Research Square

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Nutrient profiles govern organic-mineral fertilizer interactions on maize yield in Kenya

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Abstract

Co-applying mineral and organic nutrient inputs is widely recommended to enhance maize yields and soil fertility in sub-Saharan Africa. However, long-term on-farm evaluations that assess how input combinations, baseline soil fertility, and climatic conditions affect yield trajectories remain scarce.

Over 10 seasons (5 years), this study investigated maize yield and agronomic nitrogen- and phosphorus use efficiencies (AEN; AEP) across 20 farms in two Kenyan counties (Vihiga and Siaya, ~ 48% and 64% clay content, respectively), comparing high- and low-fertility fields. Treatments evaluated local versus improved maize varieties (IR maize) and the addition of multi-component fertilizer (MCF), farmyard manure, and calcium-ammonium-nitrate (CAN) top-dressing in an additive split-plot design (only to IR maize).

While combining all three inputs (MCF, manure, and CAN) achieved the highest overall yields, no treatment could significantly increase yields over time, highlighting the challenge of achieving positive temporal trends in continuous maize monoculture at realistic input rates. A significant negative interaction between MCF and manure negated ~ 70% of manure's positive effect, potentially due to overlapping nutrient profiles. MCF significantly outperformed manure, showing higher yields and AEN values (39–43 kg yield kg^{-1} N); AEP was highest under manure combined with CAN (52–62 kg yield kg^{-1} P). CAN provided a modest yield benefit (+ 141 kg ha^{-1} $season^{-1}$), showing no negative interactions with MCF or manure.

Our findings suggest that effective plant nutrition in smallholder systems should focus on complementing nutrient profiles and consider both current yield and yield trajectories.

1. Introduction

Despite maize being one, if not the most important staple crop in eastern Africa, the yields that most smallholder farmers achieve are often low compared to global averages. For example, between 2014 and 2023, maize yields in eastern Africa averaged 1.9 t ha^{-1} $season^{-1}$, while globally they averaged at 5.7 t ha^{-1} $season^{-1}$ in the same period (FAO 2025). Additionally, declining soil fertility over time, a consequence of long-term farming with insufficient nutrient replacement (Cobo et al. 2010; Falconnier et al. 2023), is common in many farmers' fields. This degradation is often more severe in fields that are far away from the homestead and/or market infrastructure because they receive low inputs (Vanlauwe et al. 2015; Kayani et al. 2021).

To combat soil fertility problems and to increase soil fertility, several practices, such as increasing mineral fertilizer inputs (Sanchez 2015), increasing organic resource inputs (Bautze et al. 2024), improved varieties (Vanlauwe et al. 2011), or combinations of several practices in umbrella terms such as conservation agriculture (Hobbs 2007), integrated soil fertility management (Vanlauwe et al. 2015), or regenerative agriculture (Giller et al. 2021b), have been suggested as potential solutions. The individual components are targeted at different soil fertility issues, offering the potential for both synergistic and redundancy effects (MacLaren et al. 2022). Multi-component fertilizers are targeted at soils with multiple nutrient deficiencies, supplying not only nitrogen, phosphorus, and potassium but also secondary- and micronutrients, such as sulfur (S), calcium (Ca), magnesium (Mg), zinc (Zn), and boron (B) (Abuom et al. 2014; Vanlauwe et al. 2014). Their broader nutrient spectrum is particularly valuable in smallholder contexts, where soils are often deficient in multiple elements and where applying only a single macronutrient can leave other shortages unresolved, thereby limiting yield responses (Kihara et al. 2016a). Organic resources, such as farmyard manure, supply labile carbon and microbial substrates and can thus increase microbial biomass and improve soil structure, water retention, and soil organic matter if they are applied over longer time spans (Giller et al. 2021a). They also provide a range of plant nutrients that can be mineralized over time (Palm et al. 2001; Sileshi et al. 2025). Top-dressing of calcium-ammonium-nitrate (CAN) provides readily available nitrogen, allowing for rapid early- mid-season growth (Chivenge et al., 2011), but has limited to no effect on soil fertility indices such as soil organic carbon (SOC) (Laub et al. 2023a). Improved maize varieties are also recommended, mainly in combination with higher input levels, since they react more strongly to mineral fertilizers than traditional varieties and can show higher resistance to pests, such as striga (Vanlauwe et al. 2010; Nyangena and Juma 2014). Yet, despite their higher yield potential (Krishna et al., 2023), their adoption remains uneven, as factors such as seed cost, limited access to certified seed, and farmers' perceptions of variety attributes continue to pose challenges for many smallholders (Fisher et al., 2015; Nyangena and Juma, 2014). Local varieties, often passed down across generations, are commonly evaluated by farmers as being more tolerant to droughts or poor soils, having better taste and storage characteristics (Almekinders et al. 1994).

All the abovementioned components are aimed at different underlying soil fertility constraints and thus, there is the potential for synergistic effects when applying multiple inputs or nutrients in combination, which could affect both yield and long-term soil fertility trajectories. For example, it has been shown that long-term trajectories of yield and SOC can be correlated under conditions that are favorable for maize growth (Laub et al. 2025). A study in western Kenya showed that multi-component fertilizer (MCF) of the brand “Mavuno”, containing N, P, K, S, Ca, Mg, and micronutrients (trace amounts: B, Zn, Mo, Cu, and Mn) outperformed single-nutrient products, especially when integrated with organic inputs (Abuom et al. 2014). However, Vanlauwe et al. (2011), studying the effects of combining mineral N with organic resources, only found synergistic effects when organic resources alleviated nutrient deficiencies other than N, and redundancies when they mainly supplied N. They also found that the agronomic efficiencies of applied N depended on the baseline soil fertility. This is in alignment with recent research showing that local conditions, such as baseline SOC levels, soil fertility and soil properties, as well as moisture conditions, strongly influence the efficacy of fertilizer and/or soil amendment applications (Mutuku et al. 2020; Laub et al. 2023a). In fact, both high- and low-fertility soils can show no yield response to nutrient addition or soil amendments in up to 25% of cases, which is attributed to micronutrient imbalances, amongst others (Kihara et al. 2016b; Laub et al. 2023b). This context dependency calls for detailed studies of the efficacy of different combinations across different conditions and their influence on yield and yield development.

The context dependency may be especially critical where baseline soil fertility status varies widely, as low-fertility fields can respond more dramatically to organic inputs and balanced fertilizer, while in high-fertility fields, the balance between nutrient mining and overfertilization can be hard to achieve (Vanlauwe et al. 2014; Kihara et al. 2016a). In many smallholder systems, fields closer to the homestead tend to receive more inputs and thus maintain higher soil organic carbon, pH, and nutrient reserves, whereas distant fields accumulate fertility constraints over time (Tittonell et al. 2007). Given the resource and time constraints that many smallholder farmers face, it is important to know which specific measures are most effective and to which extent the efficacy is context- and time dependent. Furthermore, it is important to know in which situations the combination of several practices results in synergistic versus redundancy effects and whether this is influenced by soil fertility and feeds back to changes in soil fertility over time.

Against this background, the goal of this study was to analyze a number of on-farm trials conducted in two counties of Kenya, Siaya and Vihiga county, which have considerably different soil properties (i.e., Siaya soils have more clay and SOC compared to Vihiga soils). A specific focus of this study was to elucidate the influence of baseline soil fertility, clay content and rainfall on the maize yield response to different varieties and fertilizers and on their influence on yield trajectories. The study established plots on two different fields per farmer; the field that the farmers considered to be the highest fertility one, and the one they considered to be the least fertile. It tested local maize varieties compared to improved varieties, the application of farmyard manure vs a multi component fertilizer, and the combination of both. Finally, it tested the importance of additional nitrogen provision via the calcium-ammonium-nitrate top-dressing (CAN) in a split-plot setup, but only in the treatments already receiving external inputs.

The following questions and hypotheses guided our research:

RQ1

How do different input treatments and treatment components influence maize yields and what is the mediation effect of soil fertility status, clay content and rainfall?

We hypothesized that the combination of manure, multi-component fertilizer and CAN would lead to the best yields and that soils with higher clay content would have higher yields. We also hypothesized that clay-poor soils would have higher yields with farmyard manure addition, while clay-rich soils would have higher yields with multi-component fertilizer. Additionally, we hypothesized that, due to the relatively similar nutrient profiles, there would be redundancies between farmyard manure addition and multi-component fertilizer, while CAN, mainly supplying N, would have positive interactions with the other inputs that are relatively richer in other nutrients. Lastly, we hypothesized higher yields in the high- compared to low-fertility fields and a unimodal change of yield with rainfall.

RQ2

Do fields with a differing fertility status require different combinations and amounts of inputs to achieve a good yield?

We hypothesized that in the high-fertility fields, the multi-component fertilizer alone would be sufficient to achieve high yields (i.e., at the same level as all inputs combined, with no benefit of the addition of manure over the sole addition of mineral fertilizers), while in low fertility fields only the combination of all three inputs would provide maximum yields.

RQ3

How do the maize yields of different treatments change over time (as proxy for soil fertility changes) and how is this influenced by the fertility status, clay content, and rainfall?

We hypothesized that treatments with no additions would lose yields over time, most strongly in the fertile fields with low clay content, because there would be more fertility to be lost. In contrast, we hypothesized that treatments receiving a combination of mineral fertilizer and manure would increase yields over time in the low-fertility fields (due to soil fertility and SOC increase) and maintain yields in the high-fertility fields, eventually leading to no difference between low-fertility and high-fertility site at the end of the experiment. However, those with only a single input would not increase/maintain yields.

2. Material and Methods

2.1 Site information

The study was conducted in Kenya in the counties Siaya (0.06 °N, 34.29 °E) and Vihiga (0.06 °N, 34.72 °E). Both counties are located in the humid tropics, receiving about 1850 mm of precipitation per year, with two distinct rainy seasons from March to August (long rainy season; LRS; around 1070 mm) and from September to January (short rainy season; SRS; around 720 mm). The mean annual temperatures are also very similar; in Siaya ~ 22°C and in Vihiga ~ 20°C. Siaya is located at an altitude between 1200 and 1300 m asl., Vihiga between 1400 and 1600 m asl. The soils in Siaya county, with mean C contents of 21 g kg^{-1} (range from 14 to 31 g kg^{-1}), mean N contents of 1.9 g kg^{-1} (1.4 to 2.6 g kg^{-1}), a mean pH of 6 (5.5 to 6.8), 64% clay (52 to 74%), and 19% sand on average (12 to 32%) are more fertile than those of Vihiga with mean C contents of 17 g kg^{-1} (9 to 24 g kg^{-1}), mean N contents of 1.4 g kg^{-1} (0.9 to 1.9 g kg^{-1}), a mean pH of 5.7 (5.1 to 6.3), 48% clay (32 to 58%), and 36% sand (26 to 56%) on average (Fig. S1).

