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Combining manure with mineral N fertilizer maintains maize yields: Evidence from four long-term experiments in Kenya

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ABSTRACT

Context: Crop productivity in sub-Saharan Africa cannot be substantially improved without simultaneously addressing short-term crop nutrient demand and long-term soil fertility. Integrated soil fertility management tackles both by the combined application of mineral fertilizers and organic resource inputs but few studies examined its‘ long-term effectiveness.
Objective: To address this knowledge gap, this study analysed maize yield trends in four long-term (31–37 cropping seasons) field experiments in Kenya with contrasting soil textures and under different climates.
Methods: All sites had two maize cropping seasons per year, received a base P and K fertilization and tested combinations of organic resource addition (1.2 and 4 t C ha^{-1} yr^{-1} ranging from farmyard manure, to high-quality *Tithonia diversifolia* and *Calliandra calothyrsus* material to low-quality saw dust), combined with (+N) and without (-N) mineral N fertilizer (120 kg N ha^{-1} season^{-1}). General maize yield trends across sites and site specific trends were analyzed.
Results: Across sites, the no-input control experienced significant average maize yield reductions of 50 kg ha^{-1} yr^{-1} over the study period. In contrast, the treatment with farmyard manure +N maintained yields at both 1.2 and 4 t C ha^{-1} yr^{-1}. High initial yields following additions of *Tithonia* and *Calliandra*, reduced over time. Assessment by site showed site specificity of maize yields and yield trends. For example, the two climatically favorable sites in western Kenya experienced yield gains with high quality organic resources at 4 t C ha^{-1} yr^{-1}, leading to yields of up to 8 t ha^{-1} per season, while sites in central Kenya experienced yield losses, leading to 3.5 t ha^{-1} per season. Yield site specificity for ± mineral N treatments was stonger than for organic resource treatments, e.g. the clayey site in central Kenya in the end showed no yield differences between ± N, except for the 1.2 t C ha^{-1} yr^{-1} farmyard manure treatment. Yet, farmyard manure plus mineral N consistently achieved highest yields of all organic resource treatments at all sites and farmyard manure addition at 1.2 t C ha^{-1} yr^{-1} (about 5 t dry matter) was the most N-efficient treatment.
Conclusions: At realistic application rates, maize yield in integrated soil fertility management is best sustained by a combined application of farmyard manure and mineral N.
Implications: Mixed crop-livestock systems and a combined manure and mineral N application are key ingredients for sustained productivity of smallholder systems in sub-Saharan Africa.

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Table 1
Locations, soil properties and climatic conditions of the study sites. Soil properties are given for the 0–15 cm depth layer, and are based on a measurement before experiment start (1 reference profile per site). Coordinates are given in the WGS 84 reference system.

Soil characteristics	Embu	Machanga	Sidada	Aludeka
Latitude	-0.517	-0.793	0.143	0.574
Longitude	37.459	37.664	34.422	34.191
Initial soil C (g kg^{-1})$^{+}$	29	3	15	8
Initial N (g kg^{-1})$^{+}$	3.0	0.2	1.2	0.8
Initial bulk density (g cm^{-3})	1.26	1.51	1.3	1.45
pH (H_2O)	5.43	5.27	5.4	5.49
Clay (g kg^{-1})	598	132	557	134
Soil type (IUSS Working Group, 2014)	Humic Nitisol	Ferric Alisol	Humic Ferralsol	Haplic Acrisol
Altitude (m)	1380	1022	1420	1180
Mean annual rainfall (mm)*	1175	795	1730	1660
Mean annual temperature (°C)*	20.1	23.7	22.6	24.4
Months of long rainy season	3–8/9	3–8	3–8	3–8
Months of short rainy season	10–1/2	10–1/2	9–1	9–1

$^{+}$By dry combustion (CHN628, LECO Corporation, Michigan, USA) *Means calculated based on measured data from 2005 to 2020.

1. Introduction

The yields of maize (*Zea mays L.*) lag behind their potential in several countries of sub-Saharan Africa. For example, average maize grain yields in Kenya have stagnated around 1.65 t ha^{-1} over the last two decades (World-Bank, 2021). On the other hand, the yield potential for rainfed maize in the high-potential agroecological zones of Kenya is about 10 t ha^{-1} (Ittersum et al., 2016, https://www.yieldgap.org/). Many studies have shown that it is possible to close the maize yield gaps in sub-Saharan Africa if appropriate crop and soil management practices are implemented (e.g. Kiboi et al., 2017; Mutuku et al., 2020; Sileshi et al., 2010; Jindo et al., 2020).

Integrated Soil Fertility Management (ISFM) can contribute to increased maize yields and closing yield gaps in sub-Saharan Africa. It is a set of practices based on the combined use of fertilizer, organic resources, and improved crop varieties. ISFM is driven by the recognition that crop productivity in sub-Saharan Africa cannot be improved substantially without simultaneously addressing the short-term nutrient demand of crops as well as the long-term maintenance of soil fertility (Vanlauwe et al., 2010). The recommendation for a combined application of mineral fertilizer and organic resources is based on positive interactions between both inputs (Vanlauwe et al., 2001). The adaptation to local conditions and a focus on input use efficiency (Vanlauwe et al., 2010) aim to minimize the risk of nutrient losses polluting the environment. As such, ISFM is, among other practices, a practical pathway towards sustainable intensification.

The effectiveness of typical ISFM practices to increase maize yields by a factor of two or more compared to low/no input systems has been demonstrated in both on-station (Chivenge et al., 2009) and on-farm experiments (Mutuku et al., 2020) in central Kenya, but these studies only analyzed data from five and two years, respectively. Long-term experiments have given conflicting results. For example, long-term implementation of ISFM practices in a 50-year trial in a sandy soil in Burkina Faso led to sorghum yield increases (Adams et al., 2020), but maize yields under typical ISFM practices in a sandy soil in Nigeria experienced a steady decline over time (Vanlauwe et al., 2005). On the other hand, in a sandy soil in Ivory Coast, maize yields were sustained over 20 years with the combined application of N fertilizer and compost, despite losses in soil organic carbon (Cardinael et al., 2022). The reason for the different outcomes may be the differences in responsiveness of soils to mineral and/or organic fertilizer. For example, crop yields are known to be more responsive to mineral fertilizer addition in clayey soils than in coarse textured soils (Vanlauwe et al., 2015). Hence, the site specificity of the performance of ISFM practices should be examined in detail. Another reason for different outcomes of long-term studies on maize yield under ISFM could be that qualities of the added organic resources differed. Palm et al. (2001a); b) defined high-quality resources as high in N and low in lignin/polyphenols and low-quality resources as low in N and high in lignin and/or polyphenols. They also formulated three important concepts to be evaluated: 1) the potential and need of synchronization of crop N demand with N release by the organic resource for optimal crop responses, 2) that low-quality organic resources rich in recalcitrant lignin and polyphenol lead to more soil organic matter formation than high-quality resources, and 3) the potential trade-off between enhancing the synchrony with plant nutrient demand and increasing long-term soil fertility. In particular, a reexamination of this trade-off is timely, because new concepts of soil organic matter formation have evolved (Cotrufo et al., 2013; Denef et al., 2009). Finally, as recent studies also highlight the importance of pedoclimatic conditions for tropical soil carbon formation (Doetterl et al., 2018; von Fromm et al., 2021), any reevaluation of ISFM practices should also include studies across multiple sites subject to the exact same experimental treatments.

Here, we present such a study of the effect of different organic resource qualities and quantities combined with and without mineral N fertilizer addition on maize grain yields, yield trends over time and N use efficiencies. The study uses combined data from four long-term experiments, located in different parts of Kenya. They include typical ISFM treatments, such as the application of farmyard manure, but also treatments aimed at testing the hypotheses of Palm et al. (2001a, 2001b). Hence, the experiments are valuable to better understand the interactions of different factors, relevant within ISFM.

The specific research questions posed were i) how do combinations of different organic resource quantities and qualities with mineral N fertilizer affect maize yields in the short- and long-term, ii) how does the effect differ between sites with different soil textures/climates, and iii) which of these combinations utilize N most efficiently. We first hypothesized that in the shortterm, mineral N fertilizer application leads to a larger maize grain yield increase than organic resource application. Secondly, we hypothesized that only the addition of high amounts of high-quality organic resources (i.e. with a C/N ratio < 15 and low lignin/polyphenol content) increases yields over time. Consequently, we expected that high-quality organic resource treatments lead to highest yields in the long term. Thirdly, the effect of organic resources was hypothesized to be stronger in coarse textured soils, as they are usually more limited by water and nutrients. Our fourth hypothesis was that the best synchronisation of N supply and plant demand is realized by organic resources that slowly release their N (e.g. farmyard manure and externally sourced *Calliandra* material that is rich in polyphenols), and that these resources therefore possess the highest agronomic use efficiency of applied N.

2. Material and methods

This study used combined data from four ongoing long-term field experiments on different sites in Kenya, with identical experimental design and treatments. They include treatments that are relevant for maize cultivation under ISFM, yet at rather high rates of inputs to facilitate scientific understanding. Two experiments in central Kenya, located at Embu and Machanga, started in early 2002, whereas two experiments in western Kenya, at Sidada and Aludeka, were initiated in early 2005 (Table 1). Except for Machanga, the sites are representative of the high potential zones for maize cultivation in Kenya. Due to the bimodal rainfall regime, there are two maize growing seasons per year at all four sites. The long rainy season usually starts in March and lasts until August/September, while the short rainy season lasts from September/

Table 2
Dry matter based mean measured chemical characteristics (and 95% confidence intervals) of organic resources applied at all sites. Measurements were available from Embu and Machanga from 2002 to 2004, all sites from 2005 to 2007 and in 2018. Significant differences in residue properties were found between the different organic resources, but not between sites and years. Same letters within the same row indicate the absence of significant differences for that property ($p < 0.05$). Abbreviations: n.c. = not classified.

