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RESEARCH ARTICLE

Fertiliser use efficiency, production risks and profitability of maize on smallholder farms in East Africa

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Abstract

The use of fertilisers in maize production has been the focus for many years of agronomic studies on research stations in East Africa. However, information on production risks and profitability of fertiliser use on smallholder farms is generally lacking because most of the early studies have focused on mean yields and yield components on research stations. This study applied rigorous analyses to determine conditions under which (1) production risks are low; (2) the recommended nitrogen (N) and phosphorus (P) fertiliser rates achieve a yield target of ≥ 3 t ha^{-1} believed to be a necessary condition to kick start a smallholder-led 'green revolution' in Africa and (3) N and P fertiliser use is profitable on smallholder farms in East Africa. Analysis of data from 464 on-farm trials in Kenya, Rwanda, Tanzania and Uganda revealed significant variations in production risks and nutrient use efficiency with season and soil type. On most sites, except in Uganda, production risks were lower with the recommended N and P fertilisers than the control during both the short and long rains. Production risks were three to four times higher with N and P fertiliser relative to the control on Lixisols and Ferralsols, but such risks were much lower on Nitisols, Leptosols, Vertisols, Plinthosols and Cambisols. The probability of exceeding grain yields of 3 t ha^{-1} with the recommended N and P rates was over 0.60 on Nitisols and Leptosols, but less than 0.20 on Lixisols and Plinthosols. The agronomic use efficiencies of N (AEN), P (AEP) and value cost ratios (VCR) were highest on Cambisols and lowest on Plinthosols. The VCR increased linearly with increase in AEN ($R^2 = 0.92$) and AEP ($R^2 = 0.87$) and less so with increase in grain yields ($R^2 = 0.47$–0.60). Net present values indicated profitably of N and P fertiliser over the long term in only 30% of the site by season combinations in Uganda compared with 69% in Kenya, 81% in Rwanda and 84% in Tanzania. Patterns of N use efficiencies were different from P use efficiencies across soil types. Therefore, we recommend that N and P fertilisers should be appropriately targeted to soils where applied nutrients are used efficiently by maize crops.

Keywords: agronomic efficiency; downside risk; net present value; value cost ratio

Introduction

Maize (*Zea mays* L.) is one of the staple crops and a source of income for many households in East Africa (Abate et al., 2015; Wambugu et al., 2012). Much of the maize production in East Africa occurs under rain-fed conditions, which makes it vulnerable to climate variability (Omoyo et al., 2015; Shi and Tao, 2014). Extreme weather events such as droughts and heat, which are predicted to become more frequent under climate change in East Africa, can affect both yields and total production (Lyon and DeWitt, 2012; Mutegi et al., 2018). Since 1996, there has been a decline in rainfall of 50–150 mm per season and a corresponding decline in yields of long-cycle crops (e.g., slow-maturing varieties of maize) across most parts of Eastern Africa (Shi and Tao, 2014).

Much of East Africa has been subjected to land degradation through decades of nutrient mining and soil erosion (Mulinge *et al.*, 2016). Consequently, nutrient deficiencies, especially those of nitrogen (N) and phosphorus (P), severely constrain maize productivity in this region (Kihara *et al.*, 2016; Kiwia, *et al.*, 2019; Mutegi *et al.*, 2018; Sileshi *et al.*, 2019). P limitation is severe in some parts where the parent materials have inherently low levels of P or on soils with high P-retention capacity (Batjes, 2011). However, most smallholder farmers in East Africa rarely apply the recommended fertiliser rate (Duflo *et al.*, 2008; Kiwia *et al.*, 2019; Sileshi *et al.*, 2019). One of the reasons for under-investment in fertiliser by farmers is perception of production risk (Simtowe, 2006). Inefficient use of nutrients by crops during times of moisture stress (Snapp *et al.*, 2003) often results in considerable variability in profitability of fertiliser use (Shiferaw *et al.*, 2014).

Landscape-scale modelling results, field trials and policy experiments all demonstrate that small increases in inputs, coupled with good agronomic practices, are sufficient to double maize yields in many parts of Africa (Kisinyo *et al.*, 2015; Kiwia *et al.*, 2019; Mourice *et al.*, 2014). However, the blanket fertiliser recommendations mostly derived using data from research stations are often not adopted by smallholder farmers in East Africa. The high diversity of soils and farmers' endowment in East Africa means that the application of blanket fertiliser recommendations is not likely to be effective in addressing declining land productivity (Snapp *et al.*, 2003). This may also prove unprofitable on some farms. It is, therefore, important to determine the production risks faced by farmers and the financial benefits of applying recommended rates of fertiliser at the scale of typical smallholder farms. It is also important to determine the conditions under which fertiliser use becomes unprofitable.

The prevailing maize yields are low (usually 1–2 t ha^{-1} per season) in many parts of East Africa (Sánchez, 2015; Shi and Tao 2014). Agricultural experts in general concur that a yield target of 3 t ha^{-1} would be necessary to kick start a smallholder-led ‘green revolution’ in Africa (UN Millennium Project, 2005; Sánchez, 2015). In that spirit, the Alliance for Green Revolution in Africa (AGRA) supported several partners to establish participatory trials to create awareness on the use of fertilisers and improved seeds among farmers. These trials have generated valuable data that can be used to inform policymakers and improve the existing recommendations. These results can be used to fill the information gaps in terms of returns to investment in fertiliser and where such investment may face production risks in maize growing regions of East Africa. This kind of information is useful to farmers in making decisions based on improved fertiliser recommendations which improve incomes and minimise risks associated with its use. Insurance companies could also benefit from these findings using fertiliser use rate as basis of computing potential production risks and the corresponding payoff. It is also useful to policymakers in targeting government subsidy programmes and other incentives in the effort to improve fertiliser use by farmers. Therefore, the objective of this analysis was to determine conditions under which (1) production risks are low; (2) N and P fertiliser rates achieve a yield target of $\geq$3 t ha^{-1} believed to be a necessary condition to kick start a smallholder-led green revolution in Africa and (3) NP fertiliser is profitable on smallholder farms in East Africa. Given the above, the key research questions were (1) where and on which soils can the threshold yield target of 3 t ha^{-1} be realised with minimal financial risks and (2) which soil types carry greater production risks?

Materials and Methods

Study areas

This analysis covered data from more than 464 on-farm trials across Kenya, Rwanda, Uganda and northern Tanzania (Supplementary Table S1). The trial sites were purposefully selected to fall within the maize production zones of the four countries. The selection was informed by the local knowledge of researchers and extension staff in each country. Within each location, the specific sites were selected based on their potential to facilitate learning by farmers and extension staff.

Across the study sites, rainfall is characterised by a bimodal annual cycle, with the major rainy season (often called the long rains) occurring during March–May and the short rains during October–December (Yang *et al*., 2014). Therefore, two maize harvests are possible. The major soil types in the study areas classified based on the harmonised soil atlas of Africa following the World Reference Base for Soil Resources (WRB) (Dewitte *et al*., 2013; Jones *et al*., 2013) are Acrisols, Cambisols, Ferralsols, Leptosols, Lixisols, Nitisols, Plinthosols and Vertisols (Supplementary Table S1).