2.2 Experimental setup

Table 1
Overview of the soil fertility at the start of the experiments by county and pre-identified soil fertility status. Site and fertility status combinations not sharing any lowercase letter differ statistically within each soil property ($p < 0.05$).

County	Fertility status	n	SOC (g kg^{-1})		TN (g kg^{-1})		pH		Clay (%)		Sand (%)	P (mg/kg)	
			mean ± SD	range	mean ± SD	range	mean ± SD	range	mean ± SD	range	mean ± SD	mean ± SD	range
Siaya	high	50	21.5 ± 4.3^{a}	14.4–31.5	1.92 ± 0.3^{a}	1.47–2.65	6.1 ± 0.3^{a}	5.5–6.8	62 ± 5^{b}	52–71	20 ± 5^{c}	11 ± 12^{a}	1–55
Siaya	low	49	20.4 ± 3.1^{bc}	14.4–25.9	1.79 ± 0.19^{b}	1.42–2.18	5.9 ± 0.2^{bc}	5.6–6.4	66 ± 4^{a}	57–74	17 ± 3^{d}	6 ± 6^{b}	1–24
Vihiga	high	50	17.0 ± 3.9^{ab}	9.4–24.5	1.46 ± 0.28^{c}	0.89–1.92	5.8 ± 0.0b^{b}	5.1–6.4	46 ± 6^{d}	32–56	38 ± 8^{a}	6 ± 4^{ab}	2–25
Vihiga	low	50	16.0 ± 4.0^{c}	9.9–22.4	1.41 ± 0.27^{c}	0.98–1.87	5.7 ± 0.3^{c}	5.1–6.1	49 ± 5^{c}	36–58	35 ± 6^{b}	4 ± 1^{b}	2–9

The experiments were carried out on 10 farms per county, in two distinct fields per farm. To choose the fields, each farmer was asked to delineate their most fertile and least fertile field, according to their own assessment. These delineations were later confirmed by laboratory measurements of soil samples taken from each field (Table 1). For example, high fertility fields in Siaya had a mean SOC content of 21.5 g kg^{-1} with significantly lower values in low fertility field (by 1.1 g kg^{-1}), pH was 6.1 (significantly

lower by 0.2 in low fertility fields), and clay content was 62% (significantly higher by 4% in low fertility fields). In the high fertility fields in Vihiga mean SOC content was 17 g kg^{-1} (significantly lower by 1.0 g kg^{-1} in low fertility fields), pH was 5.8 (significantly lower by 0.1 in low fertility fields), and clay content was 46% (significantly higher by 3% in low fertility fields).

The experiments were carried out as an additive split plot design, with five main treatments. The first two main treatments were i) growing a local variety compared to ii) an improved variety (IR maize) of maize, both of which were grown without any addition of external inputs. The other treatments were iii) IR maize grown with the addition of farmyard manure (from cowsheds) prior to planting at a dry matter rate of 2 t ha^{-1} $season^{-1}$ (typical nutrient contents: 1.2–1.4% N, 0.4–0.6% P, 1.3–1.6% K, 0.6–0.8% Ca, 0.3–0.5% Mg, 0.02–0.13% S (Sileshi et al. 2017); thus for further calculations, we assumed that manure would be supplying a mean rate of 26 kg N, 10 kg P, 29 kg K, 14 kg Ca, 8 kg Mg, and 1.5 kg S ha^{-1} $season^{-1}$) iv) IR maize grown with the addition of MCF at a rate of 150 kg ha^{-1} $season^{-1}$ (having 10% N, 11.3% P, 8.3% K, 5.8% Ca, 2.4% Mg, 4% S and traces of B, Zn, Mo, Cu, Mn, thus supplying 15 kg N, 17 kg P, 12.5 kg K, 8.7 kg Ca, 3.6 kg Mg, and 6 kg S ha^{-1} $season^{-1}$; 1/3rd as basal application, 2/3rds as top dressing at six weeks after planting) v) IR maize grown with the addition of MCF and manure in combination.

The split plots were the addition of 100 kg ha^{-1} $season^{-1}$ calcium-ammonium-nitrate as top-dressing (CAN; 30% N, 10% Ca, 5% S, supplying 30 kg N, 10 kg Ca, and 5 kg S ha^{-1} $season^{-1}$) on half of the plot, which was only done in treatments iii to v. The full plots had a dimension of 6 × 4.2 m, the split plots 6 × 2.1 m (Fig. S2). The longer side of the plots were oriented in a north-south direction. To avoid border effects, a strip of 0.375 m on top and below the plots and a strip of 0.5 m left and right of the plots were not included in the measurements. In the split plots, an additional strip of 0.5 m width between the two split plots was also excluded, leading to a net plot area of 16.8 m^2 per full plot and 7.08 m^2 per split plot (Fig. S2). In each field, the five main treatment plots were located next to each other, the location of each treatment and the location of the CAN split plot were randomly chosen.

2.3 Field management and harvest

As the first step of land preparation each season, the organic resources were evenly spread across the plots that received them. Then, all plots were ploughed with a hand hoe to 15–20 cm soil depth to prepare fields for planting, thereby also incorporating the applied organic resources. The date for planting was chosen by each farmer individually, based on his/her assessment of the rainy season having started. All plots of each individual farmer were planted at the same dates, with dates differing between farmers and seasons.

The planting was conducted in the same way on all experimental fields. The spacing was 75 × 25 cm (i.e., 53,300 plants ha^{-1}). Two seeds per hill were planted and later thinned to one plant per hill. Three weeding events were done up until 10 weeks after planting, when the maize usually started to outcompete all weeds. The planted improved variety was the striga-resistant IR OPV, except in the year 2009 where availability issues led to a switch to W303. The local varieties were WS403 in 2005, H513 in 2006, H514 in 2007, DH04 in 2008 and 2009 and WS505 in 2010 (Table S1).

Similar to the planting, harvest dates were individually selected by the farmers with all plots from each individual farmer being harvested at the same date. At harvest, the net plot was demarcated, leaving a 50 cm margin on both ends and excluding the outer lines (37.5 cm). All plants within the net plot were cut at the soil surface level and counted. The ears were separated from the stovers and counted. The fresh weight of the stovers and ears was measured separately using a field balance. The stover of three maize plants was subsampled for oven dry weight computation. The ears were shelled, and the fresh grain weight was recorded. A subsample of the grain was taken for oven dry weight assessment. All yields are given on a dry matter basis.

2.4 Calculation of agronomic use efficiency of applied N

The agronomic use efficiency of applied total N (AEN), was calculated according to Vanlauwe et al. (2011), considering all N that was applied through MCF, manure, and CAN fertilizer. The same was done for the agronomic use efficiency of applied total P (AEP).

$$AEN\ \left(kg\ yield\ kg^{-1}\ N\right) = \frac{Y_{TRT} - Y_{CT}}{N\ applied}$$

1

$$AEP\ \left(kg\ yield\ kg^{-1}\ P\right) = \frac{Y_{TRT} - Y_{CT}}{P\ applied}$$

2

Here, Y_{TRT} and Y_{CT} correspond to the yields of each treatment and the control (IR maize without any inputs), respectively, P and N applied to total amounts from all sources (manure, MCF and CAN). Extreme outliers with values that were at least 3 standard deviations from the mean were removed from the datasets of AEN and AEP.

2.5 Statistical analysis

For the analyses, we made use of R software version 4.4.3 (R Core Team 2025) in the Rstudio environment v2024.12.0, using the packages nlme (Pinheiro et al. 2016), MASS (Venables and Ripley 2002), emmeans (Lenth 2020), multcomp (Hothorn et al. 2008), and ggplot2 (Wickham 2016).

To answer our research questions, we performed mixed linear model analysis, to account for autocorrelation in the data. Yield, AEN and AEP were the dependent variables. Yield had to be square-root transformed to ensure homoscedasticity and normality of residuals. The random effect structures were similar for all models, consisting of nested random effects of the individual plot (the unit on which measurements were repeated) nested in a particular field (high or low fertility), which was nested in a particular farm. Furthermore, the model accounted for temporal autocorrelation of the residuals using an exponential correlation structure, assuming that the correlation between observations from the same plot decreases as the time interval between them increases. To determine which fixed effects to have in the final model, we used the automatic backwards elimination of the MASS package (stepAIC), which sequentially removes all non-significant fixed effects based on model Akaike information criterion (AIC), starting with the highest level of interactions. We started with the highest level of interactions of fixed effects (e.g., four-way interaction between clay content, fertility status, rainfall, and treatment). As is typical for mixed models, the selection of fixed effects was done using maximum likelihood, and then the final model fit using restricted maximum likelihoods (Zuur et al., 2009).

Instead of choosing categorial covariates to explain differences in yield, such as long- or short rainy season or county, we aimed for continuous covariates with biophysical meaning. Rainfall was chosen as a continuous covariate that represented between season differences, while clay content was chosen as a continuous covariate that was mostly independent of previous management and represented differences between counties. To analyze which of the treatments performed best overall, we used a model type with treatment, clay content, rainfall (derived from intersecting rainfall data per county (obtained from the NASA “Tropical Rainfall Measuring Mission”), with planting and harvesting dates), fertility status, and all their possible four way and lower interactions as fixed effects. To account for the hypothesized nonlinear responses of yield to rainfall, we also added a quadratic term for rainfall. To maintain model parsimony and limit computational complexity, we restricted the quadratic rainfall term to two-way interactions with other covariates, while the linear rainfall term could have higher order interactions. This model type was used to analyze the data of yield, AEN, and AEP. Note that the treatments in this type of model represent the combination of all different measures that were applied (e.g., IR maize with manure, MCF, and CAN was a single treatment).

To estimate the effect of individual treatment factors (such as individual manure or MCF addition) on yield, we split the factorial treatment variables of the model with yield as dependent variables into binary variables, representing variety (IR or local), and the absence or presence of the application of CAN, manure, MCF. The model also contained the interaction between MCF and manure (due to the presence of a treatment that applied both). Additionally, we tested all interactions that were needed to answer our research questions (of manure, MCF, and CAN with each other), even if removed in the final model. To make effect sizes interpretable, we backtransformed them by adding them individually to the median yield (1150 kg ha^{-1}) on the square root transformed scale, then backtransforming and calculating the difference at that yield level.

To analyze the yield development over time, we expanded the first model type, adding a temporal trend. This model therefore had the fixed effects time since experiment start, treatment, clay content, rainfall, fertility status, and all their potential interactions. This model had one addition to the nested random intercepts that all models had, namely random slopes of the temporal effect at the farm and field level (but not at the plot level, which, according to AIC, would have been overfitting).