Measured property Abbreviation[x]	*Tithonia* TD1.2 (TD4) ± N	*Calliandra* CC1.2 (CC4) ± N	Maize stover MS1.2 (MS4) ± N	Sawdust SD1.2 (SD4) ± N	Farmyard manure FYM1.2 (FYM4) ± N
C (g kg^{-1})[+]	345[b] (333–357)	396[c] (383–409)	397[c] (386–408)	433[d] (416–449)	234[a] (213–255)
N (g kg^{-1})[+]	33.2[d] (28.9–38.2)	32.5[d] (28.3–37.3)	7.2[b] (6.5–8)	2.5[a] (2.1–2.8)	18.1[c] (15–21.8)
C/N ratio	12.4[a] (10.8–14.1)	13.6[a] (11.9–15.5)	58.7[b] (52.8–65.2)	199.1[c] (174.1–227.7)	12.3[a] (9.9–15.4)
P (g kg^{-1})[#]	2.3[d] (1.8–2.9)	1.1[c] (0.8–1.5)	0.4[b] (0.3–0.6)	0.1[a] (0–0.2)	3.1[d] (2.3–3.9)
K (g kg^{-1})[#]	37.2[c] (21.2–65.2)	8.7[b] (5–15.3)	9[b] (6–13.5)	2.8[a] (1.6–4.9)	19.4[bc] (7.8–48.6)
Lignin (g kg^{-1})[#]	90[ab] (62–117)	105[b] (77–133)	48[a] (37–60)	172[c] (144–199)	198[c] (154–242)
Polyphenols (g kg^{-1})[#]	19[c] (14.9–24.3)	108.7[d] (85.3–138.6)	11.3[b] (9.5–13.6)	4.9[a] (3.8–6.2)	7.8[ab] (5.2–11.5)
Ligin/N ratio	2.6[a] (1.8–3.7)	3.1[ab] (2.2–4.3)	6.2[c] (4.8–8)	58.3[d] (41.1–82.8)	6.9[bc] (3.9–12.3)
Quality / turnover speed*	High / fast	High / slow	Low / fast	Low / slow	n.c.
Class*	1	2	3	4	n.c.
kg N in 4.0 t C ha^{-1} yr^{-1}, -N [+N]	323 [563]	295 [535]	68 [308]	20 [260]	324 [564]
kg N in 1.2 t C ha^{-1} yr^{-1}, -N [+N]	97 [337]	88 [328]	20 [260]	6 [246]	97 [337]

[x]For 1.2 (or 4.0) t C ha^{-1} yr^{-1} treatments; [+]By dry combustion (CHN628, LECO Corporation, Michigan, USA); [#]Total digestion (P, K), acid detergent fiber (lignin) and Folin-Denis (polyphenols) according to Anderson and Ingram (1993); *according to Palm et al. (2001a); +N and -N indicate 120 or 0 kg ha^{-1} mineral N fertilizer application per growing season.

October until January/February (Table 1). The four sites differ in terms of altitude, mean annual precipitation (MAP), mean annual temperature (MAT) and soil texture. MAP (from 2005 to 2020) at Embu is 1175 mm, and with a MAT of 20.1 °C, it is the coldest of all sites. Machanga has a MAT of 24.4 °C, and with 795 mm MAP, it receives the lowest average annual rainfall. The sites in western Kenya both receive more annual rainfall than the central Kenyan sites; Aludeka has a MAT of 23.7 °C with 1660 mm MAP, while Sidada has a MAT of 22.6 °C with 1730 mm MAP. With clay contents of less than 15%, the soils at Machanga and Aludeka have a coarser texture than the soils at Sidada and Embu, which contain 56% and 60% clay, respectively. The soils at all sites are heavily weathered tropical soils, i.e. a Humic Nitisol at Embu, a Humic Ferralsol at Sidada, a Ferric Alisol at Machanga and a Haplic Acrisol at Aludeka (IUSS Working Group, 2014).

2.1. Description of the experiments and management

All four experiments were set up in a split plot design with three replicates, with plot sizes of 12 m x 5 m (Embu) or 12 m x 6 m (all other sites). The application of different organic resources in quantities of either 1.2 or 4 t C ha^{-1} yr^{-1} was the main treatment, while the addition of either no mineral N (-N treatment) or 120 kg N ha^{-1} per season (+N treatment) was the subplot treatment. The applied organic resources (Table 2) represented all four different classes of organic resources that were defined by Palm et al. (2001a): *Tithonia diversifolia* (TD; high quality and fast turnover; class 1) and *Calliandra calothyrsus* (CC; high quality and slower turnover; class 2) were externally sourced (i.e. cut-and-carry system) for this experiment. The stover of *Zea mays* (MS; low quality and fast turnover; class 3) was sourced from within the experiment, while sawdust from *Grevillea robusta* trees (SD; low quality and slow turnover; class 4), and locally available farmyard manure (FYM; no defined class by Palm et al., 2001a due to variability in quality) were externally sourced. A treatment without any organic resource addition served as the control (CT). Organic resources were applied once a year in the long rainy season before planting and were incorporated to 15 cm soil depth using hand hoes. The mineral N fertilizer (Ca NH_4 NO_3) was applied in a split application, with 40 kg N ha^{-1} applied at planting and 80 kg N ha^{-1} about six weeks later. In each season, all plots received a blanket application of 60 kg P ha^{-1} as triple superphosphate and 60 kg K ha^{-1} as muriate of potash at planting to ensure that P and K were not limiting. No lime was added. Experiments were subject to management practices typical of the regions, with tilling of plots using a hand hoe before planting in each season. Planting was done when the rains started. Plant spacing was 90 cm x 30 cm at Machanga and 75 cm x 25 cm at all other sites. A gap filling followed in the case of poor maize emergence, about two weeks after planting. Two weeks after gap filling, maize plants were thinned to reach the desired plant density (37.000 plants ha^{-1} at Machanga and 53.000 plants ha^{-1} at the other sites). Hand weeding was conducted two to three times per season. Selective pesticide application was done when necessary to protect against armyworm (*Spodoptera exempta*), stemborer (*Busseola fusca*) or termites (*Macrotermes* spp.). Yield assessment was conducted at maize maturity by hand harvesting a representative sub-plot with an area of 20 m^2 (Machanga), 18 m^2 (Embu), and 13.5 m^2 (Sidada and Aludeka), excluding the plot boundaries. The fresh weight of all cobs was recorded, and a representative sub-sample of 10 cobs was ovendried to constant weight to determine moisture content. From this, grain dry matter yield per ha was calculated. In a similar way, using measured moisture content of a sub-sample, dry matter yield of maize stover and the core of the cobs were calculated on ha^{-1} basis. After harvest, all maize stover was removed from all plots, so that apart from maize roots, the only input of organic material was that applied by the treatment. Further details on the experiments in central Kenya can be found in Chivenge et al. (2009) and Gentile et al., (2009, 2011). The data included in this study cover the entire experimental period until the year 2021, consisting of 31 cropping seasons (16 calendar years) in Sidada and Aludeka, and 37 cropping seasons (18 calendar years) in Embu and Machanga.

2.2. Statistical analyses and calculation of yield indices

All statistical analyses were conducted with mixed linear effects models using the 'nlme' package (Pinheiro et al., 2021) of the R software, version 4.0.4 (R Core Team, 2021). Plots were created with the 'ggplot2' package (Wickham et al., 2021). Post-hoc pairwise comparison of different treatments at different times was conducted by comparing their least square mean estimates computed with the mixed linear effects model. To display which treatments differed significantly from others (at $p < 0.05$), we made use of a letter design which was derived by applying the 'cld' function (Piepho, 2004) to the least square means computed with the help of the 'emmeans' package (Lenth, 2021). The degrees of freedom were estimated using the 'containment' method.

Note that throughout the whole paper, the term significant refers to the $p < 0.05$ threshold if not explicitly specified otherwise.

2.2.1. Analysis of grain yield and harvest index

Maize grain dry matter yield in t ha^{-1} per season was the dependent variable of the statistical models, while the organic resource treatment, the mineral N fertilizer treatment, the time in years passed since the start