Acrisols were the dominant soils on the trial sites in Busia and Kakamega in Kenya, and Gatsibo, Huye, Kamonyi, Kayonza, Kirehe, Muhanga and Nyanza in Rwanda. Acrisols are strongly weathered acid soils with low base saturation (IUSS, 2014). When cultivated for long, they degrade irreversibly through intense acidification, and high Al and Mn toxicity and P fixation (Batjes, 2011). Cambisols dominated the trial sites in Biharamulo, Bukoba and Muleba in Tanzania. These soils consist of medium and fine-textured materials derived from a wide range of rocks. Cambisols generally make good agricultural land because they are richer than associated Acrisols or Ferralsols (IUSS, 2014). Ferralsols were the dominant soils in Apac, Busia and Tororo in Uganda. Ferralsols are the red- and yellow-coloured tropical soils derived from strongly weathered material (IUSS, 2014). Ferralsols have good physical properties, great soil depth, good permeability and stable microstructure, making them less susceptible to erosion (IUSS, 2014). However, they are often characterised by low pH, low nutrient concentrations and high P-retention capacity (Batjes, 2011; IUSS, 2014). Leptosols dominated the trial sites in Arumeru, Kondoa, Misenyi and Muleba in Tanzania and Dokolo in Uganda. Leptosols comprise very thin soils over continuous rock commonly occurring in mountainous regions or hilly areas. They are rich in coarse fragments and prone to erosion (IUSS, 2014). Lixisols dominated the trial sites in Kakamega in Kenya and Busia in Uganda. These soils originate from a wide variety of parent materials, notably in unconsolidated, strongly weathered, fine-textured materials. The low level of plant nutrients and cation retention by Lixisols makes recurrent inputs of fertilisers a precondition for continuous cultivation (IUSS, 2014). Nitisols were the dominant soils in Embu in Kenya and Hai and Moshi in Tanzania. Nitisols are deep, well-drained soils that are far more productive than most other red tropical soils (IUSS, 2014), but they suffer from acidity and P retention (Batjes, 2011). Plinthosols were found in Iganga, Namutumba and Tororo in Uganda. Poor natural soil fertility caused by strong weathering, waterlogging in bottomlands and drought are serious limitations (IUSS, 2014). Vertisols were found in Dokolo in Uganda. Vertisols have considerable agricultural potential due to their good chemical fertility, but they are and susceptible to waterlogging during the rainy season and moisture stress during dry periods (IUSS, 2014).

Trial design and treatments

On each site, a number of treatments were established between 2009 and 2014 using the mother-and-baby participatory trial design described in Snapp *et al.* (2003). This design systematically links a central 'mother' trial managed by researchers and extension staff to numerous farmer-managed 'baby' trials, facilitating rigorous cross-checking of biological performance with farmer assessment. Mother trials are replicated and managed by researchers to test many different crop technologies on a few farms. Baby trials are not replicated and farmer managed and thus used to test subsets of the technologies on many farms (Kamanga et al., 2010). The 'mother' trials plot sizes were 10 × 10 m, while the 'baby' trials were 5 × 5 m. In each country and region, trial sites were selected through a consultative process involving researchers, extension staff and other stakeholders. The selection of the specific farms for mounting the demonstrations was informed by their potential to facilitate hosting field days and co-learning by farmers and extension staff. Those farmers with suitable land were selected after careful consideration of factors such as land size to accommodate the required number of plots, slope, absence of termite mounds and other objects that interfere with the demonstration of treatment effects.

For the present analysis, two treatments that were available across almost all sites were used. These are monoculture maize crop that received the recommended rate of N and P fertiliser (hereafter referred to as 'NP fertiliser') and maize grown without any external inputs (control). In fertiliser recommendations in some countries (e.g., Kenya), potassium (K) is missing or considered non-limiting. Therefore, the focus of this analysis is on N and P inputs.

In Kenya, the nutrient rates were 60 kg N ha^{-1} and 20 kg P ha^{-1} on sites in Kakamega and Busia counties, and 60 kg N ha^{-1} and 22 kg P ha^{-1} on sites in Embu County. The nutrient sources on the Kakamega and Embu sites were di-ammonium phosphate (DAP) + urea or DAP + calcium ammonium nitrate (CAN), whereas on sites in Busia, single superphosphate (SSP) + CAN was used. In Uganda, the rates were 80 kg N ha^{-1} and 15 kg P ha^{-1} applied as DAP + urea. In Rwanda, the rates were 66 kg N ha^{-1} and 18 kg P ha^{-1} on some sites, but 32 kg N ha^{-1} and 12 kg P ha^{-1} applied as DAP + urea or NPK + urea. In northern Tanzania, the rates were 60 kg ha^{-1} N and 20 kg ha^{-1} P applied as DAP + urea or triple super phosphate + urea. In all cases, fertilisers were applied manually as basal and top dressing close to the plant using 5 ml water bottle cap (lid). Split application of the N fertiliser was done; 30% of the N was applied at planting while the remaining 70% was applied 5 weeks after germination. The nutrient rates applied are close to the national recommendations, and the decision to use them was informed by the local knowledge of researchers and extension staff in the specific areas.

All trials took place with optimal management, including site-specific recommended agronomic practices. Dates of planting, plant density and weeding were performed as per recommendations for the specific site. Improved varieties of maize recommended for the sites were used. All varieties had water-limited yield potential of more than 4 t ha^{-1} (Supplementary Table S2).

Statistical analysis

This study applied rigorous analyses focusing on grain yield, yield differences, production risk, N and P use efficiency and financial returns. Yield differences refer to increase or decrease due to treatment/intervention relative to the control. Statistical analysis was conducted on data from the baby trials to assess variations with season in each country. In addition, variations in response to fertiliser with soil type were assessed at the aggregate level (across sites and seasons). For the different levels of analyses, a linear mixed effects modelling framework was used because of the imbalance in terms of sample size, non-normality and possible internal correlation (dependence of observations within sites). The procedure used here fits the covariance structure of the data using the method of restricted (residual) maximum likelihood. Treatment, seasons and soil type were held as the fixed effects and site as the random effect. Given the unequal sample sizes between trials, the Kenward–Roger method was used for approximating the degrees of freedom as it is preferable to other approaches (Spilke *et al.*, 2005). In all cases, the 95% confidence intervals (CIs) of estimates were used for statistical inference because CIs provide information about statistical significance as well as the direction and strength of the effect. Means were deemed significantly different from one another only if their 95% CIs were non-overlapping. We also used the width of the 95% CI as an indication of uncertainties around estimated values.

Traditionally, the performance of treatments has been judged based on mean yields. However, inferences based on the mean yields can be misleading if the variance (representing production risk) is large. One of the most commonly used measures of risk is the coefficient of variation (CV); a larger CV reflecting more volatility and risk (Kalkuhl *et al.*, 2016). Therefore, the CV in the control (CVc) and the fertiliser treatment (CVf) were calculated. If the ratio (i.e., CVf/CVc) is greater than unity, it was interpreted as indication of higher risk with fertiliser than the control in a given season or soil type. In the context of sustainable intensification, risk is generally measured as either production risk or perceived risk (Smith et al., 2017). Production risk can be quantified as the probability that sufficient yields are produced to meet the food or nutritional needs of the household (Smith *et al.*, 2017). Production risk can also be assessed economically as the chance that incomes will exceed expenses (Kamanga *et al.*, 2010; Smith *et al.*, 2017). Successful reduction of production risk is assumed to stabilise incomes, which can then reduce vulnerability (Kamanga *et al.*, 2010). In this analysis, we apply both the probability of yields falling below certain minimum requirements and incomes from maize production exceeding expenses. In the case of yields, we used the average minimum maize requirement of 1.3 t per household per year for an average family size of five people (Kamanga *et al.*, 2010). NP fertiliser is said to be risky when yields fall below this minimum acceptable yield. In addition, we applied the concept of downside risk which can be measured either as the number of years or sites for which returns or yields are below a target yield (Langemeier, 2015). For this purpose, the probability of maize yields falling below the target yield of 3 t ha^{-1} was estimated for the treatment and control. First cumulative probability distributions of yields were generated, and then the probability of exceeding the target yield was obtained by subtracting the cumulative probability from 1.

The efficiency with which N and P were used by the crop was assessed, with a focus on the agronomic efficiency (AE) of N and P. According to Snyder and Bruulsema (2007), AE answers the question, ‘How much productivity improvement was gained using this nutrient input?’ In this analysis, AE of N (AEN) and of P (AEP) were calculated as follows:

$$AEN = \frac{(GYN_x - GYN_0)}{N_x} \text{ and } AEP = \frac{(GYP_x - GYP_0)}{P_x}$$

where GYN_x and GYP_x represent the grain yield at a given rate of N (N_x) and P (P_x), respectively. GYN_0 and GYP_0 are the grain yield in the plots without N and P input. Thus, AEN and AEP represent how much yield is increased for each unit of added N and P, respectively (Jama et al., 2017; Kihara and Njoroge, 2013).