After each model was fit, we visually assured to meet model assumptions of homoscedasticity and normality of residuals (plotting residuals vs fitted values, histograms of residuals, and qqplots). Independence of residuals was ensured by plotting residuals against each independent variable. In the case of the AEN and AEP models, this was initially not the case, and thus we had to allow treatment specific variances to comply with model assumptions.

To visualize the results, we created post-hoc predictions of least square means (and trends for the temporal model), adjusting the degrees of freedom based on the “sidak” method. The “cld” function was used to derive a letter design from the post-hoc predictions, displaying in which cases yields differed by treatments, fertility status, and other explanatory covariates (Piepho 2004). In the case that clay content was a significant predictor, we displayed the post-hoc predictions per county-typical clay content. Finally, all post hoc predictions that represented transformed data (2nd root of yield), including 95% confidence intervals, were backtransformed to make results easier to interpret.

3. Results

3.1 Mean performance per treatment and by county-typical clay contents

Combining data from all seasons, yields were consistently lowest for the unfertilized treatments, both with the local and the IR maize variety, and they were consistently highest with the IR maize variety combined with MCF, manure, and CAN. Without inputs, the local variety tended to have higher yields than the IR maize variety, but the effect was not significant in the model that combined the variety and all inputs into a single “treatment” variable (Fig. 1).

Clay content had significant ($p < 0.001$) two-way interactions with rainfall and rainfall² (Table 2). Yields were generally highest at intermediate rainfall levels, but at 48% clay content (mean of Vihiga county) maize yields were better at very low compared to very high rainfall levels, while at 64% clay content (mean of Siyaya county) this was the opposite (Fig. 1). However, rainfall and clay content did not interact with the treatment effects, which were similar across all conditions. For example, with mean yields around 2200 kg ha^{-1} $season^{-1}$ at 64% clay content, high fertility, and medium rainfall (650 mm), the treatment combining MCF, manure, CAN and IR maize significantly out-yielded not only the two unfertilized treatments (around 1040 to 1180 kg ha^{-1} $season^{-1}$) but also the IR maize treatments that either only received MCF, manure, or manure plus CAN (around 1550 to 1860 kg ha^{-1} $season^{-1}$). The yield reduction per treatment at low rainfall amounts (320 mm per season, representing the 10th quantile of rainfall) compared to medium rainfall ranged from 270 to 420 and from 560 to 860 kg ha^{-1} $season^{-1}$ at 48% and 64% clay content, respectively. For 1240 mm per season (representing the 90th quantile) compared to medium rainfall it ranged from 430 to 690 and from 370 to 570 kg ha^{-1} $season^{-1}$ lower at 48% and 64% clay content, respectively. Apart from that, both treatments that did not receive any fertilizer inputs had significantly lower yields than any of treatments with inputs under any conditions. Further, the treatments that received MCF had significantly higher yields than the treatments that received manure, regardless of whether CAN was added or not. Fertility status had a significant effect ($p < 0.01$), but no interactions with any other effect.

Table 2
Analysis of variance table for the model with yield (2nd root) as response variable and the treatment, clay content, fertility status, and seasonal rainfall as independent variables. Displayed are the type 3 significance tests that remained significant after backwards elimination of non-significant effects, starting with all possible two, three, and four way interactions. Autocorrelation in the data (due to up to 10 seasons) were accounted for by random intercepts for each plot nested in field and farm.

(Intercept)	**Chisq**	**Df**	**Pr(> Chisq)**	
	19.91564674	**1**	**8.09E-06**	*******
Clay content (g g^{-1})	13.01346508	1	0.0003	***
Rainfall (mm $season^{-1}$)	3.03806637	1	0.0813	
Rainfall²	0.216703688	1	0.6416	
Fertility status	6.629936604	1	0.0100	**
Treatment	327.9324429	7	6.49E-67	***
Clay content : rainfall	21.66127268	1	3.25E-06	***
Clay content : rainfall²	11.44023301	1	0.0007	***

3.2 Importance of treatment components and interactive effects between them

Also in the model in which the treatment effects were represented by boolean variables of the individual components (i.e., maize variety, MCF, manure, CAN, and fertility status), there were no significant interactions of treatment components with rainfall and clay content. However, the interaction between manure and MCF was highly significant ($p < 0.001$) and had an effect size of -5.01 (kg yield $ha^{-1})^{0.5}$ (Table 3). Due to the transformation, these values are difficult to interpret, but for a median yield level of 1150 kg ha^{-1}, this effect would translate into − 315 kg ha^{-1}. Nevertheless, individual treatment effects were significant, with the local variety having an effect size of 2.13 (kg yield $ha^{-1})^{0.5}$ (or, backtransformed, 149 kg ha^{-1} at median yields) more yield than the IR variety (note that this comparison is only valid for the case of no inputs), manure additions having a effect size of 7.11 (kg yield $ha^{-1})^{0.5}$ or 533 kg ha^{-1} at median yields, MCF having 10.59 (kg yield $ha^{-1})^{0.5}$ or 830 kg ha^{-1} at median yields, CAN having 1.7 (kg yield $ha^{-1})^{0.5}$ or 118 kg ha^{-1} at median yields, and low fertility fields having an effect size of -4.41 (kg yield $ha^{-1})^{0.5}$ compared to high fertility fields or -279 kg ha^{-1} at median yields. Interactions of CAN and either manure or MCF were initially included to test for positive interactions between these components but they were nonsignificant ($p > 0.05$) and therefore removed in the final model. In summary, this meant that, as the first model already showed, MCF had a stronger effect than manure. Furthermore, the negative interactive effect of MCF and manure canceled out about 70% of the positive effect of the manure, showing clear redundancies between MCF and manure.

Table 3
Analysis of variance table for the model with the square root of yield as response variable and the treatment, dissected into variety, manure, multi-component fertilizer (MCF) and top-dressing of calcium-ammonium-nitrate (CAN), fertility status, clay content, and seasonal rainfall, as independent variables. The model was derived from the final model of Table 2, by splitting the treatment effect into individual binary variables. Displayed are the type 3 significance tests. Autocorrelation in the data (due to up to 10 seasons) were accounted for by random intercepts for each plot nested in field and farm.

(Intercept)	**Chisq**	**Df**	**Pr(> Chisq)**		**Fixed effects coefficients ± standard error** $(kg\ ha^{-1})^{1/2}$
	18.0642	**1**	**2.14E-05**	***	**42.99 ± 10.11**
Clay content ($g\ g^{-1}$)	13.0135	1	0.0003093	***	-63.51 ± 17.61
Rainfall (mm $season^{-1}$)	3.0381	1	0.0813327		-0.04 ± 0.02
Rainfall²	0.2167	1	0.6415631		1e-5 ± 1.4e-5
Fertility status (low = 1)	6.6299	1	0.0100279	**	-4.41 ± 1.71
Variety (local = 1)	3.9464	1	0.0469715	*	2.13 ± 1.07
Manure (yes = 1)	44.9186	1	2.05E-11	***	7.11 ± 0.97
MCF (yes = 1)	104.7724	1	< 2.2e-16	***	10.59 ± 0.96
CAN (yes = 1)	0.1885	1	0.6641871		1.7 ± 0.61
Manure:MCF (both present = 1)	13.282	1	0.000268	***	-5.01 ± 1.22
Clay content : rainfall	21.6613	1	3.25E-06	***	0.18 ± 0.04
Clay content : rainfall²	11.4402	1	0.0007187	***	8e-5 ± 2.4e-5
Manure:CAN[x]	0.0787	1	0.7790574		
MCF:CAN[x]	0.3863	1	0.5342556		

[x]Removed in the final model, but added to test for a significant interaction between Manure or MCF with CAN

3.3 Temporal developments of yield

While a significant ($p < 0.05$) four way interaction of clay content, rainfall, and fertility status with time existed (Table 4), the only significant interaction of treatment was the one with time. Analysis of the post-hoc estimates showed that the significant interactions with time since the start of the experiment mainly influenced the extent to which yields declined or were maintained over time. For example, at median rainfall levels of 650 mm $season^{-1}$, only the local variety without any inputs experienced significant declines in yield over time in all clay contents and fertility status (Fig. 2). However, at low rainfall amounts (320 mm $season^{-1}$), all treatments at the high clay content and all treatments in the high fertility at the lower clay content experienced significant declines in yield over time (Fig. S3); yields at the lower clay content and low fertility status being low from the start and therefore not further declining. Importantly, no rainfall and clay combination experienced significant yield increases over time, not even at high rainfall levels (Fig. S4). The interaction of treatment with time in this model led to a deterioration of treatment differences over time. Specifically, while many treatments differed in their yields in the first experimental year, the only differences at the last experimental year were those between the treatments that did not receive inputs (Local and IR treatment) to all other treatments (receiving either manure, MCF, CAN or combinations thereof; Fig. 2).

Table 4
Analysis of variance table for the model with yield (2nd root) as response variable and the time since experiment start, treatment, clay content, seasonal rainfall, and fertility status as independent variables. Displayed are the type 3 significance tests of the reduced model that contained all significant two and three way interactions. Autocorrelation in the data (due to up to 10 seasons) were accounted for by random slope and intercepts for the time effect for each farmer.

(Intercept)	**Chisq**	**Df**	**Pr(> Chisq)**	
	5.847	**1**	**0.0156**	*
Clay content (g g^{-1})	1.5717	1	0.20996	
Rainfall (mm $season^{-1}$)	1.9478	1	0.16283	
Rainfall²	1.8103	1	0.17847	
Fertility status	1.4231	1	0.23289	
Treatment	137.494	7	< 2.2e-16	***
Time (yrs)	0.2184	1	0.64028	
Clay content : rainfall	16.066	1	0.00006117	***
Clay content : rainfall²	22.7815	1	1.815E-06	***
Clay content : fertility status	0.3511	1	0.55347	
Rainfall : fertility status	3.1521	1	0.07583	.
Clay content : time	2.6662	1	0.1025	
Rainfall : time	0.8445	1	0.3581	
Fertility status : time	5.6919	1	0.01704	*
Treatment : time	16.331	7	0.02226	*
Clay content : rainfall : fertility status	2.2319	1	0.13519	
Clay content : rainfall : time	2.4386	1	0.11838	
Clay content : time : fertility status	3.645	1	0.05624	.
Rainfall : fertility status : time	5.5412	1	0.01857	*
Clay content : rainfall : fertility status :time	3.9928	1	0.04569	*

3.4 Agronomic use efficiency of nitrogen and phosphorus application

Generally, agronomic use efficiency of nitrogen application (AEN) had a high variability, ranging from − 83 to 127 kg yield kg^{-1} total N application. Despite this variability, some significant clay-content and soil-fertility specific differences existed and as for yield, values were highest at intermediate rainfall levels (Table S2). Interestingly, the treatments did not significantly interact with any other covariate. The treatments that only received MCF had significantly higher AEN than any other treatment at both clay contents and soil fertility status (39 to 43 kg yield kg^{-1} total N application at intermediate rainfall levels; Fig. 3). On the other end of the spectrum, the treatment that received manure and CAN had significantly lower AEN values than any other treatment (9 to 14 kg yield kg^{-1} total N application). The treatment that received all inputs had significantly lower AEN than the treatments receiving either only MCF, MCF plus manure, or MCF plus CAN. Significant interactions of clay content with rainfall and soil fertility status led to significantly lower AEN in the low compared to high fertility status but only at 64% clay content. Additionally, it led to significantly lower AEN at 48% clay than at 64% clay, but only in the high fertility fields and at intermediate and high rainfall levels.