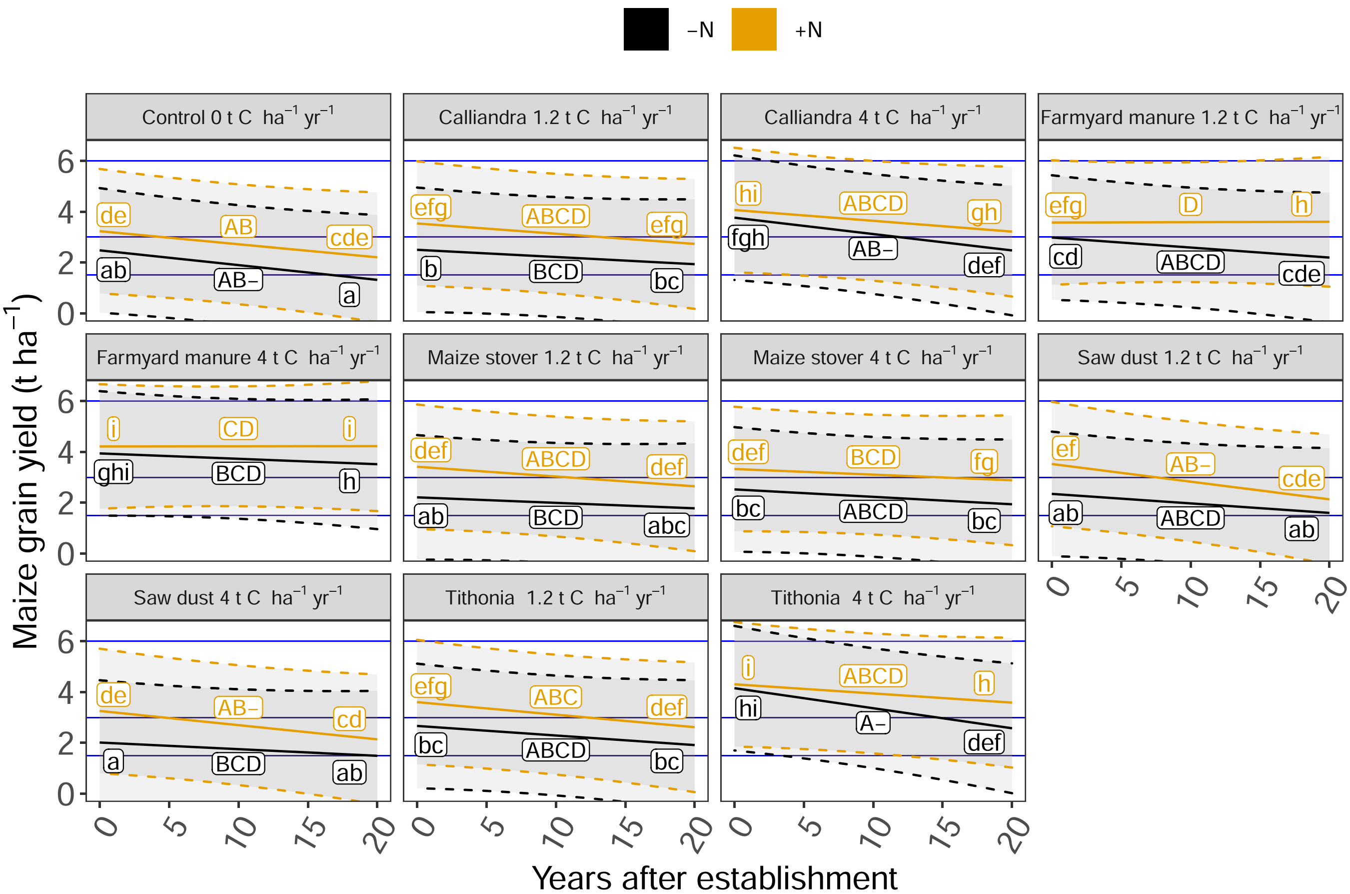

Fig. 1. Least square means of seasonal maize grain yields over time for different organic resource applications at either 1.2 or 4 t C ha^{-1} yr^{-1} and with versus without 120 kg mineral N ha^{-1} per season (+N and -N) across all sites (Random Site model). Same lowercase letters at the same time indicate the absence of a significant difference between treatments at that time (calculated for year 1 and 18). Treatments that share capital letters do not have significantly different slopes for the temporal development; the - indicates a negative temporal trend that is significantly different from zero (all $p < 0.05$). The thin blue lines indicate a poor, acceptable and above average yield (1.5, 3 and 6 t ha^{-1} per season, respectively). The grey shaded areas constrained by the dashed lines indicate the 95% confidence intervals across sites. Values for the slope are in Table B1.

of the experiment, the season and the interactions thereof up to the level of four-way interactions, were the independent fixed effects. The hierarchical structure of the split plot design was accounted for by nested random effects. In a first model, site was additionally treated as a random effect with the goal of obtaining general trends across all sites (Random Site model). A second model was used to make sitespecific evaluations (Fixed Site model). In this model, the random intercept for site was removed, and a fixed interaction of site with the other fixed effects was introduced. Apart from that, model construction followed the same procedure in both the Random Site and Fixed Site model. For a further analysis of harvest index and agronomic use efficiency of N, only a Fixed Site model was constructed.

For both Random Site and Fixed Site models, different random effect structures including random slope and intercept were compared and evaluated based on the Akaike information criterion (AIC) using restricted maximum likelihood estimation (Zuur et al., 2009). The lowest AIC was obtained by the models with nested random intercepts for the main plot nested in block, season and site, in that order. After accounting for the random variability from season to season by a random intercept for each individual season, random slopes for the time since the start of the experiment were, according to the AIC, not needed. A visual inspection of residuals and comparison of the AICs revealed variance heterogeneity between sites, so residual variance was allowed to differ between sites. Visual inspection also revealed slightly tailed quantile-quantile plots, mostly due to complete yield failure in some years, which happened most often at Machanga. A log-transformation of the dependent variable did little to improve quantile-quantile plots while introducing bias to the residuals, and was thus not used. Considering the large number of observations (>8000), the tails represented only a small fraction of data while histograms of residuals were nearly normally distributed (skewness = 0.3, kurtosis = 5.4 for both models). With the prior points in mind, the models were considered suitable (likelihood-based pseudo R^2 of 0.79 and 0.82 for the model with site as random and fixed effect, respectively; Nagelkerke, 1991). The estimations of fixed effects within linear mixed effects models are robust against slight cases of heteroscedasticity (Jacqmin-Gadda et al., 2007) and even severe cases of skewed residual patterns (Schielzeth et al., 2020). Violations mainly result in increased uncertainty of model predictions, which was counteracted by the large number of seasons represented, and thus a severe bias is avoided (Schielzeth et al., 2020). After determining the most suitable random effects structure and checking model assumptions by plotting residuals against the dependent variable and all fixed effects, a backwards elimination of fixed effects interactions was done (Zuur et al., 2009) by applying maximum likelihood estimation, removing them one by one starting with highest-order interactions until all remaining interaction effects were significant (see Appendix B1 for the ANOVA table of the final model and the graphical model evaluation). A limitation of treating site as random (Random Site model) is that experimental sites are usually not randomly selected locations (Piepho, 1998). Yet, the four experimental sites covered a range of soil fertility and climatic conditions, and the statistical model accounts for the use of only four sites through the prediction uncertainty. To obtain

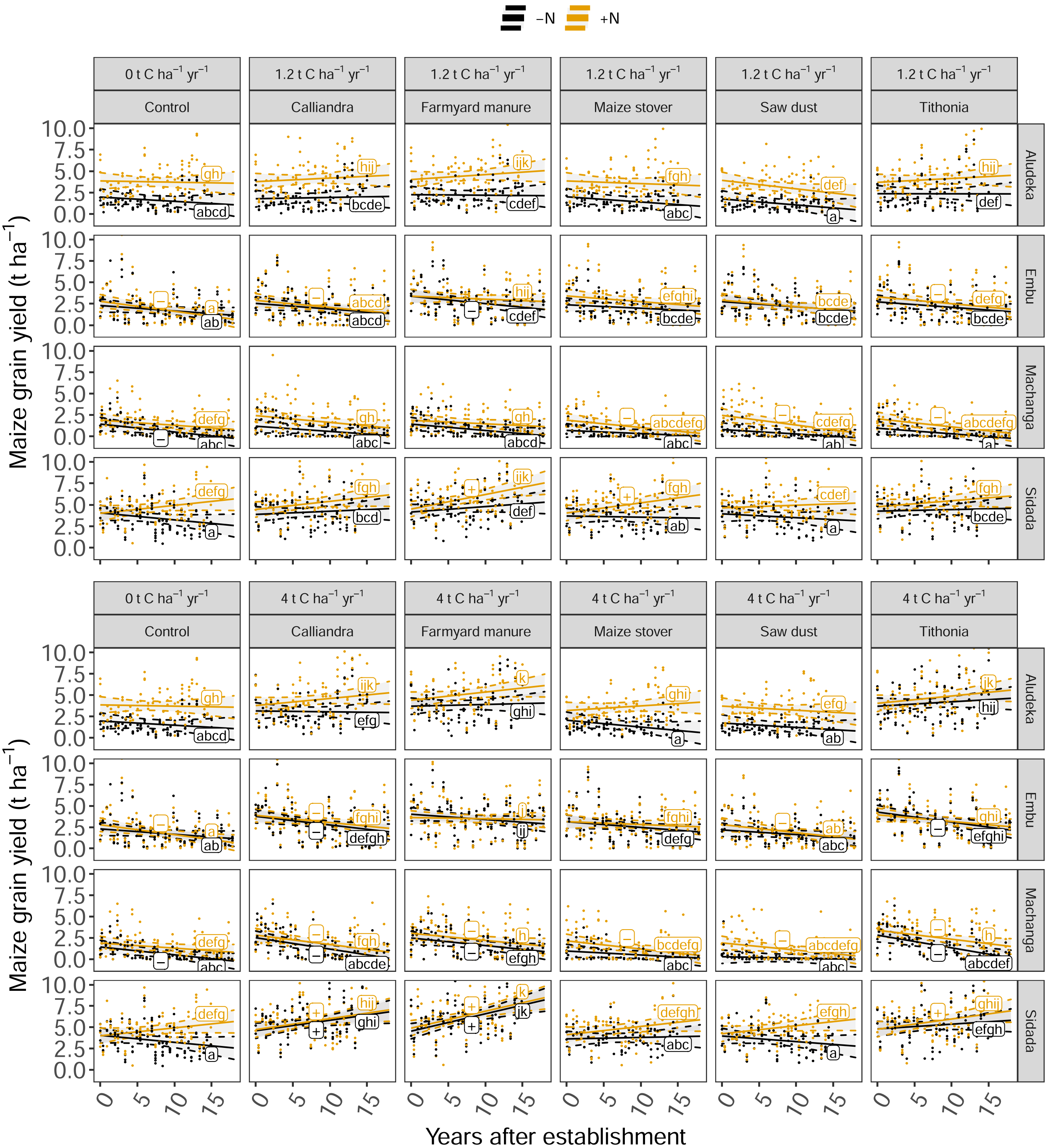

Fig. 2. Least square means of seasonal maize grain yields over time for different organic resource applications at either 1.2 or 4 t C ha^{-1} yr^{-1} and with or without 120 kg ha^{-1} per season (+N and -N) by site (Fixed Site model). Same lowercase letters within the same site indicate the absence of a significant difference between treatments at that site in year 16 (chosen because the western Kenya sites only existed since 16 years). Where either + or - are displayed at the regression center, the temporal trend was is significantly larger or smaller than zero (all $p < 0.05$). The grey shaded areas constrained by the dashed lines indicate the 95% confidence interval of the treatment mean for each site. Dots represent measured data (n = 3 per season and treatment). Values for the trends and yields are in Table 3.

