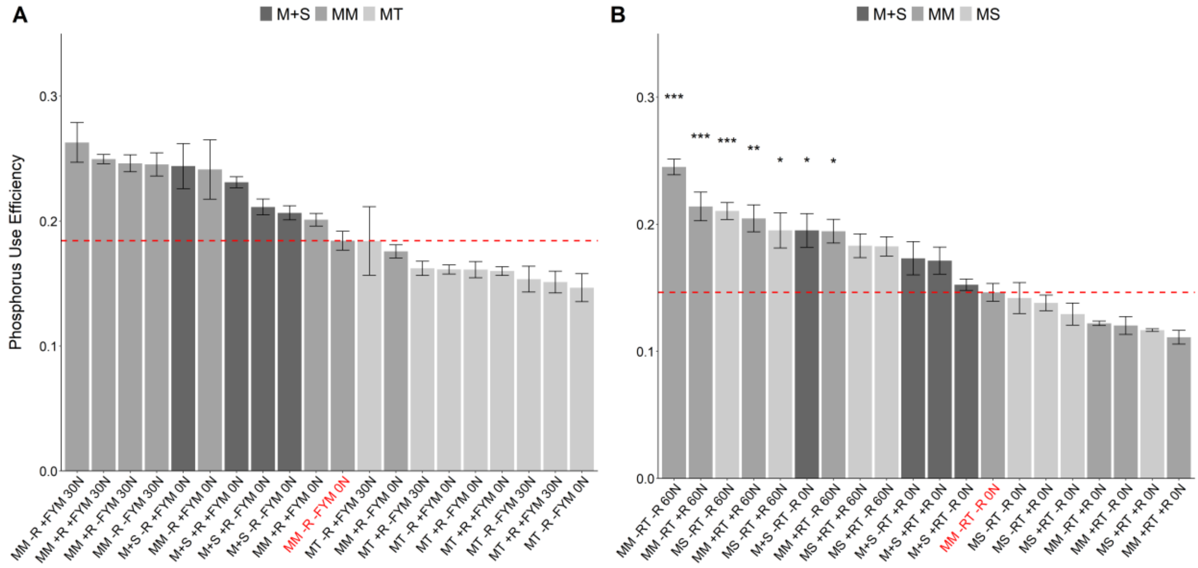

Figure 2. Phosphorus use efficiency (PUE) (Total outputs included grain (maize and/or soybean grain) and residue, and inputs included returned residue, farmyard manure and inorganic fertiliser) under A. integrated soil fertility management practices under maize-maize (MM), maize-tephrosia (MT) rotation or maize-soybean intercropping (M+S) and a combination of farmyard manure (±FYM), maize residue (±R) and inorganic nitrogen (N) fertiliser (0 and 30 kg ha^{-1}), and B. conservation agriculture treatments with MM, maize-soybean (MS) rotation and M+S, and a combination of reduced (+RT) or conventional tillage (-RT), ±R and inorganic N (0 and 60 kg ha^{-1}). Dashed line represents baseline PUE of control treatment at each trial (highlighted in red). Error bars represent ± standard error of the mean (n=4) and treatments are significantly different at ≤ 0.05 '*', ≤ 0.01 '' and ≤ 0.001 '***').**

Effect of N treatment

In addition to fertiliser N, treatments with farmyard manure applied had higher PUE across all cropping rotations. Manure contributes large quantities of organic carbon to the soil, which builds soil structure, creating favourable conditions for microbial activity and can lead to the transfer of previously unavailable P into more available forms for plant uptake (i.e., nutrient-P mining) (Richardson et al. 2011). Manure also supplies a significant amount of organic N, which may have alleviated soil N constraints.