The pattern of significantly lower values in the low fertility compared to the high fertility soils at 64% clay content was also seen in AEP, and so were there significant differences in AEP between the different clay contents at the high fertility level at intermediate

and high rainfall levels (Fig. 4). Also as for AEN, treatments did not interact with clay content, rainfall, or fertility status, but clay content interacted with rainfall and fertility status (Table S3). In contrast to AEN values, AEP values were not highest in treatments that only received MCF but instead in the treatment that received manure plus CAN. The latter had significantly higher AEP (52 to 62 kg yield kg^{-1} total P application at intermediate rainfall levels) than the treatments receiving either manure plus MCF or manure and MCF plus CAN. The treatment that only received manure and MCF had the lowest AEP of all treatments (30 to 39 kg yield kg^{-1} total P application at intermediate rainfall levels) and the only treatments it did not significantly differ from were the treatments receiving only manure or the ones receiving manure and MCF plus CAN.

4. Discussion

4.1 Maintenance at best, but no increases of yields over time

In general, the high variability in seasonal conditions makes isolation of signals, such as changes of yield over time, difficult to identify, resulting in a limited number of significant temporal trends in this study. Nevertheless a few significant temporal trends existed, and as hypothesized, the local treatment (and in tendency the IR treatment) without any inputs lost yields over time (in 3 of 4 cases under medium rainfall (exception at 64% clay and low initial fertility)). However, contrary to our expectations, no treatment could significantly increase yields over time, even in the low-fertility soil conditions with maximum inputs. Thus, we have to reject our hypothesis regarding positive long-term effects on maize yields over time with a combination of all inputs. Earlier studies showed that the higher the initial fertility, the faster yields can be lost over time (Kihara et al. 2016b), which aligned with our results from the higher clay sites. Interestingly, while treatment differences decreased over time (i.e., in the last year only no vs any input treatments differed significantly), the difference between low- and high rainfall seasons increased over time (Figs. S3 & S4), indicating a potential nutrient leaching issue. In contrast, high clay sites with high fertility status led to yield losses at low rainfall levels, indicating that drought was more detrimental than a lot of rainfall under those conditions. While not significantly losing yield over time, the tendentially decreasing yields in most treatments highlighted the difficulty of maintaining yields over time with monocultures of maize. Maize is a highly demanding crop that, even with external inputs, tends to extract more (micro-)nutrients than the soil can replenish (Alamnie Asrade et al. 2022). Effective amounts of nutrient inputs in this studies' treatments may still be too low to increase SOC and nutrient stocks. For example, a recent study showed that yield increases over time were only possible at high, but not medium (i.e., 4 vs 1.2 t C ha^{-1} yr^{-1} of manure input; about 17 and 5 t of dry matter) input levels (Laub et al., 2023a).

In light of what is reported in the literature, it is important to make a clear distinction between what many studies call "yield increase due to ISFM", which in fact is merely a higher yield of a treatment compared to the control (Mucheru-Muna et al. 2014; e.g., Adolwa et al. 2019; Mutuku et al. 2020; Doldt et al. 2023; Lelei et al. 2025), and temporal increases of yield over time. While any treatment with inputs in this study offered the former, none of them achieved the latter. However, within the context of ISFM and sustainable intensification, one must look at the temporal trend, since only a treatment that increases (or at least maintains) yields over time can be considered sustainable. This is of special importance in tropical soils, characterized by a fast loss but slow gain of soil fertility (Doetterl et al. 2025). Recent studies have shown that tropical maize cultivation in sub-Saharan Africa, even under high inputs, often suffers from soil fertility decline (Sommer et al. 2018; Cardinael et al. 2022; Laub et al. 2023a), notably even in treatments with increasing yields over time (e.g., Laub et al. 2023b). This means that improved management or varieties can mask soil fertility losses. That the majority of studies on ISFM report yield declines or at best maintenance prompts the question whether emphasis should be shifted from a focus on external inputs to the crop to generating more in-situ inputs with the cropping systems, for example by crop rotations or intercropping with legumes (Laub et al. 2024). It has been hypothesized that in-situ inputs accumulate soil organic matter more efficiently than external inputs (Sokol and Bradford 2019). In the context of our study, it is important to have more medium to long-term on-farm experiments with repeated measurements, because only those can detect significant temporal trends.

Given that the treatment differences diminished over time (Fig. 2), it is likely that short-term and long-term effects are not the same for many types of inputs.

4.2 Integrated approaches work best with complementing nutrients

While not being able to increase yields over time, our results clearly demonstrate the yield benefits of applying nutrients of various origins compared to applying no external nutrients at all. As hypothesized, the combination of manure, MCF and CAN led to the

best maize yields. However, a significant dependency of the treatment effect on other conditions, such as rainfall, soil fertility, or clay content, was not found. Furthermore, the highest yields were not necessarily an indicator of efficient nutrient use - redundancies existed in cases where inputs with roughly the same nutrients (i.e., MCF and manure) were combined (Palm et al. 1997). Specifically, the significant negative interaction between MCF and manure cancelled out about 70% of the positive effect of manure (Table 3). Given that a meta-analysis showed that negative interactions are rare in the combination of two or more single element fertilizers (~ 15% of cases; Rietra et al., 2017) and that interactions between mineral N and manure application are usually positive (Vanlauwe and Sanginga 2004; Gram et al. 2020; Laub et al. 2023b), the strength of this negative interaction was unexpected. However, despite being a mineral fertilizer, MCF only contains 10% of mineral N, and both MCF and manure supply similar nutrient profiles and element ratios (i.e., N, P, K, Ca, Mg, and S, and Ca; see Material and Methods). Additionally, it has been reported that high K inputs, such as those from manure, can in some cases lead to nutrient imbalances (Aliyu et al. 2021), specifically reducing the uptake of Mg (Xie et al. 2021). Tropical soils are often depleted in Mg (Fageria and Baligar 2008; Nawaz et al. 2010) and, thus, this could be another explanation for the negative interaction and the lower performance of manure compared to MCF. In fact, when combining organic resources and mineral fertilizer, redundancies, as indicated by diminishing rates of return, or reduced AEN or AEP are, in contrast to absolute yield decreases (Vanlauwe and Sanginga 2004), not uncommon. For example, in a large-scale analysis of sustainable intensification practices across Europe and Africa, adding either manure to soils or fertility crops to a rotation had a small effect in fields that already received high loads of mineral N while having a strong effect in fields without mineral N inputs (MacLaren et al. 2022).

To identify redundancies, it is thus important to either simultaneously assess the effect of the individual components and their interactions, or to assess the AEN or AEP (Vanlauwe et al. 2011). The reason is that the integrated treatments often supply more total nutrients than the sole mineral or sole manure treatments, and higher yields due to higher total nutrient inputs often mask the negative interactions that are typical for input rates > 30 kg N ha^{-1} (Chivenge et al. 2011). Thus, it is recommended to test for potential nutrient profile overlaps before combining organic and mineral fertilizers. This should help to assure that they supply different nutrients, ideally the most limiting ones (given that this information is available for manure).

Apart from the treatment effects, the higher yields in higher soil fertility show clearly that soil fertility matters - with and without nutrient additions. This supports the notion that soil fertility gradients are relevant from the county scale (Kayani et al. 2021) to the individual farm (Vanlauwe et al. 2015). One local adaptation of ISFM (Vanlauwe et al. 2015) is to stress the combined application of mineral and organic fertilizers in lower fertility sites that potentially suffer from multiple nutrient limitations. However, in contrast to our hypothesis, we did not find that treatment effectiveness differed between different soil fertility levels or clay contents.

4.3 Which nutrients were likely most limiting?

To our surprise, MCF, despite supplying lower amounts of most nutrients, except P and S, had a significantly stronger effect on crop yields (+ 830 kg ha^{-1} $season^{-1}$ at median yields) across sites and fertilities compared to manure (+ 533 kg ha^{-1} $season^{-1}$ at a median yield level), even in cases of low initial soil fertility. Our findings align with those of another study conducted in Vihiga county, where sole MCF also tended to outperform sole manure, though not significantly (Abuom et al. 2014). Consequently, we reject our hypotheses that sites with lower fertility respond more to manure than MCF. It has been found that substituting mineral fertilizer by organic fertilizer can improve yields at high total nutrient input rates while it can reduce yields at low inputs rates (Wei et al. 2020). In that sense, the reason for MCF outperforming manure additions could be the relatively low inputs rates in this study and that, in contrast to mineral fertilizers, the nutrients from manure are released too slowly, namely typically over many years (Silva et al. 2014).

With 15 kg N ha^{-1} $season^{-1}$, MCF likely supplied less N than 2 t of manure ha^{-1} $season^{-1}$ on a dry matter basis (roughly 24 to 32 kg N ha^{-1} $season^{-1}$). However, despite having the highest AEN, the sole MCF treatment was among the best yielding treatments, suggesting it was not limited by N. In fact, the only treatment having higher yields was the treatment combining manure, MCF and CAN (Fig. 1), albeit at much lower AEN and AEP (Figs. 3 and 4). Instead of N, it is thus likely that MCF outperformed manure due to its higher amounts of other typically limiting nutrients in highly weathered tropical soils, such as P (Chukwuma et al. 2024), S (Broderick 2004), or micronutrients (Kihara et al. 2020). In fact, an indication that P could indeed be limiting in manure and manure plus CAN treatments is that they led to the highest AEP values (Fig. 4) and simultaneously have significantly lower yields than MCF treatments in several instances. Hence, MCF has an advantage over manure that sole mineral N fertilizers usually lacks (e.g.,

Cardinael et al. 2022; Laub et al. 2023b). Thus, these results corroborate the better performance of multi-component fertilizers over those supplying mainly mineral N (Adu-Gyamfi et al. 2019a, b; Agyin-Birikorang et al. 2018).