Cost-benefit analysis was conducted to determine benefits of fertiliser use from the perspective of a farm. Data on input prices (costs of fertiliser, labour and transport) and output (selling prices of maize) were acquired through market surveys in each country. Using these data, the value cost ratio (VCR) and marginal rates of return (MRR) were calculated to determine the short-term profitability of fertiliser use by farmers. The use of VCR is preferred over other measures of profitability if data on full production costs are unavailable (Jama *et al.*, 2017; Kihara *et al.*, 2016; Xu *et al.*, 2009). The VCR was calculated as a ratio of value of increased crop output to the cost of fertiliser applied:

$$VCR = \frac{P_c \times Q_c}{P_f \times Q_f}$$

where P_c is the price of crop and Q_c is the quantity of additional crop yield, and P_f is the price of fertiliser and Q_f is the quantity of fertiliser applied (Jama et al. (2017). A VCR value greater than 1 means that the cost of fertiliser is recovered, while a VCR of 2 represents 100% return on the money invested in fertiliser and is enough to warrant investment in fertiliser (Kihara et al., 2016; Xu et al., 2009). In high-risk production environments, other studies have proposed VCR >3 as an appropriate threshold (Jama et al., 2017). African farmers face significant liquidity and risk constraints that limit their uptake of fertiliser unless it is highly profitable (Kelly, 2006). In order to accommodate price and climatic risks with a satisfactory incentive to farmers, VCR > 4 was suggested by some experts as the optimum. In this analysis, VCR $\geq$ 2 was considered as the minimum but VCR $\geq$ 4 as more appropriate to guarantee adequate risk coverage against investment in fertiliser on smallholder farms in high-risk areas. To determine the yield level at which fertiliser becomes profitable, scatter plots of VCRs against the corresponding grain yield from fertilised plots were generated. Similarly, scatter plots of VCRs against AEN and AEP were generated. In addition, cumulative probability distributions were generated to estimate the probabilities of exceeding VCRs of 2 and 4.

Acceptability of fertiliser by farmers is best judged by MRR, an approach used to maximise profit (Kelly, 2006). Therefore, MRR was computed as the ratio of the marginal benefit (i.e., the change in net benefit) to the marginal cost (i.e., the change in costs) relative to the control. As a rule of thumb, MRR of 50% is considered the lower threshold for acceptability of a simple technological package to farmers, but MRR must exceed 100% if the package involves significant changes from current farmer practices (ibid.). As the trials involved improved seed, recommended fertiliser rates and all other good agronomic practices, MRR of 100% was set as an acceptable minimum in this analysis.

Because the benefits of investing in P fertiliser can take several years to accrue, the net present values (NPVs) were estimated to determine the long-term profitability of fertiliser use. Crop uptake is generally <20% of the P fertiliser applied in the current year (Batjes, 2011), but residual soil P contributes to crop production with a considerable lag time (Sattari *et al.*, 2012). Therefore, a 5-years' time horizon was considered reasonable for calculating NPV. For discount rates, NPV analyses typically use a fixed value ranging between 10% and 30% or loan interest rates as proxies. The loan interest rate set by the national bank in each country was used as the proxy for the discount rate. During the study period, the loan interest rates were 14–17% in Kenya, 15–17% in Rwanda and Tanzania and 20–23% in Uganda (World Bank, 2015). Therefore, the discount rates used were 17% for Kenya, 16% for Rwanda and Tanzania and 23% for Uganda to reflect the inflation economy of the countries. Fertiliser application was deemed profitable when NPV exceeded the critical minimum of 0; NPV $\leq$ 0 was deemed unprofitable. The NPV was calculated as follows:

$$NPV = \sum \frac{B_t - C_t}{(1+r)^t}$$

where B_t is the total benefit in year t, C_t is the total costs in year t and r is the discount rate.

Results

Grain yield

NP fertiliser significantly ($p < 0.05$) increased grain yields over the control in most of the season-site combinations except in Kenya (Figure 1a–d). In the control, the probability of yields falling below the minimum acceptable yield of 1.3 t per year was 0.33 for Kenya, 0.08 for Rwanda, 0.60 for Tanzania and 0.45 for Uganda (Figure 2a–d). In the case of NP fertiliser, the probability of yields falling below this minimum acceptable yield was nil in Rwanda and Tanzania, but 0.17 and 0.19 in Kenya and Uganda, respectively (Figure 2a–d). In Kenya, grain yields with NP fertiliser were low and comparable with those in the control during the 2009 and 2011 short rains (Figure 1a). During the long rains, production risks with NP fertiliser were higher than the control in Rwanda and Uganda (Figure 1e). Across all sites, production risks with NP fertiliser were consistently lower than in the control during the short rains (Figure 1f). Yield gains over the control were generally lower during the short rains compared with the long rains on the sites in Rwanda (Figure 1f) and Uganda (Figure 1h). In Kenya and Tanzania, the differences between the short and long rains were not significant (Figure 1e, 1g). There were also cases where yields were below the control; the risk being 24% during both short and long rains in Kenya (Figure 1e) and 7–12% in Uganda (Figure 1h).

Eight out of the 14 maize cultivars used in the study achieved <50% of their yield potential with the recommended NP fertiliser rates (Supplementary Table S2). The probability of grain yields exceeding 3 t ha^{-1} with NP fertiliser was lowest (0.28) in Uganda, followed by Rwanda (0.46),

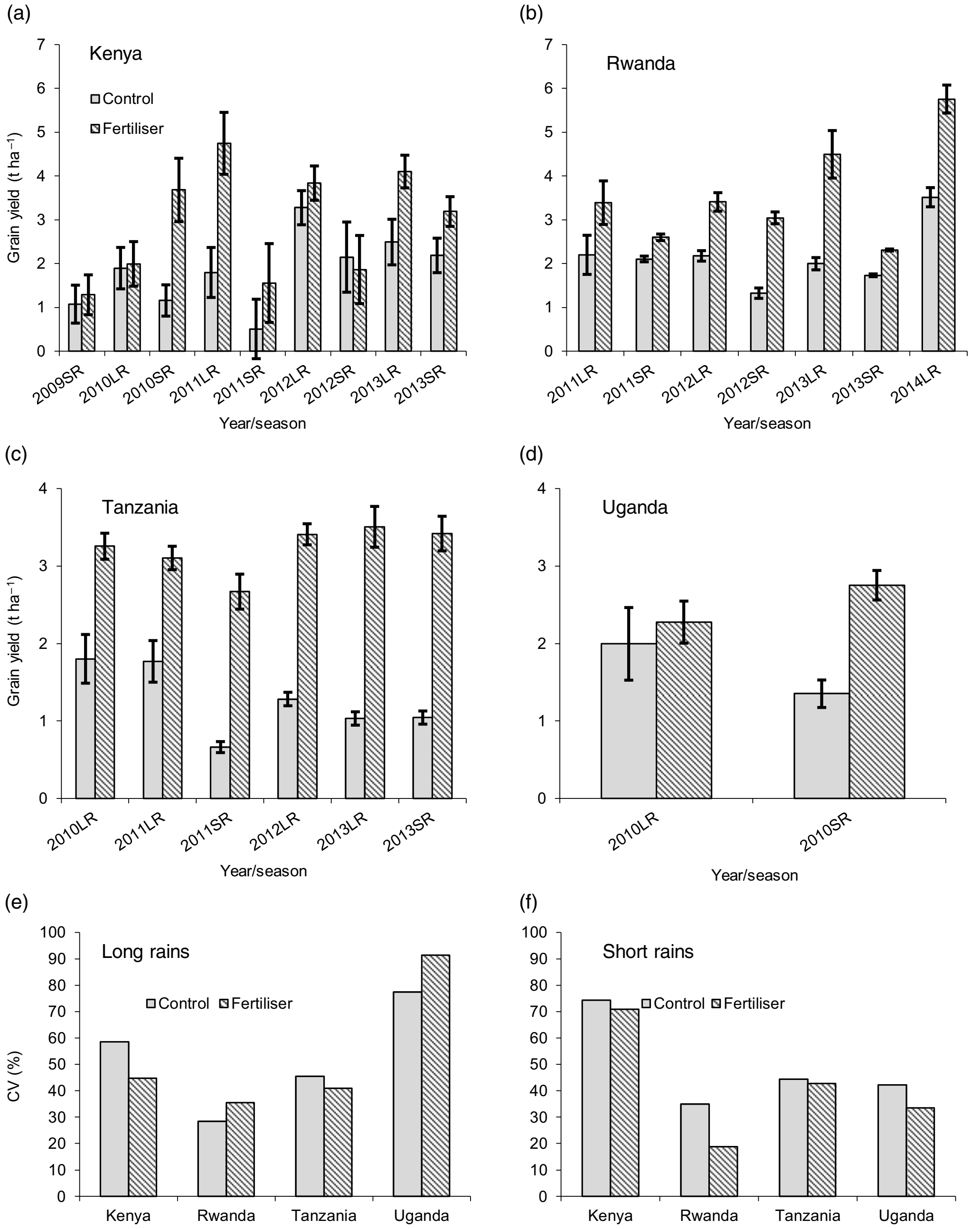

Figure 1. Variation in maize grain yield (t ha^{-1}) (a–d) and its coefficient of variation (e and f) across seasons in each country. (a–d) LR and SR represent the long and short rainy seasons for each year. Error bars represent 95% confidence limits.