Application to smallholder farming systems

Applying 4 t ha^{-1} of manure and 30 kg ha^{-1} of inorganic N to monoculture maize increased the use of applied P by 44 % compared to treatments with no inputs. Applying inorganic N under a CA system was necessary to receive any return on P, with the greatest increase in PUE generated under high cropping intensity (monoculture), conventional tillage, no maize residue application and 60 kg ha^{-1} of inorganic N. Such management for smallholder farmers may not be viable over the long term, given the high economic costs and low availability of fertiliser (Nziguheba et al. 2016). Negative implications of monocultures on soil health have not been identified to impact yield at this site but may require further research. In situations where N fertiliser is unavailable, the adoption of intercropping soybean increased use of applied P by 17 % and maintained relatively stable average yields (~5.8 t ha^{-1} maize plus soybean). Similarly, intercropping increased returns by 33 % under CA. Average maize yields improved under rotations compared to monoculture (data not presented), however, equal application rates of P to all crop types lowered PUE under rotations. Local or cultural preferences may be in favour of sowing legumes and further investigation is needed for tailored P application rates.

Conclusions

This study of maize-based cropping systems confirmed that N is critical in increasing PUE. CA and ISFM systems that introduced an organic or inorganic N source increased PUE by 7 - 44 %. The most effective rotations had high cropping intensity and increased N input (i.e., legume intercrops or inorganic N fertiliser application). Overall, all treatments remained below 0.26 PUE, which remains inefficient and further work is required. Whilst increased N fertiliser use is not always feasible, intercropping with soybean could be a viable option under low input systems, however further investigation into maximising PUE is necessary.

References

Delve RJ, et al. (2009). Simulating phosphorus responses in annual crops using APSIM: model evaluation on contrasting soil types. Nutrient cycling in agroecosystems 84, 293–306. (doi:10.1007/s10705-008-9243-6).

Grain Research and Development Corporation (GRDC) (2016). Soybean: Nutrition and Fertiliser, Section 5. Growers notes. https://grdc.com.au/__data/assets/pdf_file/0029/370658/GrowNote-Soybean-North-05-Nutrition.pdf (Accessed 24 December 2020).

Kihara J and Njoroge S (2013). Phosphorus agronomic efficiency in maize-based cropping systems: A focus on western Kenya. Field crops research 150, 1-8. (doi:10.1016/j.fcr.2013.05.025).

Margenot A.J., 2014. [Unpublished Data] Elemental analysis of INM3 manure, March 5, 2014. (Accessed 29 October 2021)

Margenot AJ, et al. (2017). Can conservation agriculture improve phosphorus (P) availability in weathered soils? Effects of tillage and residue management on soil status after 9 years in a Kenyan Oxisol. Soil and tillage research 166, 157-166. (doi:10.1016/j.still.2016.09.003).

Masvayaa EN, et al. (2017). Is maize-cowpea intercropping a viable option for smallholder farms in the risky environments of semi-arid southern Africa? Field crops research. 209, 73-87. (doi:10.1016/j.fcr.2017.04.016).

Nziguheba G, et al. (2016). Phosphorus in smallholder farming systems of sub-Saharan Africa: implications for agricultural intensification. Nutrient cycling in agroecosystems 104, 321-340. (doi:10.1007/s10705-015-9729-y).

Richardson AE, et al. (2011). Plant and microbial strategies to improve the phosphorus efficiency of agriculture. Plant Soil 349, 121-156.

Roberts TL and Johnston AE (2015). Phosphorus use efficiency and management in agriculture. Resources, Conservation & Recycling. 105, 275-281. (doi:10.1016/j.resconrec.2015.09.013 0921-3449).

Sileshi G, et al. (2010). Variation in maize yield gaps with plant nutrient inputs, soil type and climate across sub-Saharan Africa. Field Crops Research 116, 1-13. (doi:10.1016/j.fcr.2009.11.014).

Sommer R, et al. (2018). Reducing losses but failing to sequester carbon in soils – the case of Conservation Agriculture and Integrated Soil Fertility Management in the humid tropical agro-ecosystem of Western Kenya. Agriculture, Ecosystems & Environment 254, 82-91. (doi:10.1016/j.agee.2017.11.004).

Syers JK, Johnston AE and Curtin D (2008). Efficiency of Soil and Fertilizer Phosphorus. FAO Fertilizer and Plant Nutrition Bulletin 18. Food and Agriculture Organization of the United Nations, 107 pp.

Vandamme E, et al. (2014). Residual phosphorus effects and nitrogen 3 phosphorus interactions in soybean–maize rotations on a P-deficient Ferralsol. Nutrient cycling in agroecosystems 98, 187-201. (doi:10.1007/s10705-014-9605-1).