We also reject the hypothesis about positive interactions between either MCF with CAN, or manure with CAN (Iqbal et al. 2019) because both interactions were not significant. Nevertheless, the lack of negative interactions with CAN supports that nutrient profiles in combined applications should differ to achieve maximum benefit (Ayamba et al. 2023) and that negative interactions are mainly a consequence of inputs providing roughly the same nutrient profiles or ecosystem services (MacLaren et al. 2022). Calcium-ammonium-nitrate in that sense is quite distinct from MCF and manure, since it provides only N, Ca, and S, and all of them are rapidly available. This transient nutrient supply of a nutrient that was not the main limiting one, could be the reason why CAN, despite supplying high amounts of total N (30 kg N ha^{-1} $season^{-1}$) compared to MCF (15 kg N ha^{-1} $season^{-1}$) and manure (24–32 kg N ha^{-1} $season^{-1}$), had a rather small effect on maize yields (+ 141 kg ha^{-1} $season^{-1}$). The fact that N, Ca, and S are also supplied by the other inputs could explain why the interactions with MCF ($p = 0.1$) and manure ($p = 0.49$) were both non-significant.

An alternative explanation could be that there was no treatment applying solely CAN, making it more difficult to detect real interactive effects, as a result of the additive design (Burgess et al. 2022); due to this design, the model would most likely give a stronger effect to MCF and manure compared to CAN. Combining all results, we conclude that overlaps in the nutrient profiles of organic and mineral fertilizer types are common, and synergistic interactions thus difficult to achieve. Given this, it is advisable to focus on fertilizer combinations with very distinct nutrient profiles, e.g., MCF with CAN, or manure with CAN (Laub et al. 2023b), where there are at least no negative interactions.

4.4 Do local varieties lead to better yields?

The better performance of the local compared to the “improved” IR variety without input, as suggested by our model dissecting the effect of each treatment factor independently, shows the importance of having varieties that are adapted to local conditions (Janzen et al. 2022). Importantly, the models suggestion that this was independent of treatments (Table 3) should not be accepted without further investigation. With our experimental structure, it is impossible to determine whether there is a significant interaction between variety and treatment in the sense that IR varieties perform better under nutrient-optimal scenarios, because only the IR treatments received inputs of MCF, CAN, and/or manure. It is known from nearby long-term experiments that varieties such as DH04 (used in 4 of 12 seasons of this study), react well to both organic resource and mineral N fertilizer additions and is therefore also suitable in ISFM (Laub et al. 2023b). Nevertheless, this does not tell us whether the local varieties would have a weaker, stronger, or similar reaction than the IR maize to inputs. However, past studies (e.g., Vanlauwe et al. 2011) found improved and hybrid varieties to generally have higher yields and AEN, suggesting that the reaction of local varieties to external inputs is lower than the one of improved varieties.

4.5 Implications for Management in Smallholder Settings

Our results clearly show that nutrient inputs increase maize yields in Kenyan smallholder systems over no inputs, and that the different efficiency due to different fertility levels of soils warrants input strategies that are tailored to resource availability and yield potential (Vanlauwe and Sanginga 2004; Vanlauwe et al. 2015). While the combined use of manure, MCF and CAN produced the highest yields, this intensive approach is often not practical or economically feasible for most farmers, particularly given the low AEN and AEP of this combination. Especially the addition of CAN would likely not be economic given the low average yield increase (~ 120 kg ha^{-1} $season^{-1}$). In contrast, single input strategies, such as the sole addition of manure or MCF maintained intermediate yields at high AEN and medium AEP, making them more suitable for farmers with limited resources or access to only one input type. Because the effectiveness of combined inputs depends on their nutrient profiles, farmers should prioritize fertilizers that complement each other and address site-specific deficiencies. Here, soil and manure testing are particularly important, as this enables the identification of both macro- and micronutrient limitations and supply, allowing for more precise and efficient fertilizer recommendations (Kihara et al. 2020). Effective extension support and farmer training on input efficiency, soil testing, and locally relevant soil management will further enable context-specific, sustainable productivity improvements (Chivenge et al. 2011; Aramburu-Merlos et al. 2024).

Despite the generally inferior performance of manure compared to MCF, the significantly higher yields compared to no inputs suggest that manure may be the best option for farmers that own livestock. On the other hand, if inputs need to be bought, the purchasing of MCF is probably more effective than CAN for smallholder farmers. Because topdressing with CAN led to decreases

in the AEN, it may only be used with caution if manure or MCF are already used. Nevertheless it could be feasible in promising seasons and in soils that react to mineral N. Overall, the lack of synergies between fertilizers suggests that farmers should choose their inputs and combinations carefully, ideally integrating knowledge on soil fertility and on nutrient profiles of their manure.

5. Conclusion

Our study, conducted over ten consecutive seasons in western Kenya, reveals that at input rates that are realistic to farmers, no treatment could increase maize yields over time. Nevertheless, treatments with higher inputs of nutrients led to higher yields than treatments with no or lower inputs, with highest yield benefits and nutrient use efficiencies of MCF, followed by manure addition. Further, the effective combination of mineral and organic inputs for sustainable maize yields critically depends on their specific nutrient profiles and on initial soil conditions. Instead of synergies between MCF and farmyard manure, a significant negative interaction indicated nutrient redundancies. In contrast, CAN top-dressing offered a modest but distinct yield benefit independent of the two other inputs, suggesting a complementary nutrient profile to both MCF and manure. The findings emphasize that achieving good maize yields requires a nuanced approach, prioritizing the addition of several over individual nutrients, and the integration of inputs with complementary rather than overlapping nutrient profiles. The observed differences between treatment effects and trends over time highlight the need for more intermediate to long-term soil fertility management studies. While most studies report treatment effects, only treatments that do not lose their yield benefits over time offer a sustainable production in the long term.

Declarations

Competing Interests:

The authors declare no competing interests.

Author Contribution

B.V. designed the experiments, acquired the funding, and led the research. L.N. executed the field research and gathered the results. M.L. analyzed the data, curated the results, and, with help from J.M., wrote the original draft. J.S. and B.V. provided feedback during the draft development. B.V., J.S., J.M., and M.L. together curated the final draft.

Data Availability

The data used in this article belongs to IITA and it not publicly available. It will be made available by the authors upon reasonable request.

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References

1. Abuom PO, Nyambega LA, Oum G (2014) Effect of Mavuno Phosphorus-Based Fertilizer and Manure Application on Maize Grain and Stover Yields in Western Kenya. J Environ Earth Sci 4:43
2. Adolwa IS, Schwarze S, Buerkert A (2019) Impacts of integrated soil fertility management on yield and household income: The case of Tamale (Ghana) and Kakamega (Kenya). Ecol Econ 161:186–192. https://doi.org/10.1016/j.ecolecon.2019.03.023

3. Adu-Gyamfi R, Agyin-Birikorang S, Tindjina I, et al (2019a) One-Time Fertilizer Briquettes Application for Maize Production in Savanna Agroecologies of Ghana. Agron J 111:3339–3350. https://doi.org/10.2134/agronj2019.04.0292
4. Adu-Gyamfi R, Agyin-Birikorang S, Tindjina I, et al (2019b) Minimizing nutrient leaching from maize production systems in northern Ghana with one-time application of multi-nutrient fertilizer briquettes. Sci Total Environ 694:133667. https://doi.org/10.1016/j.scitotenv.2019.133667
5. Agyin-Birikorang S, Winings JH, Yin X, et al (2018) Field evaluation of agronomic effectiveness of multi-nutrient fertilizer briquettes for upland crop production. Nutr Cycl Agroecosyst 110:395–406. https://doi.org/10.1007/s10705-018-9905-y
6. Alamnie Asrade D, Kulhánek M, Černý J, et al (2022) Effects of long-term mineral fertilization on silage maize monoculture yield, phosphorus uptake and its dynamic in soil. Field Crops Res 280:108476. https://doi.org/10.1016/j.fcr.2022.108476
7. Aliyu KT, Huising J, Kamara AY, et al (2021) Understanding nutrient imbalances in maize (Zea mays L.) using the diagnosis and recommendation integrated system (DRIS) approach in the Maize belt of Nigeria. Sci Rep 11:16018. https://doi.org/10.1038/s41598-021-95172-7
8. Almekinders CJM, Louwaars NP, de Bruijn GH (1994) Local seed systems and their importance for an improved seed supply in developing countries. Euphytica 78:207–216. https://doi.org/10.1007/BF00027519
9. Aramburu-Merlos F, Tenorio FAM, Mashingaidze N, et al (2024) Adopting yield-improving practices to meet maize demand in Sub-Saharan Africa without cropland expansion. Nat Commun 15:4492. https://doi.org/10.1038/s41467-024-48859-0
10. Ayamba BE, Abaidoo RC, Opoku A, Ewusi-Mensah N (2023) Mechanisms for nutrient interactions from organic amendments and mineral fertilizer inputs under cropping systems: a review. PeerJ 11:e15135. https://doi.org/10.7717/peerj.15135
11. Bautze D, Karanja E, Musyoka M, et al (2024) Closing the crop yield gap between organic and conventional farming systems in Kenya: Long-term trial research indicates agronomic viability. J Agric Food Res 18:101499. https://doi.org/10.1016/j.jafr.2024.101499
12. Broderick CE (2004) Sulfur requirements, fertilizer supply and use are critical to Sub-Saharan agriculture. Pennsylvania Geographer 42:74–90
13. Burgess BJ, Jackson MC, Murrell DJ (2022) Are experiment sample sizes adequate to detect biologically important interactions between multiple stressors? Ecol Evol 12:e9289. https://doi.org/10.1002/ece3.9289
14. Cardinael R, Guibert H, Kouassi Brédoumy ST, et al (2022) Sustaining maize yields and soil carbon following land clearing in the forest–savannah transition zone of West Africa: Results from a 20-year experiment. Field Crop Res 275:108335. https://doi.org/10.1016/j.fcr.2021.108335
15. Chivenge P, Vanlauwe B, Six J (2011) Does the combined application of organic and mineral nutrient sources influence maize productivity? A meta-analysis. Plant Soil 342:1–30. https://doi.org/10.1007/s11104-010-0626-5
16. Chukwuma CC, Oraegbunam CJ, Ndzeshala SD, et al (2024) Phosphorus Mineralization in Two Lithologically Dissimilar Tropical Soils as Influenced by Animal Manure Type and Amendment-To-Sampling Time Interval. Commun Soil Sci Plant Anal 55:707–722. https://doi.org/10.1080/00103624.2023.2276269
17. Cobo JG, Dercon G, Cadisch G (2010) Nutrient balances in African land use systems across different spatial scales: A review of approaches, challenges and progress. Agric Ecosyst Environ 136:1–15. https://doi.org/10.1016/j.agee.2009.11.006
18. Doetterl S, Berhe AA, Heckman K, et al (2025) A landscape-scale view of soil organic matter dynamics. Nat Rev Earth Environ 6:67–81. https://doi.org/10.1038/s43017-024-00621-2
19. Doldt J, Yilma K, Ellis-Jones J, et al (2023) The role of integrated soil fertility management in improving crop yields in the Ethiopian Highlands. Exp Agric 59:e24. https://doi.org/10.1017/S0014479723000212
20. Fageria NK, Baligar VC (2008) Chap. 7 Ameliorating Soil Acidity of Tropical Oxisols by Liming For Sustainable Crop Production. In: Advances in Agronomy. Academic Press, pp 345–399
21. Falconnier GN, Cardinael R, Corbeels M, et al (2023) The input reduction principle of agroecology is wrong when it comes to mineral fertilizer use in sub-Saharan Africa. Outlook Agric 00307270231199795. https://doi.org/10.1177/00307270231199795
22. FAO (2025) FAOSTAT Online Database. https://www.fao.org/faostat/en/#data/QCL. Accessed 6 Mar 2025
23. Giller KE, Delaune T, Silva JV, et al (2021a) The future of farming: Who will produce our food? Food Sec 13:1073–1099. https://doi.org/10.1007/s12571-021-01184-6