Kenya (0.59) and Tanzania (0.61) (Figure 2 a–e). The corresponding risks were <5% in Rwanda and Tanzania (Figure 2f, 2g).

Across all sites and seasons, yields significantly varied ($p < 0.05$) with soil type (Figure 3a). In both fertilised and control plots, the lowest mean yields were recorded on Lixisols, whereas the highest was on Ferralsols. However, response to applied NP fertiliser (relative to the control) was

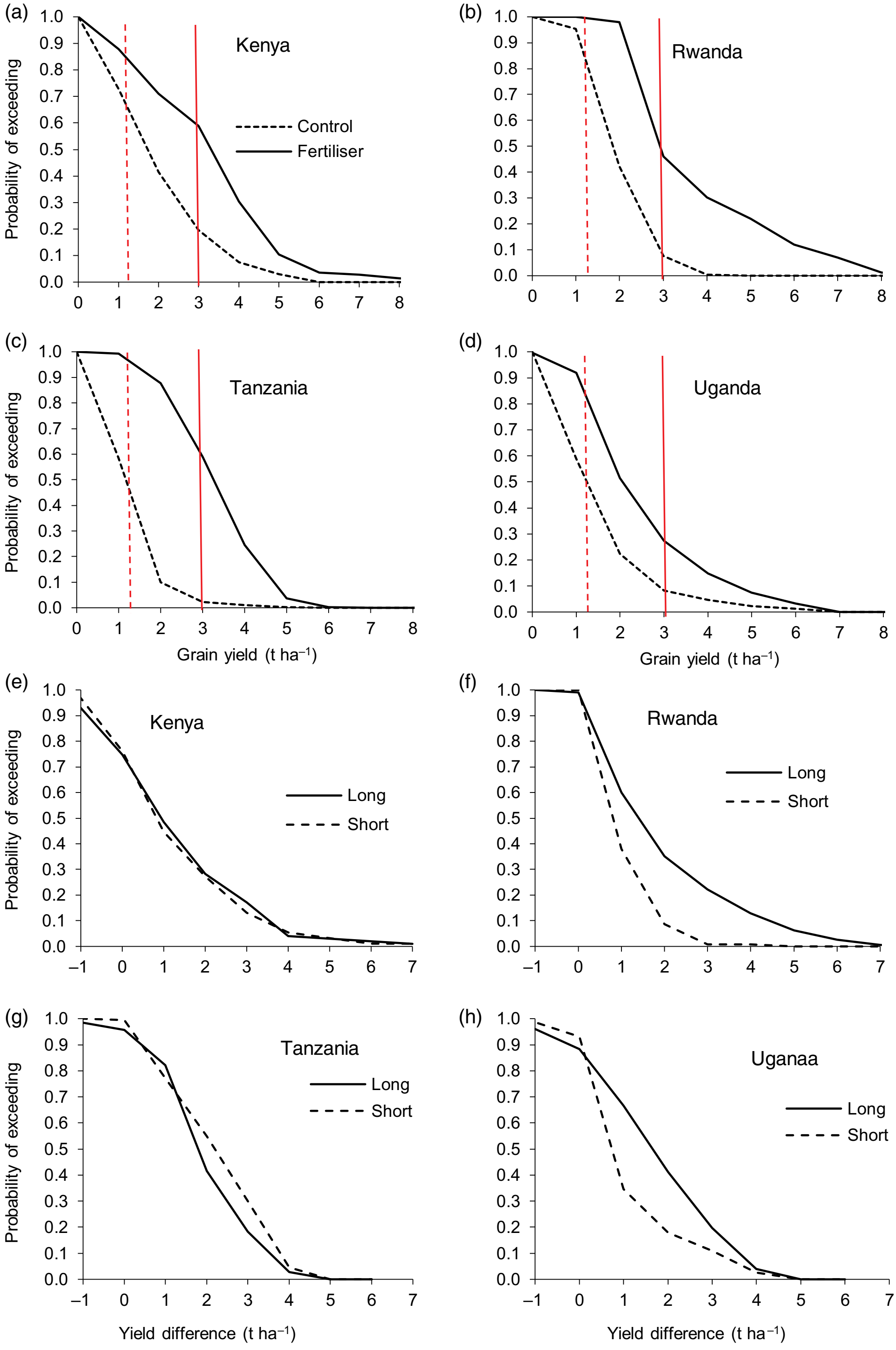

Figure 2. The cumulative probability distribution of grain yield (t ha^{-1}) exceeding a given target (a–d) and yield differences between fertiliser and control (e–h) during the long and short rains (e–h). The dashed and solid red lines in a–d represent the minimum maize requirement of 1.3 t per household per year for an average family size of five people and the African Green Revolution yield target yield of 3 t ha^{-1}, respectively.