the most general conclusions about the yield trends under ISFM, this Random Site model was considered the best option, while the Fixed Site model was used to predict site-specific yield trends (Table 3). We present average maize yields against roughly defined thresholds for a poor, medium/acceptable, and a conservative estimate of "attainable average yield". Those thresholds were chosen as 1.5 t ha^{-1} $season^{-1}$ for poor, 3 t ha^{-1} $season^{-1}$ for medium and 6 t ha^{-1} $season^{-1}$ for attainable yield, based on, respectively, the current low yields in Kenya (Anon, 2021), the target yield to achieve food self-sufficiency in Kenya (Sileshi et al., 2019; Sanchez, 2015) and 60% of the water-limited yield potential of maize in the high-potential agroecological zones of Kenya (up to 10 t ha^{-1} Ittersum et al., 2016, https://www.yieldgap.org/).

Table 3
Estimated least square means of yield by treatment, site and year and of temporal yield trends by site (Fixed Site model). Same lowercase letters within the same site and year show the absence of a significant difference in yield. Same uppercase letters within the same site show the absence of a significant difference in temporal trends of yield, an asterisk (*) shows temporal trends that differ significantly from 0 (All $p < 0.05$).

Teatment	t C ha^{-1} yr^{-1}	± N^{x}	Aludeka year 1	Aludeka year 16	Aludeka trend	Embu year 1	Embu year 16	Embu trend	Machanga year 1	Machanga year 16	Machanga trend	Sidada year 1	Sidada year 16	Sidada trend
Control	0	-N	1.92^{a}	1.17^{abcd}	-0.05^{ABCD}	2.23^{a}	1.28^{ab}	-0.06^{ABCD}	1.34^{bcd}	-0.04^{abc}	-0.09^{ABCD*}	3.97^{abc}	2.74^{a}	-0.08^{A}
Control	0	+N	3.84^{cd}	3.62^{gh}	-0.01^{ABCDE}	2.66^{abc}	0.92^{a}	-0.12^{AB*}	1.83^{cde}	0.93^{defg}	-0.06^{BCD}	4.09^{abc}	5.49^{defg}	0.09^{DEFG}
Calliandra	1.2	-N	1.79^{a}	2.01^{bcde}	0.01^{ABCDE}	2.47^{ab}	1.48^{abcd}	-0.07^{ABCD}	1.12^{bc}	0.21^{abc}	-0.06^{BCD}	3.91^{abc}	4.47^{bcd}	0.04^{ABCDE}
Calliandra	1.2	+N	3.81^{cd}	4.44^{hij}	0.04^{BCDE}	2.81^{abc}	1.58^{abcd}	-0.08^{ABCD*}	2.34^{efgh}	1.15^{gh}	-0.08^{ABCD}	4.55^{abcd}	5.96^{fgh}	0.09^{DEFG}
Calliandra	4	-N	3.14^{bc}	2.98^{efg}	-0.01^{ABCDE}	3.67^{defg}	2.15^{defgh}	-0.1^{ABC*}	2.38^{efgh}	0.38^{abcde}	-0.13^{AB*}	4.72^{bcd}	6.56^{ghi}	0.12^{EFG*}
Calliandra	4	+N	3.86^{cd}	5.11^{ijk}	0.08^{E}	3.8^{efg}	2.53^{fghi}	-0.08^{ABCD*}	2.71^{ghi}	1.05^{fgh}	-0.11^{ABC*}	4.85^{bcd}	6.79^{hij}	0.13^{EFG*}
Farmyard manure	1.2	-N	2.24^{ab}	2.14^{cdef}	-0.01^{ABCDE}	3.29^{cdef}	2^{cdef}	-0.09^{ABCD*}	1.35^{bcd}	0.24^{abcd}	-0.07^{ABCD}	4.21^{abcd}	5.17^{def}	0.06^{CDEF}
Farmyard manure	1.2	+N	4.07^{cd}	4.94^{ijk}	0.06^{DE}	3.35^{cdef}	2.83^{hij}	-0.03^{CD}	1.84^{cde}	1.22^{gh}	-0.04^{CD}	4.67^{bcd}	7.21^{ijk}	0.17^{FG*}
Farmyard manure	4	-N	3.72^{cd}	4.03^{ghi}	0.02^{ABCDE}	3.95^{fg}	3.02^{ij}	-0.06^{ABCD}	2.4^{efgh}	1.06^{efgh}	-0.09^{ABCD*}	4.75^{bcd}	7.8^{jk}	0.2^{G*}
Farmyard manure	4	+N	4.5^{d}	5.93^{k}	0.1^{E}	3.62^{defg}	3.4^{j}	-0.01^{D}	2.95^{hi}	1.7^{h}	-0.08^{ABCD*}	5.1^{d}	8.08^{k}	0.2^{G*}
Maize stover	1.2	-N	1.94^{a}	1.03^{abc}	-0.06^{ABCD}	2.34^{a}	1.73^{bcde}	-0.04^{BCD}	0.66^{ab}	0.1^{abc}	-0.04^{CD}	3.67^{a}	3.47^{ab}	-0.01^{ABCD}
Maize stover	1.2	+N	3.82^{cd}	3.36^{fgh}	-0.03^{ABCDE}	3.34^{cdef}	2.34^{efghi}	-0.07^{ABCD}	1.81^{cde}	0.52^{abcdefg}	-0.09^{ABCD*}	4.15^{abcd}	5.93^{fgh}	0.12^{EFG*}
Maize stover	4	-N	1.98^{a}	0.77^{a}	-0.08^{AB}	3.07^{bcd}	2.07^{defg}	-0.07^{ABCD}	0.91^{ab}	0.21^{abc}	-0.05^{CD}	3.65^{a}	3.91^{abc}	0.02^{ABCDE}
Maize stover	4	+N	3.25^{bc}	4.06^{ghi}	0.05^{CDE}	3.12^{bcde}	2.6^{fghi}	-0.03^{CD}	2.05^{defg}	0.62^{bcdefg}	-0.1^{ABC*}	4.22^{abcd}	5.68^{defgh}	0.1^{DEFG}
Saw dust	1.2	-N	1.68^{a}	0.63^{a}	-0.07^{ABC}	2.68^{abc}	1.78^{bcde}	-0.06^{ABCD}	0.75^{ab}	-0.03^{ab}	-0.05^{CD}	3.89^{ab}	3.22^{a}	-0.04^{ABC}
Saw dust	1.2	+N	3.82^{cd}	2.34^{def}	-0.1^{A}	2.84^{abc}	1.72^{bcde}	-0.07^{ABCD}	2.34^{efgh}	0.64^{cdefg}	-0.11^{ABC*}	4.67^{bcd}	5.13^{cdef}	0.03^{ABCDE}
Saw dust	4	-N	1.68^{a}	0.9^{ab}	-0.05^{ABCD}	2.12^{a}	1.31^{abc}	-0.05^{ABCD}	0.27^{a}	0.02^{abc}	-0.02^{D}	3.91^{abc}	2.92^{a}	-0.07^{AB}
Saw dust	4	+N	3.67^{cd}	2.94^{efg}	-0.05^{ABCD}	2.71^{abc}	1.28^{ab}	-0.09^{ABC*}	1.82^{cde}	0.56^{abcdefg}	-0.08^{ABCD*}	4.33^{abcd}	5.76^{efgh}	0.1^{DEFG}
Tithonia	1.2	-N	2.36^{ab}	2.34^{def}	0^{ABCDE}	2.66^{abc}	1.7^{bcde}	-0.06^{ABCD}	0.88^{ab}	-0.09^{a}	-0.06^{BCD}	4.27^{abcd}	4.55^{bcde}	0.02^{ABCDE}
Tithonia	1.2	+N	3.73^{cd}	4.41^{hij}	0.05^{BCDE}	3.23^{cdef}	2.02^{defg}	-0.08^{ABCD*}	1.95^{def}	0.55^{abcdefg}	-0.09^{ABCD*}	4.84^{bcd}	5.89^{fgh}	0.07^{CDEF}
Tithonia	4	-N	3.75^{cd}	4.52^{hij}	0.05^{CDE}	4.15^{g}	2.38^{efghi}	-0.12^{A*}	2.67^{fghi}	0.44^{abcdef}	-0.15^{A*}	4.86^{bcd}	5.7^{efgh}	0.06^{BCDEF}
Tithonia	4	+N	4.13^{cd}	5.42^{jk}	0.09^{E}	3.87^{fg}	2.7^{ghi}	-0.08^{ABCD}	3.29^{i}	1.71^{h}	-0.11^{ABC*}	4.89^{cd}	6.69^{ghij}	0.12^{EFG*}

^{x}Corresponds to 120 or 0 kg N ha^{-1} season^{-1}

More information can be found in Appendix (B1).