24. Giller KE, Hijbeek R, Andersson JA, Sumberg J (2021b) Regenerative Agriculture: An agronomic perspective. Outlook Agric 50:13–25. https://doi.org/10.1177/0030727021998063
25. Gram G, Roobroeck D, Pypers P, et al (2020) Combining organic and mineral fertilizers as a climate-smart integrated soil fertility management practice in sub-Saharan Africa: A meta-analysis. PLOS ONE 15:e0239552. https://doi.org/10.1371/journal.pone.0239552
26. Hobbs PR (2007) Conservation agriculture: what is it and why is it important for future sustainable food production? J Agric Sci 145:127
27. Hothorn T, Bretz F, Westfall P (2008) Simultaneous Inference in General Parametric Models. Biom J 50:346–363. https://doi.org/10.1002/bimj.200810425
28. Iqbal A, He L, Khan A, et al (2019) Organic Manure Coupled with Inorganic Fertilizer: An Approach for the Sustainable Production of Rice by Improving Soil Properties and Nitrogen Use Efficiency. Agronomy 9:651. https://doi.org/10.3390/agronomy9100651
29. Janzen GM, Aguilar-Rangel MR, Cíntora-Martínez C, et al (2022) Demonstration of local adaptation in maize landraces by reciprocal transplantation. Evol Appl 15:817–837. https://doi.org/10.1111/eva.13372
30. Kayani IB, Agumas B, Musyoki M, et al (2021) Market access and resource endowment define the soil fertility status of smallholder farming systems of South-Kivu, DR Congo. Soil Use Manag 37:353–366. https://doi.org/10.1111/sum.12691
31. Kihara J, Bolo P, Kinyua M, et al (2020) Micronutrient deficiencies in African soils and the human nutritional nexus: opportunities with staple crops. Environ Geochem Health 42:3015–3033. https://doi.org/10.1007/s10653-019-00499-w
32. Kihara J, Huising J, Nziguheba G, et al (2016a) Maize response to macronutrients and potential for profitability in sub-Saharan Africa. Nutr Cycl Agroecosyst 105:171–181. https://doi.org/10.1007/s10705-015-9717-2
33. Kihara J, Nziguheba G, Zingore S, et al (2016b) Understanding variability in crop response to fertilizer and amendments in sub-Saharan Africa. Agric Ecosyst Environ 229:1–12. https://doi.org/10.1016/j.agee.2016.05.012
34. Laub M, Corbeels M, Couëdel A, et al (2023a) Managing soil organic carbon in tropical agroecosystems: evidence from four long-term experiments in Kenya. SOIL 9:301–323. https://doi.org/10.5194/soil-9-301-2023
35. Laub M, Corbeels M, MacLaren C, et al (2025) Maize yield responses to soil organic carbon under integrated soil fertility management in tropical environments. Agron Sustain Dev 45:63. https://doi.org/10.1007/s13593-025-01054-x
36. Laub M, Corbeels M, Mathu Ndungu S, et al (2023b) Combining manure with mineral N fertilizer maintains maize yields: Evidence from four long-term experiments in Kenya. Field Crop Res 291:108788. https://doi.org/10.1016/j.fcr.2022.108788
37. Laub M, Corbeels M, Ndungu SM, et al (2024) Shifting focus from external to in situ organic resources – The redesign of four tropical long-term experiments. Eur J Agron 157:127194. https://doi.org/10.1016/j.eja.2024.127194
38. Lelei DK, Sultan MSS, Kuboja NM, et al (2025) Enhancing maize (Zea mays) productivity through integrated soil fertility management: a participatory approach in the degraded soils of Kigoma, Tanzania. Front Agron 7:. https://doi.org/10.3389/fagro.2025.1537292
39. Lenth R (2020) emmeans: Estimated Marginal Means, aka Least-Squares Means
40. MacLaren C, Mead A, van Balen D, et al (2022) Long-term evidence for ecological intensification as a pathway to sustainable agriculture. Nat Sustain 5:770–779. https://doi.org/10.1038/s41893-022-00911-x
41. Mucheru-Muna M, Mugendi D, Pypers P, et al (2014) Enhancing maize productivity and profitability using organic inputs and mineral fertilizer in central Kenya small-hold farms. Exp Agric 50:250–269. https://doi.org/10.1017/S0014479713000525
42. Mutuku EA, Roobroeck D, Vanlauwe B, et al (2020) Maize production under combined Conservation Agriculture and Integrated Soil Fertility Management in the sub-humid and semi-arid regions of Kenya. Field Crop Res 254:107833. https://doi.org/10.1016/j.fcr.2020.107833
43. Nawaz R, Garivait H, Anurakpongsatorn P (2010) Impacts of precipitation on leaching behavior of plant nutrients in agricultural soils of the tropics. In: 2010 2nd International Conference on Chemical, Biological and Environmental Engineering. pp 336–340
44. Nyangena W, Juma M (2014) Impact of improved farm technologies on yields: the case of improved maize varieties and inorganic fertilizer in Kenya.
45. Palm C, Gachengo CN, Delve RJ, et al (2001) Organic inputs for soil fertility management in tropical agroecosystems: application of an organic resource database. Agric Ecosyst Environ 83:27–42. https://doi.org/10.1016/S0167-8809(00)00267-

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46. Palm CA, Myers RJK, Nandwa SM (1997) Combined Use of Organic and Inorganic Nutrient Sources for Soil Fertility Maintenance and Replenishment. In: Replenishing Soil Fertility in Africa. John Wiley & Sons, Ltd, pp 193–217
47. Piepho H-P (2004) An Algorithm for a Letter-Based Representation of All-Pairwise Comparisons. J Comput Graph Statist 13:456–466. https://doi.org/10.1198/1061860043515
48. Pinheiro J, Bates D, DebRoy S, et al (2016) {nlme}: Linear and Nonlinear Mixed Effects Models
49. R Core Team (2025) R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria
50. Rietra RPJJ, Heinen M, Dimkpa CO, Bindraban PS (2017) Effects of Nutrient Antagonism and Synergism on Yield and Fertilizer Use Efficiency. Commun Soil Sci Plant Anal 48:1895–1920. https://doi.org/10.1080/00103624.2017.1407429
51. Sanchez PA (2015) En route to plentiful food production in Africa. Nat Plants 1:14014. https://doi.org/10.1038/nplants.2014.14
52. Sileshi GW, Nhamo N, Mafongoya PL, Tanimu J (2017) Stoichiometry of animal manure and implications for nutrient cycling and agriculture in sub-Saharan Africa. Nutr Cycl Agroecosyst 107:91–105. https://doi.org/10.1007/s10705-016-9817-7
53. Sileshi GW, Stewart ZP, Odhong J, et al (2025) A review of organic inputs to inform soil health advice for African smallholder farmers: localization matters. npj Sustain Agric 3:1–15. https://doi.org/10.1038/s44264-025-00063-3
54. Silva VB da, Silva AP da, Dias B de O, et al (2014) Decomposição e liberação de N, P e K de esterco bovino e de cama de frango isolados ou misturados. Rev Bras Ciênc Solo 38:1537–1546. https://doi.org/10.1590/S0100-06832014000500019
55. Sokol NW, Bradford MA (2019) Microbial formation of stable soil carbon is more efficient from belowground than aboveground input. Nat Geosci 12:46–53. https://doi.org/10.1038/s41561-018-0258-6
56. Sommer R, Paul BK, Mukalama J, Kihara J (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. Agric Ecosyst Environ 254:82–91. https://doi.org/10.1016/j.agee.2017.11.004
57. Tittonell P, Vanlauwe B, de Ridder N, Giller KE (2007) Heterogeneity of crop productivity and resource use efficiency within smallholder Kenyan farms: Soil fertility gradients or management intensity gradients? Agric Syst 94:376–390. https://doi.org/10.1016/j.agsy.2006.10.012
58. Vanlauwe B, Bationo A, Chianu J, et al (2010) Integrated Soil Fertility Management: Operational Definition and Consequences for Implementation and Dissemination. Outlook Agric 39:17–24. https://doi.org/10.5367/000000010791169998
59. Vanlauwe B, Descheemaeker K, Giller KE, et al (2015) Integrated soil fertility management in sub-Saharan Africa: unravelling local adaptation. SOIL 1:491–508. https://doi.org/10.5194/soil-1-491-2015
60. Vanlauwe B, Kihara J, Chivenge P, et al (2011) Agronomic use efficiency of N fertilizer in maize-based systems in sub-Saharan Africa within the context of integrated soil fertility management. Plant Soil 339:35–50. https://doi.org/10.1007/s11104-010-0462-7
61. Vanlauwe B, Sanginga N (2004) The multiple roles of organic resources in implementing integrated soil fertility management strategies. In: Delve RJ, Probert ME (eds) Modelling nutrient management in tropical cropping systems. Australian Centre for International Agricultural Research (ACIAR); Centro Internacional de Agricultura Tropical (CIAT), Canberra, AU
62. Vanlauwe B, Wendt J, Giller KE, et al (2014) A fourth principle is required to define Conservation Agriculture in sub-Saharan Africa: The appropriate use of fertilizer to enhance crop productivity. Field Crops Res 155:10–13. https://doi.org/10.1016/j.fcr.2013.10.002
63. Venables WN, Ripley BD (2002) Modern Applied Statistics with S, Fourth. Springer, New York
64. Wei Z, Ying H, Guo X, et al (2020) Substitution of Mineral Fertilizer with Organic Fertilizer in Maize Systems: A Meta-Analysis of Reduced Nitrogen and Carbon Emissions. Agronomy 10:1149. https://doi.org/10.3390/agronomy10081149
65. Wickham H (2016) ggplot2 - Elegant Graphics for Data Analysis. Springer International Publishing, Cham
66. Xie K, Cakmak I, Wang S, et al (2021) Synergistic and antagonistic interactions between potassium and magnesium in higher plants. Crop J 9:249–256. https://doi.org/10.1016/j.cj.2020.10.005