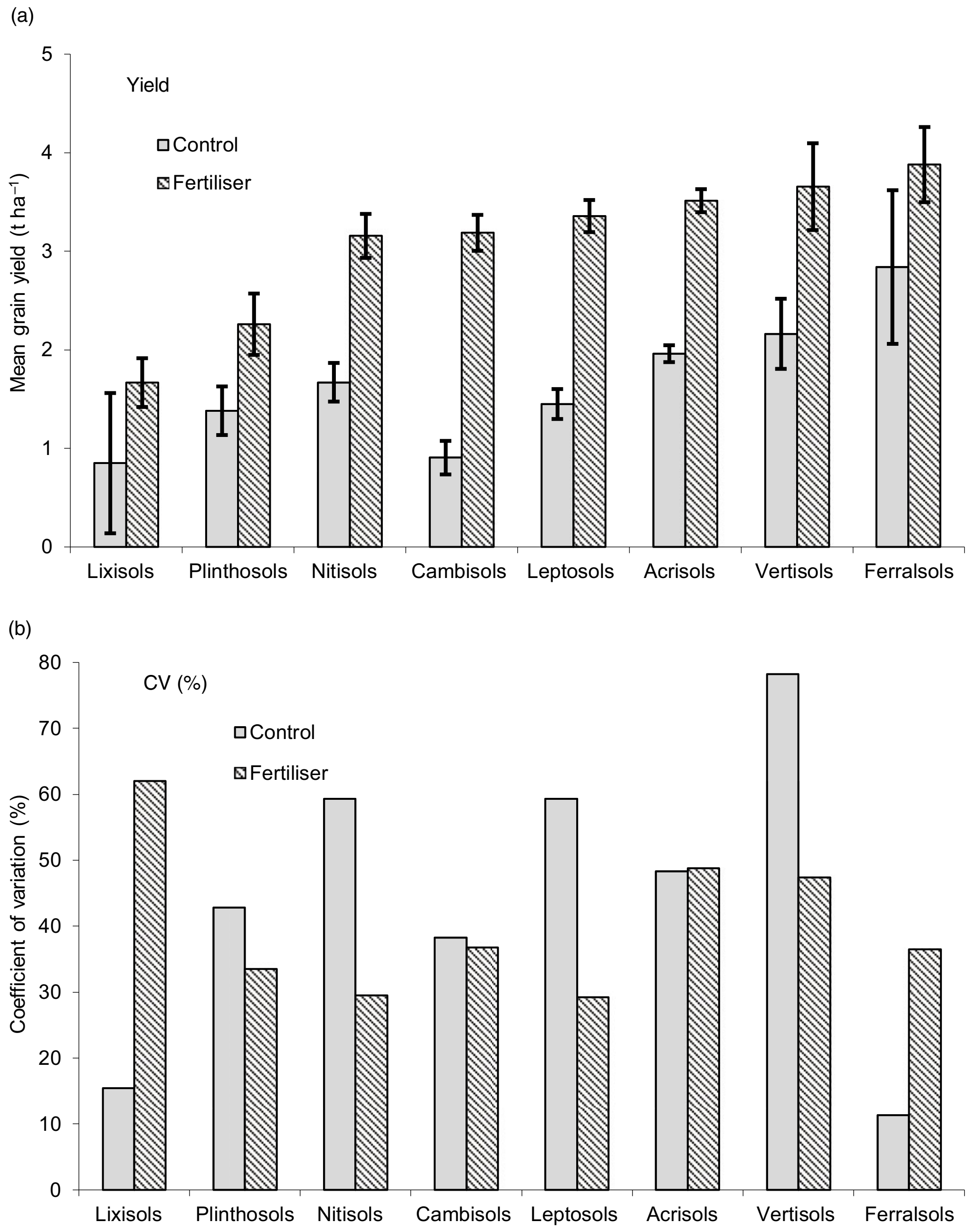

Figure 3. Variability in maize grain yield (t ha^{-1}) (a) and its coefficient of variation (CV%) with fertiliser and soil type across East Africa. Error bars represent 95% confidence limits.

higher by 252% on Cambisols, followed by Leptosols (132%), Lixisols (96%), Nitisols (89%), Acrisols (79%), Vertisols (69%), Plinthosols (64%) and Ferralsols (37%).

With NP fertiliser, the highest production risk was recorded on Lixisols (CV = 62%), followed by Acrisols (CV = 49%); the lowest (CV = 29%) was on Nitisols and Leptosols. The risk of fertiliser use relative to the control was three to four times higher on Lixisols and Ferralsols

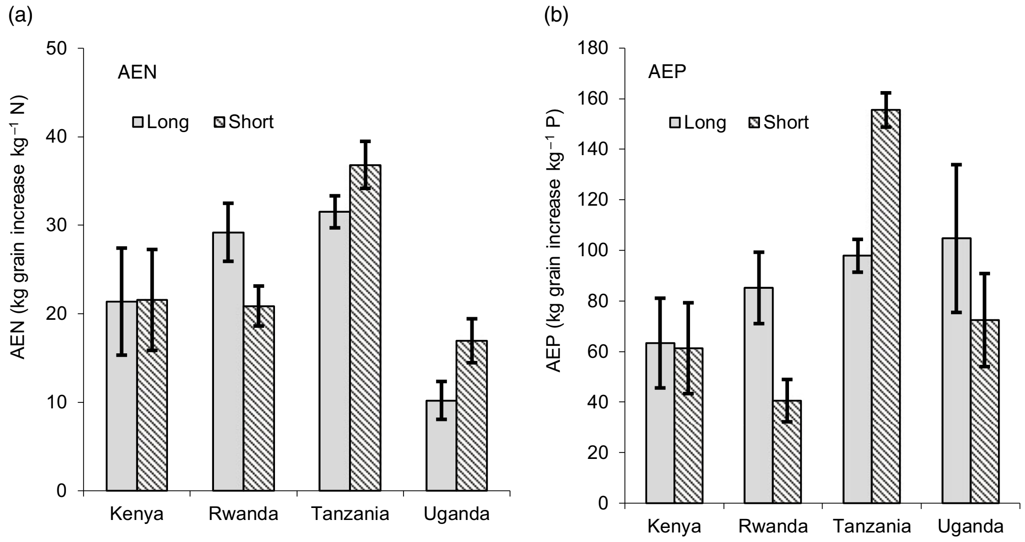

Figure 4. Variation in the agronomic efficiency (AE) of nitrogen (a) and phosphorus (b) with growing season across East Africa. Error bars represent 95% confidence limits.

(Figure 3b), whereas such risks were much lower than in the control on Nitisols, Leptosols, Vertisols, Plinthosols and Cambisols.

The probability of exceeding the target yield of 3 t ha^{-1} with NP fertiliser was 0.60 on Nitisols and 0.63 on Leptosols, 0.58 on Ferralsols and Vertisols, 0.53 on Cambisols and 0.51 on Acrisols. The corresponding probabilities were very low on Lixisols (0.11) and Plinthosols (0.18). The probabilities of getting yields less than or equal to the control using NP fertiliser were 0.14 on Vertisols, 0.05–0.09 on Leptosols, Nitisols, Plinthosols and Acrisols and nil on Cambisols.

Nutrient use efficiency

Except in Kenya, AEN significantly ($p < 0.05$) differed with season (Figure 4a) and soil type (Figure 5a). The highest AEN was recorded during the short rains in Tanzania (39 kg grain increase kg^{-1} N), whereas the lowest was during the long rains in Uganda (10 kg grain increase kg^{-1} N). Among the soil types (Figure 5a), the highest AEN was recorded on Cambisols (38 kg grain increase kg^{-1} N), and the lowest was recorded on Plinthosols (9 kg grain increase kg^{-1} N).

AEP was highest during the short rains in Tanzania (156 kg grain increase kg^{-1} P) and lowest during the long rains in Rwanda (41 kg grain increase kg^{-1} N) (Figure 4b). Ferralsols and Lixisols recorded significantly higher AEP compared with all other soils, but the lowest was recorded on Plinthosols (Figure 5b).

Returns to fertiliser use

The VCR and MRR indicated that fertiliser use is profitable in the short term across all sites except those in Uganda (Figure 6). VCR was significantly higher during the short rains than long rains on sites in Tanzania, whereas the reverse was true in Rwanda (Figure 6a). Differences between seasons were not statistically significant across sites in Kenya and Uganda. Across sites and seasons, the probability of exceeding VCR of 2 was highest (0.82) in Tanzania and lowest in Uganda (0.31). The probability of exceeding VCR of 4 was only 0.05 in Uganda, 0.11 in Rwanda, 0.31 in Kenya and 0.40 in Tanzania. Cambisols recorded higher VCR compared with Plinthosols, Vertisols,