2.3. *Calculation of agronomic use efficiency of applied N*

The agronomic use efficiency of applied N (AE_N), as defined by Vanlauwe et al. (2011), was calculated in two ways. First, it was calculated for the total amount of N applied in the form of mineral fertilizer and organic resource combined. The reference treatment for this was the replicate specific control treatment without any inputs:

$$\mathbf{AE_{totN}(kg/kgN)} = \frac{Y_{TRT} - Y_C}{totN_{appl}}$$

where AE_{totN} is the increase of maize grain yield compared to the unfertilized control treatment in kg ha^{-1} per kg N ha^{-1} applied. Y_{TRT} is the yield (kg ha^{-1}) of the treatment under consideration, Y_C is the yield of the unfertilized control (kg ha^{-1}) and $totN_{appl}$ the amount of N applied in the form of mineral fertilizer and organic resources combined (kg N ha^{-1}). Since organic resources were applied only once per year, AE_{totN} was calculated on an annual basis, based on the annual sum of applied N and the annual sum of yields per plot. Low-quality organic resources (MS and SD) without mineral N additions often resulted in unrealistically negative or positive AE_{totN}, with values up to ± 1000, far beyond the theoretical maximum dilution of N for maize, which is estimated to be 70 kg grain kg^{-1} N (Vanlauwe et al., 2011). This was interpreted as random noise, mostly due to N immobilization dynamics with low-quality organic resource additions and year to year variability of their N content. Because sole application of MS and SD to supply N is not of any field relevance, the -N treatments of SD and MS were not included in the analysis of AE_{totN} in order to be able to fit the statistical model.

As a second indicator, the agronomic use efficiency of only the mineral N applied was calculated on a seasonal basis. This could be done only for the +N treatments on the basis of the respective -N treatments:

$$\mathbf{AE_{minN}(kg/kgN)} = \frac{Y_{TRT+N} - Y_{TRT-N}}{120kg\ Nha^{-1}}$$

where AE_{minN} is the increase of maize grain yield compared to the -N treatment in kg kg^{-1} N applied. Y_{TRT+N} is the yield (kg ha^{-1}) of the +N treatment under consideration, Y_{TRT-N} is the yield (kg ha^{-1}) of the respective -N treatment. The difference of both is divided by the amount of N applied in the form of mineral fertilizer (120 kg N ha^{-1} per season). The results and discussion of the agronomic use efficiency of only the mineral N applied are found in the Appendix (A).

3. Results

3.1. *Maize yields and their trends across sites (Random Site model)*

For a general assessment of the ISFM practices, maize yield trends of the different ISFM treatments across sites were estimated with the Random Site model. Because a linear model was used to represent the yield trends over time, we show the estimated maize grain yields in the first and last year of the experiments, together with the temporal trends, i.e. slopes of the estimated linear regressions. Mean maize grain yields across sites in year 1 were between 4.27 t ha^{-1} per season (for TD4+N) and 1.99 t ha^{-1} per season (for SD4-N; Fig. 1). FYM4+N and FYM1.2+N were the only treatments for which the trend of maize yields across sites was positive (yet not significantly different from 0). In contrast, the treatments TD4-N, SD1.2+N, CC4-N, CT-N, SD4+N and TD1.2+N all experienced a decline of yields over time (Table B1). As a consequence, mean yields across sites in year 18 were between 4.22 t ha^{-1} per season (for FYM4+N) and 1.43 t ha^{-1} per season (for CT-N). With the exception of CT-N, all treatments with significant yield decline were treatments with high N loads (mineral plus organic N) and with initially relatively high yields. An increasing differentiation over time of yields in -N and +N treatments of a given organic resource treatment was found for CC4,

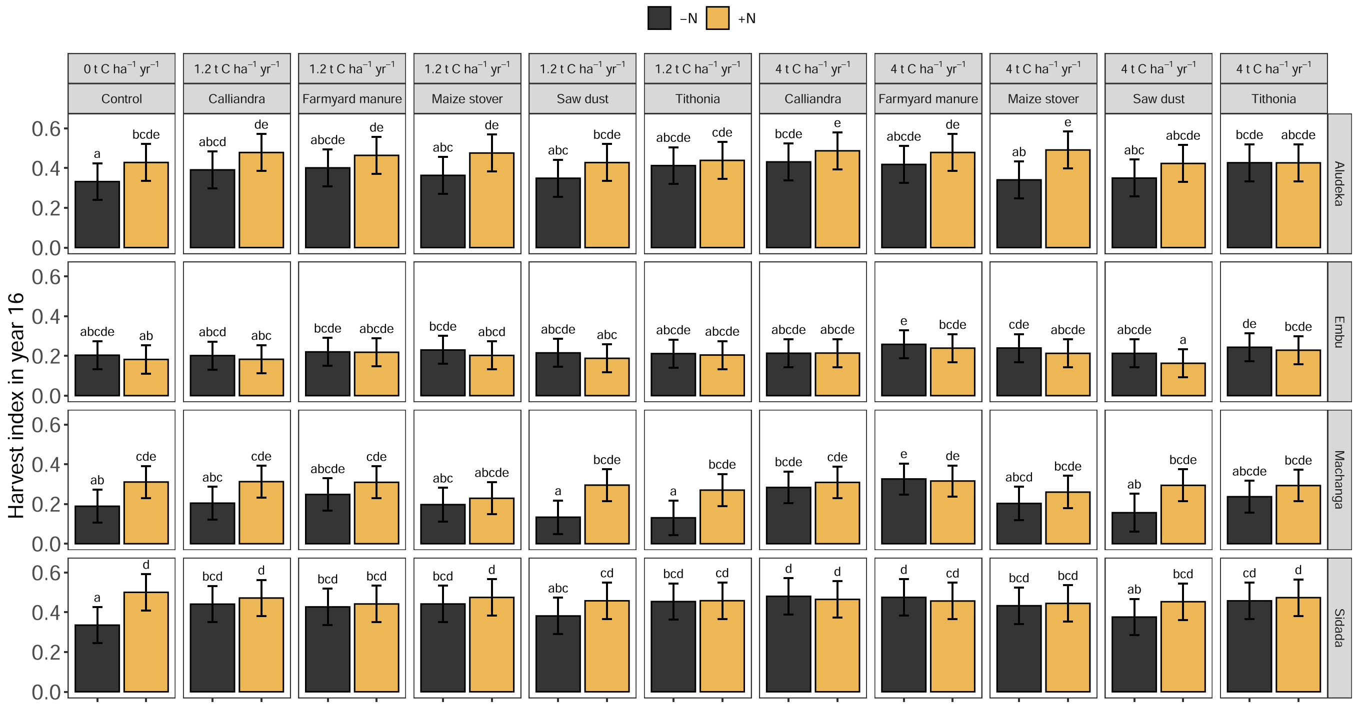

Fig. 3. Least square means of the harvest index, in year 16 by site (Fixed Site model). Same lowercase letters at the same site indicate the absence of a significant difference between treatments at that site (all $p < 0.05$). The error bars indicate the 95% confidence interval.

Table 4
Estimated agronomic efficiency of yearly N application of mineral N and N by organic resources combined. Displayed are results for year 1 and 16. Same lowercase letters indicate the absence of a significant difference between treatments at that same site and year (all $p < 0.05$).