Figures

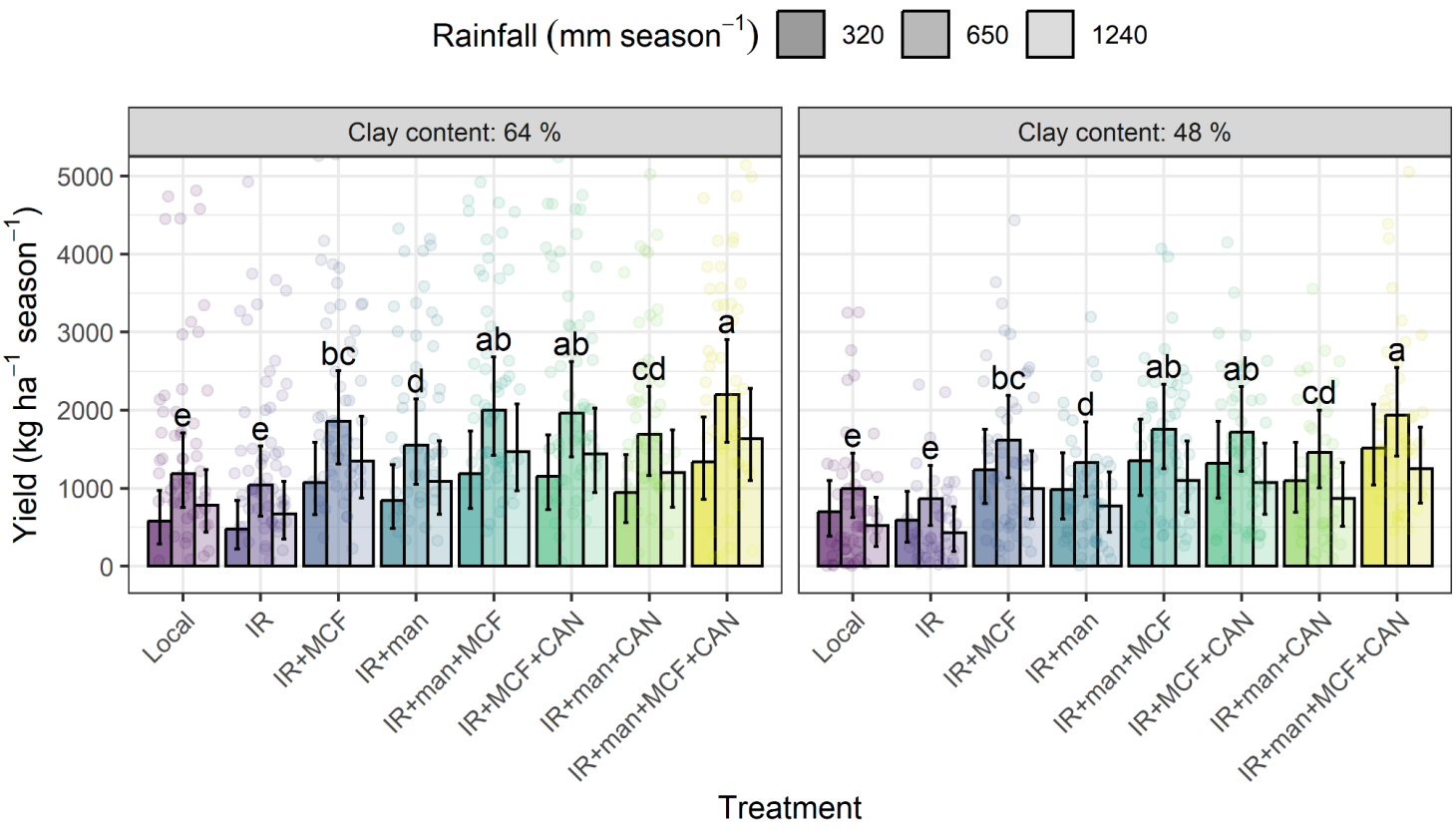


Figure 1

Estimated marginal means for maize grain yields (back-transformed from the 2nd root) for each of the eight treatments per county-typical clay content (64% for Siaya, 48% for Vihiga) by rainfall (at quantiles 10, 50, and 90%) at high fertility (low fertility yields were 300 kg ha^{-1} less; no interactions of fertility level with other covariates existed). A local maize variety without inputs served as the control; an improved variety (IR) as the treatment. The improved variety was either without inputs (IR) with manure (IR+man), multi-component fertilizer (IR+MCF), or a combination of both (IR+man+MCF). A split-plot tested the effectiveness of top-dressing calcium-ammonium-nitrate (CAN). The data were from up to ten seasons with ten farmers in each of two counties (Siaya and Vihiga) having each a high- and a low-fertility field. Bars with error bars indicate means ± 95% confidence intervals; points show individual observations. Letters denote significant differences at $p < 0.05$ (degrees of freedom adjusted by the "Sidak" method). Treatments not sharing any lowercase letter differ statistically within each clay content × fertility panel. Only yield data from high-fertility fields that were within one standard deviation of the two displayed clay contents are shown (868 of 2350 data points).

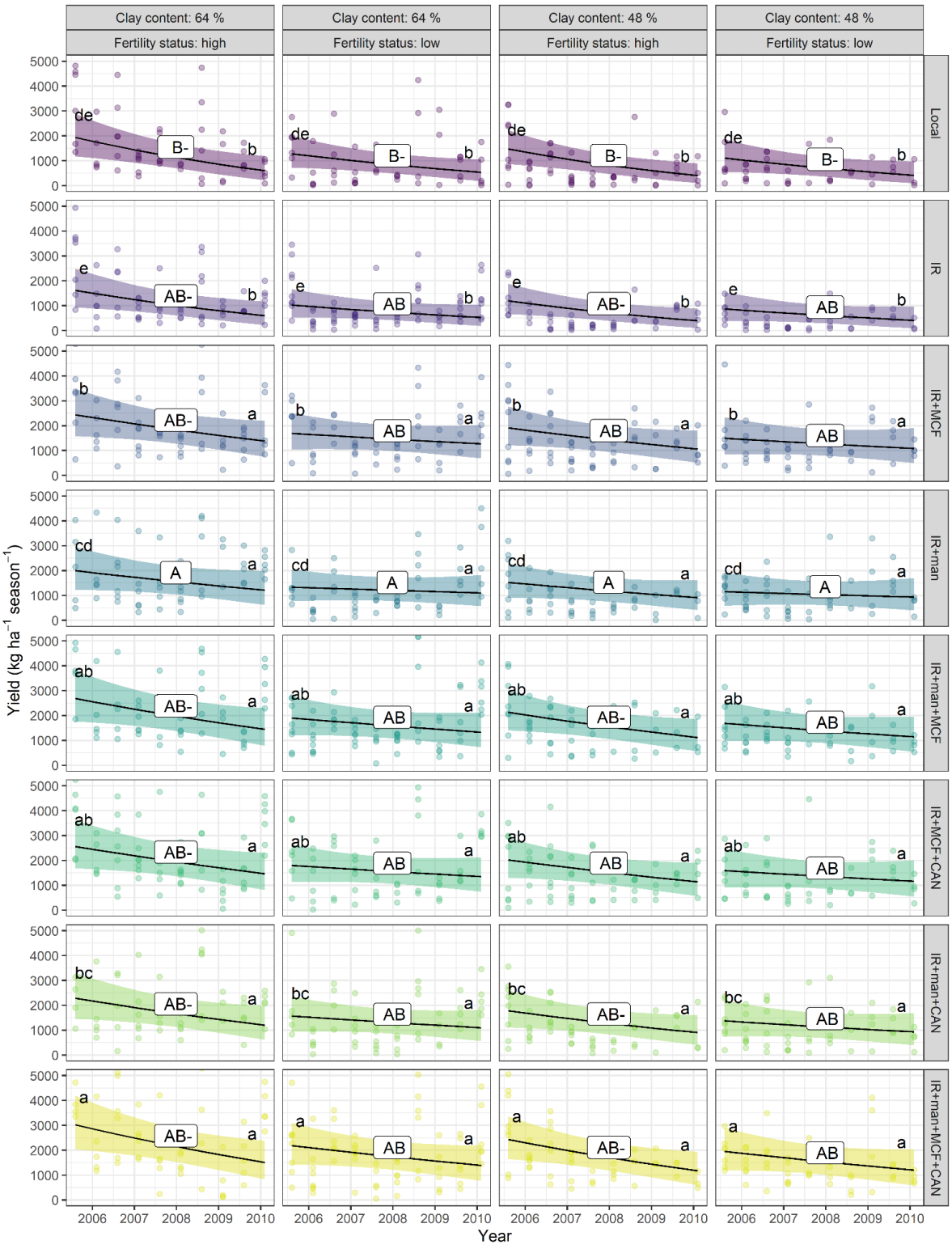


Figure 2

Estimated marginal means for maize grain yields per treatment, county-typical clay content (64% for Siaya, 48% for Vihiga), and fertility status at median rainfall (650 mm season^{-1}) over time (back-transformed from the 2nd root). A local maize variety without inputs served as the control; an improved variety (IR) as the treatment. The improved variety was either without inputs (IR) with manure (IR+man), multi-component fertilizer (IR+MCF), or a combination of both (IR+man+MCF). A split-plot tested the effectiveness of top-dressing calcium-ammonium-nitrate (CAN). The data were from up to ten seasons with ten farmers in each of two counties (Siaya and Vihiga) having each a high- and a low-fertility field. Lines with shaded areas indicate means ± 95% confidence intervals as a function of time since experiment start. Lowercase letters denote significant differences at $p < 0.05$ at the

first and 5th year of the experiment, while uppercase letters denote significant differences between the slope of the temporal trends, with a minus indicating a significantly negative slope (degrees of freedom adjusted by the “Sidak” method for all post-hoc comparisons). Treatments sharing any letter do not differ statistically at the same time point. Only yield data from fields that were within one standard deviation of the two displayed clay contents are shown (1838 of 2350 data points).