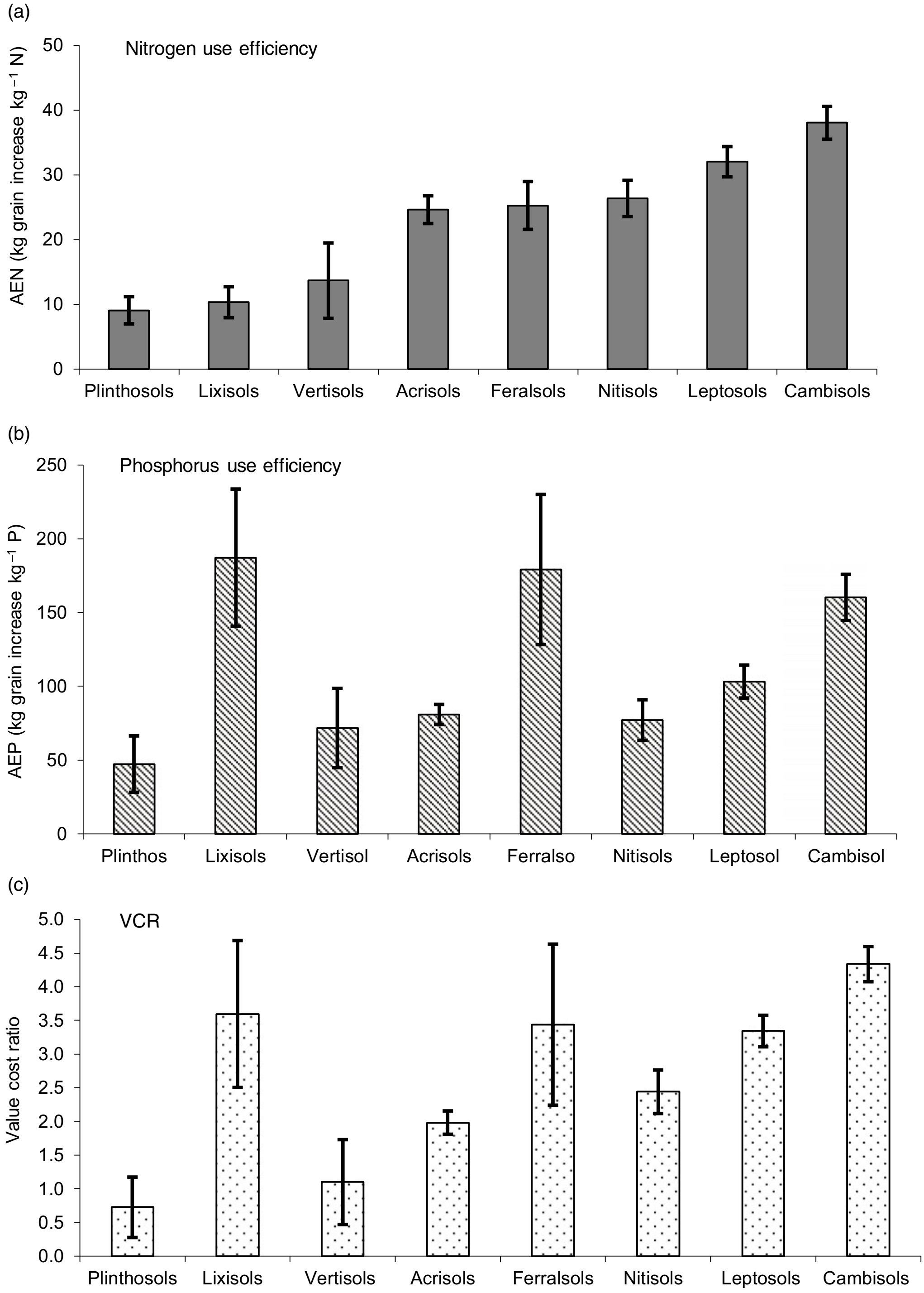

Figure 5. Effect of soil type on the agronomic efficiency (AE) of nitrogen (a) and phosphorus (b), and value cost ratios (c) across East Africa. Error bars represent 95% confidence limits.

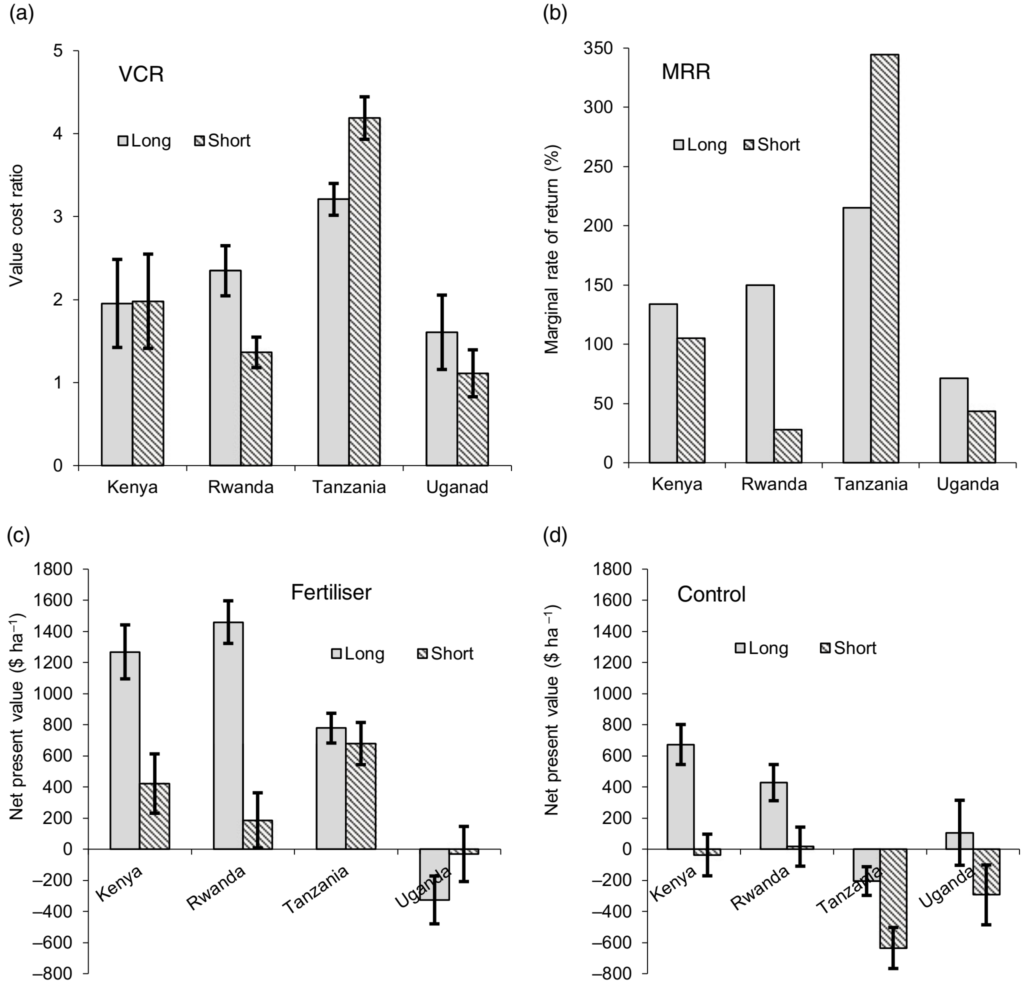

Figure 6. Value cost ratios (VCR), marginal rates of return (MRR) and net present values with N fertiliser use during the long and short rainy seasons across East Africa. Error bars represent 95% confidence limits.

Acrisols and Nitisols (Figure 5c). The VCR increased linearly with increase in AEN ($R^2 = 0.92$) and AEP ($R^2 = 0.87$) and less so with increases in grain yield ($R^2 = 0.47$–0.60) across site and season combinations. VCR consistently exceeded 2 when grain yields exceeded 3 t ha^{-1}, respectively. Across the countries, the optimum VCR of 4 was consistently achieved when grain yields exceeded 4 t ha^{-1} or where AEN and AEP exceeded 30 and 130, respectively.

With MRR greater than 100%, fertiliser use during the long rains was found to be highly profitable across Kenya, Rwanda and Tanzania (Figure 6b). During the short rains, the highest MRR (344%) was recorded in Tanzania, and the lowest (28%) was in Rwanda. Thus, Tanzanian farmers can expect to obtain $4.44 for every $1 invested, whereas Rwandan farmers can expect only $1.28 for every $1 invested in purchasing and applying fertiliser during the short season.

The NPVs of NP fertiliser ranged from −326 $ ha^{-1} in Uganda to 1460 $ ha^{-1} in Rwanda during the long rains. During the short rains, NPV was lowest (−31 $ ha^{-1}) in Uganda and highest (679 $ ha^{-1}) in Tanzania. In the control, NPV was predominantly negative except during the long rains in Kenya and Rwanda, indicating potential losses in land productivity and profitability in the absence of fertiliser use over the long term.

Discussion

The analyses above demonstrate that farmers in East Africa face large production risks if they do not apply fertiliser, with particularly greater risks (0.45–0.60) in Uganda and Tanzania. With NP fertiliser, this risk can be reduced by over 50%. The application of NP fertiliser can increase maize grain yields by 36–252% over the control depending on the season and soil type. Such increases can improve food security at household level and food production at national level. The analysis has also identified situations where the recommended rates of NP fertiliser carry some risk to the farmer depending on season and soil type. Across sites in Kenya, fertiliser application during the short rains seems to carry slightly more risk than during the long rains. This is probably related to low moisture associated with the successive failure of the short rains in 2010–2011 (Lyon and DeWitt, 2012; Yang *et al.*, 2014). Erratic rainfall distribution and suboptimal precipitation can lead to moisture deficit. Suboptimal rainfall during critical crop growth stages, especially the periods immediately before and after anthesis, can reduce N use efficiency (Calvino *et al.*, 2003). This is because water availability during critical periods of maize growth determines the utilisation of applied N fertiliser and its translation into grain yield (Calvino *et al.*, 2003). For example, Calvino et al. (2003) found that water availability during the bracketing-flowering stage of maize accounted for over 84% of the variation in maize yield.