Year	Treatment	Aludeka	95% CI	Embu	95% CI	Machanga	95% CI	Sidada	95% CI
1	Control 0 t C ha^{-1} yr^{-1} +N	17.1^{c}	12–22	4.2^{ab}	-0–9	4.9^{ab}	01–9	-0.3^{a}	-6–5
1	Calliandra 1.2 t C ha^{-1} yr^{-1}-N	0.7^{ab}	-9–10	8.5^{abcd}	01–16	1.7^{ab}	-6–9	-2.4^{a}	-13–8
1	Calliandra 1.2 t C ha^{-1} yr^{-1} +N	12.9^{abc}	09–17	3.6^{a}	-0–8	6.9^{b}	03–11	2.3^{a}	-2–7
1	Calliandra 4 t C ha^{-1} yr^{-1}-N	9.5^{abc}	05–14	9.8^{bcd}	06–14	7.4^{b}	03–12	3.6^{a}	-2–9
1	Calliandra 4 t C ha^{-1} yr^{-1} +N	8.2^{a}	05–12	5.9^{ab}	03–9	5.2^{ab}	02–9	2.5^{a}	-1–6
1	Farmyard manure 1.2 t C ha^{-1} yr^{-1}-N	9.3^{abc}	01–18	24.6^{e}	18–31	5.9^{ab}	-1–13	4.5^{a}	-5–14
1	Farmyard manure 1.2 t C ha^{-1} yr^{-1} +N	14^{bc}	10–18	7.1^{abc}	03–11	3.6^{ab}	-0–7	3.2^{a}	-1–8
1	Farmyard manure 4 t C ha^{-1} yr^{-1}-N	12.5^{abc}	08–17	11^{cd}	07–15	6.9^{ab}	03–11	3.6^{a}	-1–9
1	Farmyard manure 4 t C ha^{-1} yr^{-1} +N	10.2^{ab}	07–14	5.1^{ab}	02–8	5.9^{ab}	03–9	3.3^{a}	-0–7
1	Maize stover 1.2 t C ha^{-1} yr^{-1} +N	15.3^{bc}	10–20	9^{abcd}	05–13	4^{ab}	-0–8	-0.1^{a}	-6–5
1	Maize stover 4 t C ha^{-1} yr^{-1} +N	9.4^{abc}	05–14	6.4^{abc}	02–10	5.3^{ab}	01–9	0.4^{a}	-4–5
1	Saw dust 1.2 t C ha^{-1} yr^{-1} +N	16.1^{bc}	11–21	5.5^{abc}	01–10	9.4^{b}	05–14	4.2^{a}	-2–10
1	Saw dust 4 t C ha^{-1} yr^{-1} +N	15.1^{bc}	10–20	4.4^{ab}	-0–9	5.4^{ab}	01–10	2^{a}	-4–8
1	Tithonia 1.2 t C ha^{-1} yr^{-1}-N	15.2^{abc}	06–24	13.9^{abcde}	07–21	-5.5^{a}	-13–2	3.9^{a}	-6–14
1	Tithonia 1.2 t C ha^{-1} yr^{-1} +N	12.6^{abc}	08–17	6.2^{abc}	02–10	3.9^{ab}	00–8	3.8^{a}	-1–8
1	Tithonia 4 t C ha^{-1} yr^{-1}-N	14^{abc}	09–19	12.9^{d}	09–17	8.9^{b}	05–13	4.3^{a}	-1–9
1	Tithonia 4 t C ha^{-1} yr^{-1} +N	9.4^{ab}	06–13	6.1^{ab}	03–9	7.3^{b}	04–11	2.5^{a}	-1–6
16	Control 0 t C ha^{-1} yr^{-1} +N	19.6^{abcde}	14–26	-2.5^{a}	-7–1	7.5^{ab}	04–11	15.6^{abcd}	09–22
16	Calliandra 1.2 t C ha^{-1} yr^{-1}-N	19.9^{abcde}	09–31	$7.2^{abcdefg}$	01–14	4.9^{ab}	-2–12	30.7^{cde}	19–42
16	Calliandra 1.2 t C ha^{-1} yr^{-1} +N	18.7^{abcde}	13–24	1.9^{abc}	-2–6	6.8^{ab}	03–10	13.8^{abc}	08–19
16	Calliandra 4 t C ha^{-1} yr^{-1}-N	11.9^{ab}	06–18	5.2^{bcdefg}	01–9	2.8^{ab}	-1–7	19.6^{bcd}	13–26
16	Calliandra 4 t C ha^{-1} yr^{-1} +N	13.9^{ac}	10–18	4.1^{bcd}	01–7	3.8^{a}	01–7	11.1^{ab}	07–15
16	Farmyard manure 1.2 t C ha^{-1} yr^{-1}-N	21.1^{abcde}	11–31	14.6^{g}	08–21	5.1^{ab}	-2–12	40.3^{e}	29–51
16	Farmyard manure 1.2 t C ha^{-1} yr^{-1} +N	20.9^{e}	16–26	8.1^{efg}	05–12	6.8^{ab}	03–10	20.5^{cd}	15–26
16	Farmyard manure 4 t C ha^{-1} yr^{-1}-N	16.9^{abcde}	11–22	9.4^{fg}	06–13	6.2^{ab}	02–10	25.5^{de}	20–31
16	Farmyard manure 4 t C ha^{-1} yr^{-1} +N	15.8^{abcde}	12–20	6.5^{efg}	04–10	5.6^{ab}	03–9	14.7^{bc}	10–19
16	Maize stover 1.2 t C ha^{-1} yr^{-1} +N	16.5^{abcde}	11–23	7.5^{defg}	04–11	3.9^{ab}	-0–8	17.4^{abcd}	11–24
16	Maize stover 4 t C ha^{-1} yr^{-1} +N	17.7^{abcde}	12–23	7.7^{defg}	04–11	4.1^{ab}	00–8	13.4^{abc}	08–19
16	Saw dust 1.2 t C ha^{-1} yr^{-1} +N	9.7^{a}	03–16	3.5^{abcdef}	-1–8	5.2^{ab}	01–9	13.2^{abc}	06–20
16	Saw dust 4 t C ha^{-1} yr^{-1} +N	14.4^{abcde}	08–21	0.5^{ab}	-4–5	4.6^{ab}	00–9	19.6^{abcd}	13–26
16	Tithonia 1.2 t C ha^{-1} yr^{-1}-N	29.6^{cde}	19–40	11.5^{cdefg}	05–18	-1.6^{ab}	-9–5	32.3^{cde}	21–44
16	Tithonia 1.2 t C ha^{-1} yr^{-1} +N	19.3^{abcde}	14–24	4^{bcde}	00–8	3.3^{ab}	-0–7	14.1^{abc}	08–20
16	Tithonia 4 t C ha^{-1} yr^{-1}-N	21.7^{bde}	16–27	6.4^{bcdefg}	03–10	3^{ab}	-1–7	14.6^{abc}	08–21
16	Tithonia 4 t C ha^{-1} yr^{-1} +N	14.9^{abcd}	11–19	4.6^{bcd}	02–8	6^{b}	03–9	10.7^{a}	06–15

Table A1
Estimated agronomic efficiency of mineral nitrogen application in year 1 and 16 (in kg grain yield per kg mineral N applied; +N treatments only). Same lowercase letters indicate the absence of a significant difference between treatments at the same site and year (all $p < 0.05$).

Year	Treatment	Aludeka	95% CI	Embu	95% CI	Machanga	95% CI	Sidada	95% CI
1	Control 0 t C ha^{-1} yr^{-1}	21^{d}	16–26	2.9^{abc}	-1–7	1.2^{a}	-3–6	2.2^{a}	-3–8
1	Calliandra 1.2 t C ha^{-1} yr^{-1}	21.5^{d}	16–27	1.7^{abc}	-3–6	7.8^{ab}	03–12	6.1^{a}	00–12
1	Calliandra 4 t C ha^{-1} yr^{-1}	10.3^{abc}	05–16	0.1^{ab}	-4–4	0.7^{a}	-4–5	1.7^{a}	-4–7
1	Farmyard manure 1.2 t C ha^{-1} yr^{-1}	19.6^{cd}	14–25	-0.4^{ab}	-5–4	1.6^{a}	-3–6	4.2^{a}	-1–10
1	Farmyard manure 4 t C ha^{-1} yr^{-1}	9.8^{ab}	04–15	-3.7^{a}	-8–1	2.5^{ab}	-2–7	3.4^{a}	-2–9
1	Maize stover 1.2 t C ha^{-1} yr^{-1}	20.7^{d}	15–26	7.4^{c}	03–12	6.3^{ab}	02–11	4.7^{a}	-1–10
1	Maize stover 4 t C ha^{-1} yr^{-1}	15.9^{bcd}	11–21	-0.6^{ab}	-5–4	6^{ab}	01–11	5.4^{a}	-0–11
1	Saw dust 1.2 t C ha^{-1} yr^{-1}	23.1^{d}	18–28	0.2^{ab}	-4–5	10.3^{b}	06–15	7.2^{a}	01–13
1	Saw dust 4 t C ha^{-1} yr^{-1}	22^{d}	17–27	4^{bc}	-0–8	9.8^{b}	05–14	4.2^{a}	-1–10
1	Tithonia 1.2 t C ha^{-1} yr^{-1}	15.7^{bcd}	10–21	3.7^{bc}	-1–8	6.2^{ab}	02–11	5.2^{a}	-0–11
1	Tithonia 4 t C ha^{-1} yr^{-1}	5.8^{a}	00–11	-3.4^{a}	-8–1	3.9^{ab}	-1–9	0.8^{a}	-5–6
16	Control 0 t C ha^{-1} yr^{-1}	18.7^{abc}	12–26	-2.7^{a}	-7–2	7.2^{a}	02–12	23.8^{d}	16–31
16	Calliandra 1.2 t C ha^{-1} yr^{-1}	19.6^{abc}	13–27	1.8^{abc}	-3–7	5.6^{a}	01–10	13.1^{abcd}	06–21
16	Calliandra 4 t C ha^{-1} yr^{-1}	18.3^{abc}	11–25	4.4^{bc}	-0–9	1.9^{a}	-3–7	3.7^{a}	-4–11
16	Farmyard manure 1.2 t C ha^{-1} yr^{-1}	23.4^{bc}	16–30	8.1^{c}	03–13	5.5^{a}	01–10	20.3^{cd}	13–28
16	Farmyard manure 4 t C ha^{-1} yr^{-1}	19abc	12–26	4.4^{bc}	-0–9	2.2^{a}	-3–7	5.1^{ab}	-2–13
16	Maize stover 1.2 t C ha^{-1} yr^{-1}	17.4^{abc}	10–24	6.6^{bc}	02–11	3.3^{a}	-1–8	21.3^{cd}	14–29
16	Maize stover 4 t C ha^{-1} yr^{-1}	24.6^{c}	18–32	5.8^{bc}	01–11	3.6^{a}	-1–8	16.2^{abcd}	09–24
16	Saw dust 1.2 t C ha^{-1} yr^{-1}	11.7^{a}	05–19	0.7^{ab}	-4–5	4.8^{a}	-0–10	16.9^{bcd}	09–24
16	Saw dust 4 t C ha^{-1} yr^{-1}	13.9^{abc}	07–21	0.7^{ab}	-4–5	4.3^{a}	-1–9	24.3^{d}	17–32
16	Tithonia 1.2 t C ha^{-1} yr^{-1}	17.4^{abc}	10–24	4.3^{bc}	-0–9	3.2^{a}	-2–8	13.1^{abcd}	06–21
16	Tithonia 4 t C ha^{-1} yr^{-1}	12.5^{ab}	05–20	4.1^{bc}	-1–9	5.6^{a}	01–10	10.7^{abc}	03–18