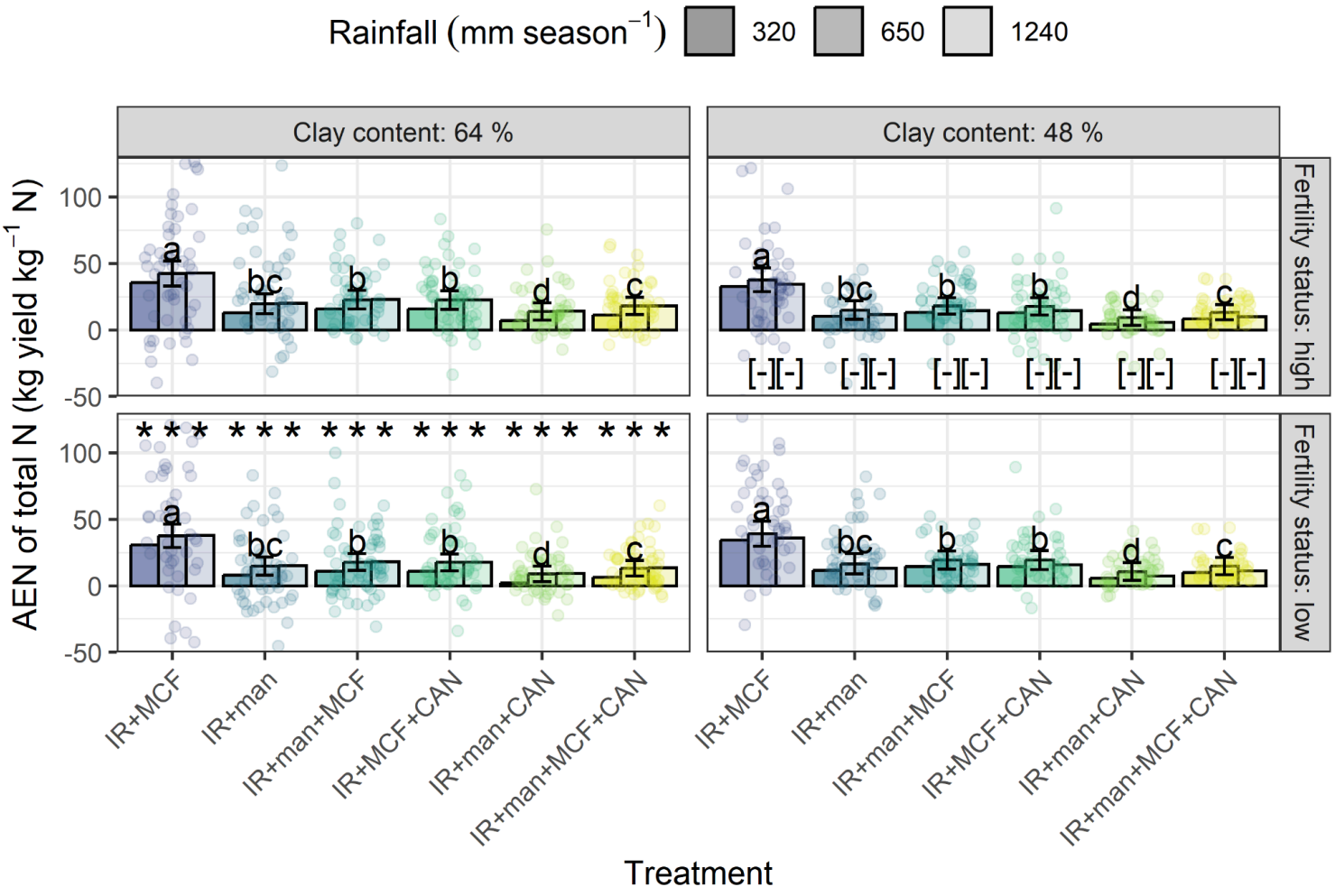


Figure 3

Estimated marginal means for agronomic N use efficiency (AEN) of total N inputs (from manure, multi-component fertilizer (MCF), and CAN) for each of the six treatments per county-typical clay content (64% for Siaya, 48% for Vihiga), by rainfall (at quantiles 10, 50, and 90%), and fertility status. The improved variety (IR) with no additional input served as the baseline yield, from which the AEN of the treatments that received manure (IR+man), MCF (IR+MCF), or a combination of both (IR+man+MCF), as well as those that received top-dressing calcium-ammonium-nitrate (CAN), was calculated. The data were from up to ten seasons with ten farmers in each of two counties (Siaya and Vihiga) having each a high- and a low-fertility field. Temporal trends were not significant ($p > 0.05$; analysis not shown here) and are therefore not displayed. Bars with error bars indicate means ± 95% confidence intervals; points show individual observations. Letters denote significant differences at $p < 0.05$ (degrees of freedom adjusted by the “Sidak” method). Treatments not sharing any lowercase letter differ statistically within each clay content × fertility panel. An asterisk above a treatment in any fertility panel and rainfall level indicates that the treatment had significantly lower AEN in that fertility and rainfall level compared to the other fertility level of the same clay content, a [-] below a treatment indicates that the treatment had significantly lower AEN at the other clay content within the same fertility status and rainfall level. Only data from fields that were within one standard deviation of the two displayed clay contents are shown (1229 of 1690 data points).

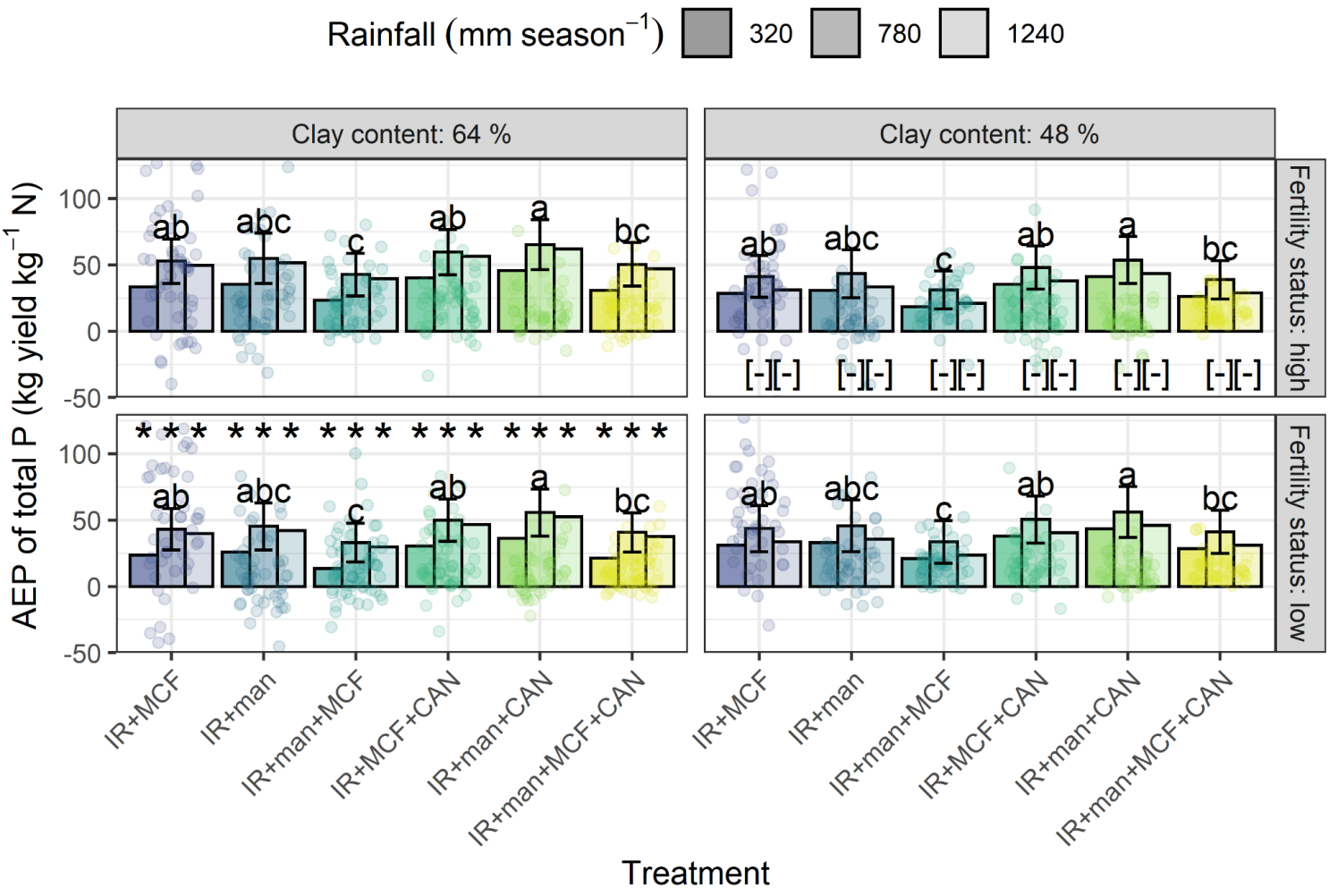


Figure 4

Estimated marginal means for agronomic P use efficiency (AEP) of total P inputs (from manure, multi-component fertilizer (MCF), and CAN) for each of the six treatments per county-typical clay content (64% for Siaya, 48% for Vihiga), by rainfall (at quantiles 10, 50, and 90%), and fertility status. The improved variety (IR) with no additional input served as the baseline yield, from which the AEP of the treatments that received manure (IR+man), MCF (IR+MCF), or a combination of both (IR+man+MCF), as well as those that received top-dressing calcium-ammonium-nitrate (CAN), was calculated. The data were from up to ten seasons with ten farmers in each of two counties (Siaya and Vihiga) having each a high- and a low-fertility field. Temporal trends were not significant ($p > 0.4$; analysis not shown here) and are therefore not displayed. Bars with error bars indicate means ± 95% confidence intervals; points show individual observations. Letters denote significant differences at $p < 0.05$ (degrees of freedom adjusted by the "Sidak" method). Treatments not sharing any lowercase letter differ statistically within each clay content × fertility panel. An asterisk above a treatment in any fertility panel indicates that the treatment had significantly lower AEP in that fertility and rainfall level compared to the other fertility level of the same clay content and rainfall level, a [-] below a treatment indicates that the treatment had significantly lower AEP at the other clay content within the same fertility status and rainfall level. Only data from fields that were within one standard deviation of the two displayed clay contents are shown (1229 of 1690 data points).

Supplementary Files

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