Although all the varieties had water-limited yield potentials of 4 t ha^{-1} or more, the probability of exceeding the yield target of 3 t ha^{-1} was less than 0.50 in Uganda and Rwanda. Indeed, the average yields achieved on most sites were less than 50% of the yield potentials of the varieties used. The N and P rates applied were deemed adequate to achieve this yield target based on past research that shows that improved cultivars of maize on average use about 20 kg N ha^{-1} (Ladha *et al.*, 2005) and 9 kg P ha^{-1} (Palm *et al.*, 1997) to produce 1 t ha^{-1} of grain. Nevertheless, the probability of achieving the 3 t ha^{-1} target yield was very low on some sites, especially on Lixisols and Plinthosols. The relative risk of fertiliser use was also four times higher on Lixisols. This is probably because Lixisols and Plinthosols have poor buffering capacity and low levels of plant nutrients (IUSS, 2014). Plinthosols also suffer from waterlogging in bottomlands and drought in uplands (ibid.). Therefore, these soils need recurrent inputs of fertilisers combined with appropriate soil and water conservation techniques if the desired yield targets are to be achieved. Although yields in the control were highest on Ferralsols, response to fertiliser application was among lowest and production risk was as high as it was on Lixisols. The high yields recorded in the control are probably because Ferralsols have good physical properties and are less susceptible to erosion (ibid.). The low response to fertiliser and high production risk on Ferralsols could be associated with their high P adsorption capacity (Batjes, 2011).

These findings highlight that there are conditions under which production risks are high. Under such conditions, farmers logically become risk averse and minimise their investments on fertilisers (Simtowe, 2006). Farmers may even forego potentially high-yielding technological packages because such packages may also be riskier (ibid.). Thus, resource-constrained farmers remain in a risk-induced poverty trap. Therefore, it is important to encourage fertiliser use by resource-poor farmers through subsidy schemes or other mechanisms. Additionally, farmers would be advised to pursue a crop mix, including maize where possible, that may reduce their risks to fertiliser use for raising productivity.

The analyses also show that N use efficiency patterns were different from P use efficiency across soil types (Figure 5). The AEN recorded on most of the sites is within range (10–40 kg increase kg^{-1} N) found on farmers' fields across southern Africa (Jama *et al.*, 2017). However, use of NP fertiliser was unprofitable in conditions where AEN falls in the lower range. The high AEN recorded in Tanzania appears to be associated with better crop response on the nutrient-rich Cambisols and Nitisols. On the other hand, Plinthosols (common on Ugandan sites) consistently had low N and P use efficiency.

The AEP recorded in this analysis is within the range (0–210 kg increase kg^{-1} P) reported for parts of East Africa (Kihara and Njoroge, 2013). However, on some soils AEP values were above 210, which has been cited as the maximum value (ibid.). As shown by Kihara and Njoroge (2013), AEP values exceeding 210 were recorded where P application rates were low (12–15 kg P ha^{-1}). In situations where AEN and AEP are low, it is important to increase N and P use efficiency through organic matter amendments that enhance both the indigenous nutrient supply and fertiliser N and P recovery efficiency. It is also important to increase P application rates on soils with high P adsorption capacity as a long-term investment. According to Batjes (2011), a one-time P application of about 600 kg ha^{-1} can be adequate for growing maize for 7–9 years on residual P. This high input strategy may be beyond the reach of smallholder farmers in East Africa (van der Eijk *et al.*, 2006), but they could be included in government subsidies.

This analysis also indicated conditions whereby the short- and long-term returns to investments in fertiliser can be too low (e.g., where grain yield is less than 3 t ha^{-1} or AEN and AEP are low) even though average yields may be higher than the control. While increasing crop yield is important for addressing household food security, the ability of farmers to continue to use fertiliser depends on the profitability of the crop. The use of NP fertiliser can benefit the environment because this will reduce the need to convert forests for agricultural use, while increasing soil organic carbon by promoting plant growth and biomass production. Improved varieties that give high yields remove large quantities of nutrient from the soil. Therefore, it is important to build the soil nutrient capital using organic and mineral fertiliser inputs. In addition to the supply of macronutrients (N, P and K), micronutrient deficiencies can also hold back the attainment of high crop yields in the region (Kihara *et al.*, 2017). Tailored application of specific nutrients where they are deficient is essential. Simply increasing NP fertiliser rates on some soils such as Plinthosols, Vertisols and Acrisols, however, may not increase yields.

Conclusions

The main conclusions from this analysis are fourfold: (1) application of the recommended NP fertiliser rate can be risky on some soils, particularly on Lixisols and Ferralsols that are either of low fertility and/or physical limitations, (2) fertiliser use is profitable on sites (and seasons) where maize grain yields exceed 3 t ha^{-1}, (3) profitability is associated with increasing the N and P use efficiency of the fertiliser applied and (4) growing maize without N and P inputs can result in reduced land productivity and profitability. Greater productivity growth may be achieved by shifting the emphasis from merely increasing the quantity of NP fertiliser to a more efficient use of nutrients. We recommend increasing N and P use efficiency on farmers' fields through better targeting of fertilisers to responsive soils, training farmers to correctly time applications and help them adopt other good agronomic practices, including the use of improved seeds. We also recommend greater investments in farmer participatory trials such as the mother-and-baby trial design across different landscape positions as this can be a very effective platform for enhancing experimentation and learning by farmers. Such trials can also generate valuable data and insights into the conditions under which input use can be risky or unprofitable. In addition, this approach can generate the necessary data needed to establish site-specific nutrient recommendations and decision support tools to guide farmers and the extension staff to improve fertiliser use efficiency. This requires greater investment in research on better targeting of fertiliser application within the framework of integrated soil fertility management to improve the profitability of fertiliser use and reduce financial risks associated with use in space and time. Future studies need to close our current knowledge gaps in crop response to fertilisers and nutrient use efficiency on the other soil types and landscape positions.

Supplementary material. To view supplementary material for this article, please visit https://doi.org/10.1017/S001447972200014X

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References

Abate T., Shiferaw B., Menkir A., Wegary D., Kebede Y., Tesfaye K., Kassie M., Bogale G., Tadesse B. and Keno T. (2015). Factors that transformed maize productivity in Ethiopia. *Food Security* **7**, 965–981. doi: 10.1007/s12571-015-0488-z

Batjes N.H. (2011). Global distribution of soil phosphorus retention potential. *Wageningen, ISRIC—World Soil Information (with dataset), ISRIC Report 2011/06.* https://library.wur.nl/WebQuery/wurpubs/fulltext/185289

Calvino P.A., Andrade F.H. and Sdras V.O. (2003). Maize yields as affected by water availability, soil depth and crop management. *Agronomy Journal* **95**, 275–281. doi: 10.2134/agronj2003.2750

Dewitte O., Jones A., Spaargaren O., Breuning-Madsen H., Brossard M., Dampha A., Deckers J., Gallali T., Hallett S., Jones R., Kilasara M., Le Roux P., Michéli E., Montanarella L., Thiombiano L., van Ranst E., Yemefack M. and Zougmore R. (2013). Harmonisation of the soil map of Africa at the continental scale. *Geoderma* **212**, 138–153. doi: 10.1016/j.geoderma.2013.07.007

Duflo E., Kremer M. and Robinson J. (2008). How high are rates of return to fertilizer? Evidence from field experiments in Kenya. *American Economic Review* **98**, 482–488. doi: 10.1257/aer.98.2.482

IUSS. (2014). World Reference Base for Soil Resources 2014. International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106. FAO, Rome. http://www.fao.org/3/i3794en/I3794en.pdf

Jama B., Kimani D., Kiwia A., Rebbie H. and Sileshi G.W. (2017). Maize yield response, nitrogen use efficiency and financial returns to fertilizer on smallholder farms in southern Africa. *Food Security* **9**, 577–593. doi: 10.1007/s12571-017-0674-2

Jones A., Breuning-Madsen H., Brossard M., Dampha A., Deckers J., Dewitte O, Hallett S., Jones R., Kilasara M., Le Roux P., Micheli E., Montanarella L, Spaargaren O., Tahar G., Thiombiano L., van Ranst E., Yemefack M. and Zougmore R. (Eds.) (2013). *Soil Atlas of Africa.* Luxembourg: European Commission. doi: 10.2788/52319

Kalkuhl M., von Braun J. and Torero M. (2016). Volatile and extreme food prices, food security, and policy: An overview. In Kalkuhl M., von Braun J. and Torero M. (eds), *Food Price Volatility and Its Implications for Food Security and Policy.* Cham: Springer, pp. 3–31. doi: 10.1007/978-3-319-28201-5_1

Kamanga B.C.G., Waddington S.R., Robertson M.J. and Giller K.E. (2010). Risk analysis of maize-legume crop combinations with smallholder farmers varying in resource endowment in central Malawi. *Experimental Agriculture* **46**, 1–21.