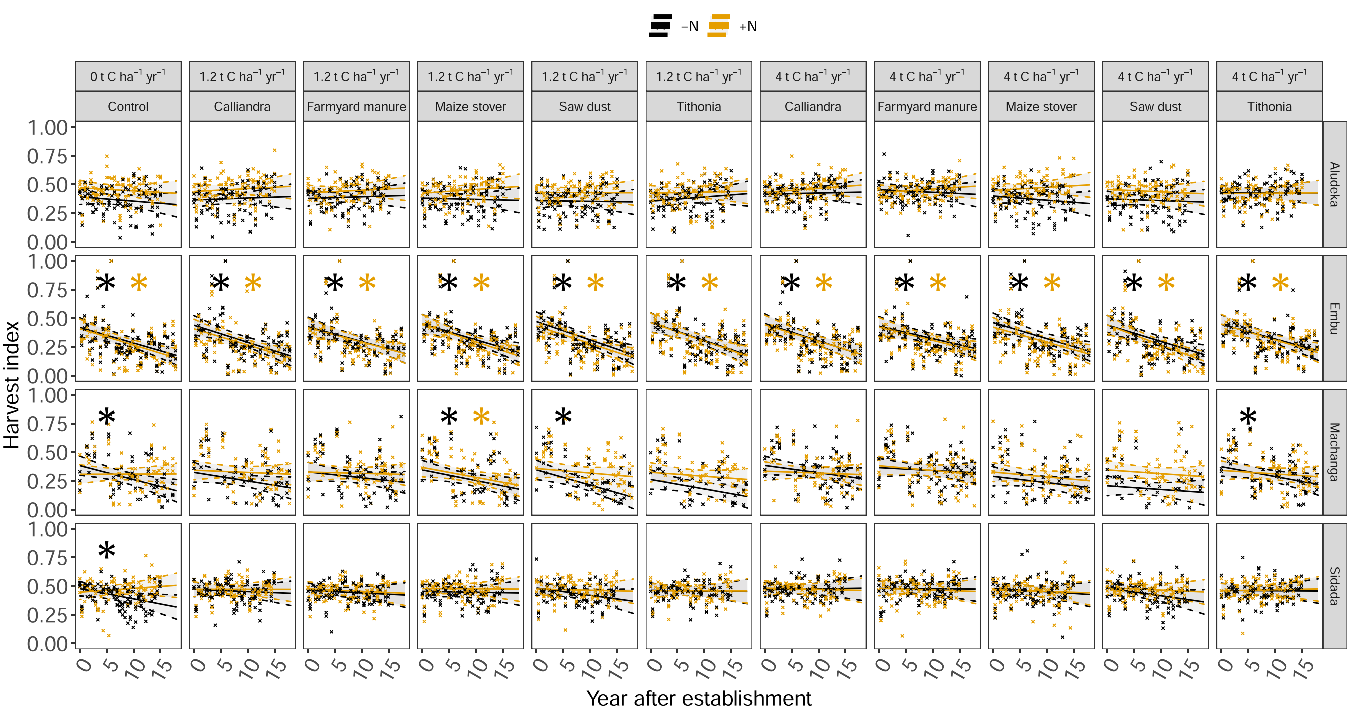

Fig. B1. Least square means (trend-lines) of the harvest index over time for different ISFM management schemes by site (Fixed Site model). Treatments that have slopes for the temporal development, which are significantly smaller than 0 (at $p < 0.05$) are indicated by an asterisk (*). The grey shaded areas constrained by the dashed lines indicate the 95% confidence intervals of the treatment mean for each site. Dots represent measured data (n = 3 per season and treatment).

FYM4 and TD4. These treatments did not show a significant yield difference between +N and -N treatments in year 1, while in year 18 they did. Because of its significant yield decline over time, TD4-N did not show significantly higher yields than CT+N in year 18. In fact, from all -N treatments only FYM4-N did have a significantly higher yield than CT+N in year 18, but it should be noted that with a total annual N input of 331 kg N ha^{-1} year^{-1} this treatment received a higher N load than CT+N. Yet, even when compared to treatments of similar N loads (i.e. TD4-N, CC4-N, and MS4+N, with 300–320 kg N ha^{-1} yr^{-1}), FYM4-N in year 18 had significantly higher yields (3.56 t ha^{-1} per season) than MS4+N, TD4-N and CC4-N (2.93, 2.73 and 2.60 t ha^{-1} per season, respectively).

Interestingly, despite the classified slower turnover rate of *Calliandra* residues compared to *Tithonia* residues (Palm et al., 2001a), there was no significant yield difference between these two treatments at the same application rate of 1.2 or 4 t C ha^{-1} year^{-1} in neither the +N nor the -N treatments. Additionally, across all sites, the application rate of organic resources had only a yield effect for high-quality resources. Significant differences in yield between the rates of 1.2 and 4 t C ha^{-1} yr^{-1} were found for *Calliandra*, *Tithonia* and farmyard manure, but not for the maize stover and saw dust treatments, regardless of ± N treatment or time since the experiment started. In general, the addition of sawdust at

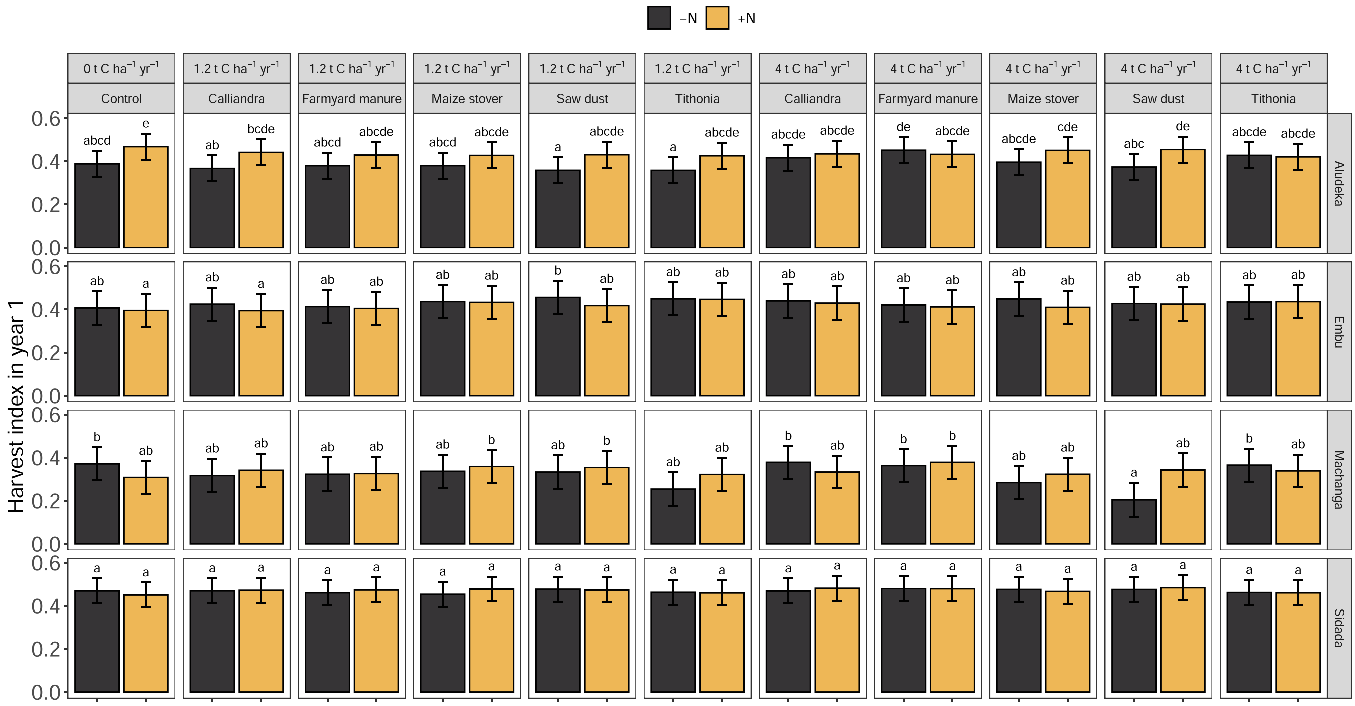

Fig. B2. Least square means of the harvest index, in the first experiment year by site (Fixed Site model). Same lowercase letters at the same site indicate the absence of a significant difference between treatments at that site (all $p < 0.05$). The error bars indicate the 95% confidence interval.