Kelly V.A. (2006). *Factors Affecting Demand for Fertilizer in Sub-Saharan Africa.* Agriculture and Rural Development Discussion Paper 23. Washington, DC: The World Bank.

Kihara J., Huising J., Nziguheba G., Waswa B.S., Njoroge S., Kabambe V., Iwuafor E., Kibunja C., Esilaba A.O. and Coulibaly A. (2016). Maize response to macronutrients and potential for profitability in sub-Saharan Africa. *Nutrient Cycling in Agroecosystems* **105**, 171–181. doi: 10.1007/s10705-015-9717-2

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

Kihara J., Sileshi W.G., Nziguheba G., Kinyua M., Zingore S. and Sommer R. (2017). Application of secondary nutrients and micronutrients increase crop yields in sub-Saharan Africa. *Agronomy for Sustainable Development* **37**. doi: 10.1007/s13593-017-0431-0

Kisinyo P.O., Opala P.A., Palapala V., Gudu S.O., Othieno C.O. and Ouma E. (2015). Micro-dosing of lime, phosphorus and nitrogen fertilizers effect on maize performance on an acid soil in Kenya. *Sustainable Agriculture Research* **4**, 21–30. doi: 10.5539/sar.v4n2p21

Kiwia A.M., Kimani D., Harawa R., Jama B. and Sileshi G.W. (2019). Sustainable intensification with cereal-legume intercropping in Eastern and Southern Africa. *Sustainability* **11**, 2891. doi: 10.3390/su11102891

Ladha J.K., Pathak H., Krupnik T.J., Six J. and van Kessel C. (2005). Efficiency of fertilizer nitrogen in cereal production: Retrospects and prospects. *Advances in Agronomy* **87**, 85–156. doi: 10.1016/S0065-2113(05)87003-8

Langemeier M. (2015). *Measuring Risk and Uncertainty*. Lafayyette, Indiana: Purdue University Center for Commercial Agriculture.

Lyon B. and Dewitt D.G. (2012). A recent and abrupt decline in the East African long rains. *Geophysical Research Letters* **39**, 1–5. doi: 10.1029/2011GL050337

Mourice S.K., Rweyemamu C.L., Nyambilila A.A. and Tumbo S.D. (2014). Narrowing maize yield gaps under rain-fed conditions in Tanzania: Effect of small nitrogen dose. *Tanzania Journal of Agricultural Sciences* **12**, 55–65. 114273-Article Text-319030-1-10-20150313.pdf

Mulinge W., Gicheru P., Murithi F., Maingi P., Kihiu E., Kirui O.K. and Mirzabaev A. (2016). Economics of land degradation and improvement in Kenya. In Nkonya E. et al. (eds), *Economics of Land Degradation and Improvement – A Global Assessment for Sustainable Development*. Cham: Springer, pp. 471–498.

Mutegi J., Ameru J., Harawa R., Kiwia A.M. and Njue A. (2018). Soil health and climate change: Implications for food security in Sub-Saharan Africa. *International Journal of Development and Sustainability* **7**, 21–33. http://eprints.icrisat.ac.in/id/eprint/15864

Omoyo N.N., Wakhungu J. and Oteng S. (2015). Effects of climate variability on maize yield in the arid and semiarid lands of lower eastern Kenya. *Agriculture and Food Security* **4**. doi: 10.1186/s40066-015-0028-2

Palm C.A., Myers R.J.K. and Nandwa S.M. (1997). Combined use of organic and inorganic nutrient sources for soil fertility maintenance and replenishment. In Buresh R.J. and Calhoun F. (eds), *Replenishing Soil Fertility in Africa*. Madison, WI, USA: SSSA Special Publication 51, pp. 193–217.

Sánchez P.A. (2015). En route to plentiful food production in Africa. *Nature Plants* **1**, 1–2. doi: 10.1038/nplants.2014.14

Sattari S.Z., Bouwman A.F., Giller K.E. and van Ittersum M.K. (2012). Residual soil phosphorus as the missing piece in the global phosphorus crisis puzzle. *Proceedings of the National Academy of Science USA* **109**, 6348–6353. doi: 10.1073/pnas.1113675109

Shi, W. and Tao, F. (2014). Vulnerability of African maize yield to climate change and variability during 1961–2010. *Food Security* **6**, 471–481. doi: 10.1007/s12571-014-0370-4

Shiferaw B., Tesfaye K., Kassie M., Abate T., Prasanna B.M. and Menkir A. (2014). Managing vulnerability to drought and enhancing livelihood resilience in sub-Saharan Africa: Technological, institutional and policy options. *Weather and Climate Extremes* **3**, 67–79. doi: 10.1016/j.wace.2014.04.004

Sileshi G., Akinnifesi F.K., Debusho L.K., Beedy T., Ajayi O.C. and Mong'omba S. (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

Sileshi G.W., Jama B., Vanlauwe B., Negassa W., Harawa R., Kiwia A.M. and Kimani D. (2019). Nutrient use efficiency and crop yield response to the combined application of cattle manure and inorganic fertilizer in sub-Saharan Africa. *Nutrient Cycling in Agroecosystems* **113**, 181–199. doi: 10.1007/s10705-019-09974-3

Simtowe F.P. (2006). Can risk-aversion towards fertilizer explain part of the non-adoption puzzle for hybrid maize? Empirical evidence from Malawi. *Journal of Applied Science* **6**, 1490–1498. https://ssrn.com/abstract=939398

Smith A., Snapp S.S., Chikowo R., Thorne P., Bekunda M. and Glover J. (2017). Measuring sustainable 709 intensification in smallholder agroecosystems: A review. *Glob Food Security* **12**, 127–138. doi: 10.1016/j.gfs.2016.11.002

Snapp S.S., Blackie M.J. and Donovan C. (2003). Realigning research and extension to focus on farmers' constraints and opportunities. *Food Policy* **28**, 349–363. doi: 10.1016/j.foodpol.2003.08.002

Snyder C.S. and Bruulsema T.W. (2007). *Nutrient Use Efficiency and Effectiveness in North America: Indices of Agronomic and Environmental Benefit*. Ref. # 07076, Georgia, USA: International Plant Nutrition Institute (IPNI).

Spilke J., Piepho H.P. and Hu X. (2005). Analysis of unbalanced data by mixed linear models using the mixed procedure of the SAS System. *Journal of Agronomy and Crop Sciences* **191**, 47–54. doi: 10.1111/j.1439-037X.2004.00120.x

UN Millennium Project. (2005). *Halving Hunger: It Can Be Done*. Summary version of the report of the Task Force on Hunger. New York, USA: The Earth Institute at Columbia University.

van der Eijk D., Janssen B.H. and Oenema O. (2006). Initial and residual effects of fertilizer phosphorus on soil phosphorus and maize yields on phosphorus fixing soils. A case study in south-west Kenya. *Agriculture, Ecosystem and Environment* **116**, 104–120. doi: 10.1016/j.agee.2006.03.018

Wambugu P.W., Mathenge P.W., Auma E.O. and vanRheenen H.A. (2012). Constraints to on-farm maize (Zea mays L.) Seed production in Western Kenya: Plant growth and yield. *International Scholarly Research Network Agronomy*. doi: 10.5402/2012/153412

World Bank. (2015). Lending interest rate (%). Available at http://data.worldbank.org/indicator/FR.INR.LEND/countries (Accessed 08 September 2015).

Yang W., Seager R., Cane M.A. and Lyon B. (2014). The East African long rains in observations and models. *Journal of Climate* **27**, 7185–7202. doi: 10.1175/JCLI-D-13-00447.1

Xu Z., Guan Z., Jayne T. and Black R. (2009). Factors influencing the profitability of fertilizer use on maize in Zambia. *Agricultural Economics* **40**, 437–446.

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