Table B1
Lest square means (ls.mean) of yields per season (2 per year) by treatment and year across sites (Random Site model) combined with the probability of a yield > 1.5, 3 and 6 t ha^{-1} $season^{-1}$. Same lowercase letters at the same year indicate the absence of a significant difference between treatments at that year. Same uppercase letters indicate the absence of a significant difference in the temporal trend between treatments (all $p < 0.05$). Standard errors were 0.76 and 0.77 t ha^{-1} $season^{-1}$ in year 1 and 18, respectively.

		year 1				year 18				temporal trend	
			probability of yield >				probability of yield >				
Residue treatment (t C ha^{-1} yr^{-1})	N⁺	ls.mean (t ha^{-1})	1.5 (%)	3 (%)	6 t ha^{-1} (%)	ls.mean (t ha^{-1})	1.5 (%)	3 (%)	6 t ha^{-1} (%)	ls.mean (t ha^{-1})	95%CI
Control 0 t	-N	2.42^{ab}	77	32	0	1.43^{a}	48	11	0	-0.058^{AB}	-0.11 to − 0.006
Control 0 t	+N	3.18^{de}	91	56	1	2.31^{cde}	74	29	0	-0.051^{AB}	-0.104–0.001
Calliandra 1.2 t	-N	2.47^{b}	78	33	0	1.99^{bc}	65	21	0	-0.028^{BCD}	-0.081–0.024
Calliandra 1.2 t	+N	3.49^{efg}	95	66	2	2.81^{efg}	85	44	1	-0.04^{ABCD}	-0.093–0.012
Calliandra 4 t	-N	3.7^{fgh}	96	71	3	2.6^{def}	81	38	0	-0.065^{AB}	-0.117 to − 0.012
Calliandra 4 t	+N	4.02^{hi}	98	80	6	3.3^{gh}	92	59	2	-0.043^{ABCD}	-0.095–0.01
Farmyard manure 1.2 t	-N	2.94^{cd}	88	48	1	2.27^{cde}	73	28	0	-0.039^{ABCD}	-0.092–0.013
Farmyard manure 1.2 t	+N	3.57^{efg}	95	68	3	3.6^{h}	95	68	3	0.002^{D}	-0.051–0.054
Farmyard manure 4 t	-N	3.92^{ghi}	97	77	5	3.56^{h}	95	67	3	-0.021^{BCD}	-0.074–0.031
Farmyard manure 4 t	+N	4.22^{i}	99	84	8	4.22^{i}	98	83	8	0.001^{CD}	-0.052–0.053
Maize stover 1.2 t	-N	2.19^{ab}	71	26	0	1.82^{abc}	60	18	0	-0.022^{BCD}	-0.074–0.031
Maize stover 1.2 t	+N	3.38^{def}	93	62	2	2.72^{def}	83	41	1	-0.039^{ABCD}	-0.091–0.014
Maize stover 4 t	-N	2.49^{bc}	79	34	0	1.99^{bc}	65	21	0	-0.029^{ABCD}	-0.082–0.023
Maize stover 4 t	+N	3.3^{def}	93	60	1	2.93^{fg}	87	48	1	-0.022^{BCD}	-0.074–0.03
Saw dust 1.2 t	-N	2.31^{ab}	74	29	0	1.67^{ab}	55	15	0	-0.037^{ABCD}	-0.09–0.015
Saw dust 1.2 t	+N	3.45^{ef}	94	64	2	2.27^{cde}	73	28	0	-0.07^{AB}	-0.122 to − 0.017
Saw dust 4 t	-N	1.99^{a}	65	21	0	1.54^{ab}	51	13	0	-0.026^{BCD}	-0.078–0.026
Saw dust 4 t	+N	3.2^{de}	91	56	1	2.25^{cd}	72	28	0	-0.056^{AB}	-0.108 to − 0.004
Tithonia 1.2 t	-N	2.63^{bc}	82	38	0	1.99^{bc}	65	21	0	-0.038^{ABCD}	-0.09–0.015
Tithonia 1.2 t	+N	3.56^{efg}	95	67	2	2.72^{def}	83	41	0	-0.049^{ABC}	-0.102–0.003
Tithonia 4 t	-N	4.08^{hi}	98	81	6	2.73^{def}	83	42	1	-0.079^{A}	-0.131 to − 0.027
Tithonia 4 t	+N	4.27^{i}	99	85	8	3.66^{h}	95	70	3	-0.036^{ABCD}	-0.088–0.016

⁺Mineral N treatments received 120 kg mineral N ha^{-1} $season^{-1}$ for the +N treatment, and no mineral N for the -N treatment.

both rates had no yield benefit over the control treatment, regardless of whether N was applied, but it also did not lead to significantly lower yields. Notably, the yields of FYM1.2-N, CC1.2-N and TD1.2-N were not significantly different from CT+N after 18 years, even though their annual N load (about 90 kg N ha^{-1} $year^{-1}$) was less than half of the 240 kg N ha^{-1} $year^{-1}$ received by the CT+N treatment. The temporal trends across sites for the different treatments also showed that the probabilities to achieve a good yield of at least 3 t ha^{-1} per season decreased over time for all but the FYM1.2 +N and FYM4 +N treatments. In year 18, only FYM4 +N, FYM4-N, FYM1.2 +N, CC4 +N and TD4 +N had a probability of > 50% to surpass 3 t ha^{-1} yield per season, while the probability for CT+N was only 29%, which was linked to a

Table B2
Analysis of variance table for the model treating site as random effect. DF = degrees of freedom; TRTcAmount = organic resource treatment (material and amount); nTRT = ±N treatment.

	numerator DF	denominator DF	F-value	p-value
Intercept	1	4449	12.30	< 0.001
years	1	129	2.72	0.10
TRTcAmount	10	4020	72.94	< 0.001
nTRT	1	4449	24.12	< 0.001
season	1	129	1.88	0.17
years:TRTcAmount	10	4020	3.67	< 0.001
years:nTRT	1	4449	0.78	0.38
TRTcAmount:nTRT	10	4449	8.94	< 0.001
years:season	1	129	0.01	0.93
nTRT:season	1	4449	4.37	0.04
TRTcAmount:season	10	4020	16.53	< 0.001
years:TRTcAmount:nTRT	10	4449	3.80	< 0.001
years:nTRT:season	1	4449	1.93	0.16

Table B3
Analysis of variance table for the model treating site as random effect. DF = degrees of freedom; TRTcAmount = organic resource treatment (material and amount); nTRT = ±N treatment.

	numerator DF	denominator DF	F-value	p-value
Intercept	1	4377	42.59	< 0.0001
years	1	120	0.00	0.99
TRTcAmount	10	3930	23.34	< 0.0001
nTRT	1	4377	44.49	< 0.0001
Site	3	270	27.21	< 0.0001
season	1	120	6.71	0.01
years:TRTcAmount	10	3930	2.95	< 0.0001
years:nTRT	1	4377	1.99	0.16
TRTcAmount:nTRT	10	4377	4.70	< 0.0001
years:Site	3	120	0.19	0.90
TRTcAmount:Site	30	3930	3.43	< 0.0001
nTRT:Site	3	4377	6.53	0.0002
years:season	1	120	0.09	0.77
nTRT:season	1	4377	0.13	0.72
Site:season	3	120	4.14	0.01
TRTcAmount:season	10	3930	18.72	< 0.0001
years:TRTcAmount:nTRT	10	4377	1.70	0.07
years:TRTcAmount:Site	30	3930	6.49	< 0.0001
years:nTRT:Site	3	4377	1.33	0.26
TRTcAmount:nTRT:Site	30	4377	1.86	0.003
years:nTRT:season	1	4377	4.36	0.04
years:Site:season	3	120	0.61	0.61
nTRT:Site:season	3	4377	21.31	< 0.0001
TRTcAmount:Site:season	30	3930	3.50	< 0.0001
years:TRTcAmount:nTRT:Site	30	4377	2.63	< 0.0001
years:nTRT:Site:season	3	4377	15.65	< 0.0001

predicted yield loss of 50 kg ha^{-1} with each additional experimental year (Table B1).

3.2. *Site specific yields, temporal trends in yield and harvest index (Fixed Site model)*

The four sites of this study differ considerably in soil characteristics, with Machanga and Aludeka both having low clay content, while Embu and Sidada are characterised by a high clay content (Table 1). Additionally, Aludeka and Sidada receive on average about 500 and 900 mm more annual rainfall than Embu and Machanga, respectively. Consequently, there is also a need to look at site specificity of maize yields (using the Fixed Site model). In fact, maximum maize grain yields differed considerably between sites in the first experimental year, being around 4.5 and 5 t ha^{-1} per season in Aludeka and Sidada, respectively, and around 4 and 3.5 t ha^{-1} per season in Embu and Machanga, respectively. The differentiation between sites increased with experimental time and maximum yields towards year 16 were around 6 and 8 t ha^{-1} per season in Aludeka and Sidada, respectively, and around 3.5 and 1.7 t ha^{-1} per season in Embu and Machanga (Fig. 2, Table 3). Thus, site specificity of the effect of organic resource and N fertilizer treatments on maize yield was highly significant ($p < 0.001$). Yet, there was a general trend in yield differences between treatments, with FYM4+N, TD4+N and CC4+N usually achieving the highest yields at all sites. Nevertheless, Sidada and Aludeka were much more responsive to mineral N fertilizer compared to Embu and Machanga. For example, for the same organic resource type and application rate, Embu, with the exception of FYM1.2, had no significant differences in yield between +N and -N treatments. Also for Machanga this was often the case; for example, in case of TD4, FYM4 and CC4 in year 1 and FYM4 in year 16 (Table 3). Yet, non-responsiveness to mineral N fertilizer was most extreme in Embu, where even after 16 years, CT showed no significant yield difference between +N and -N. In contrast, Aludeka towards year 16 showed significant yield differences between +N and -N for all organic resource treatments. Similarly, in Sidada, all but the TD4, FYM4 and CC4 treatments showed significant differences between +N and -N.

FYM4 +N was the treatment with the highest yields towards year 16 in all of the four sites (5.9, 3.4, 1.7 and 8.8 t ha^{-1} $season^{-1}$ in Aludeka, Embu, Machanga and Sidada, respectively). Furthermore, in Aludeka, Embu and Sidada, FYM4+N had no significant yield decline over time. Only in Machanga did FYM4+N, as most other treatments, experience a significant decline of yield over time. In fact, the treatments that did not experience a significant yield decline in Machanga were treatments that already had low grain yields of below 2 t ha^{-1} per season in the first experimental year (Table 3). In contrast, in Sidada FYM4 ± N and also FYM1.2+N, CC4 ± N, TD4+N and MS1.2+N experienced a significant increase in yield over time (Table 3). Yet, in Embu several treatments, namely CC1.2 +N, CC4 ± N, CT+N, FYM1.2-N, SD4+N, TD1.2+N and TD4 ± N experienced a significant decline in yield over time (Table 3). Interestingly, in Embu all treatments showed a significant reduction of harvest index over time (Fig. B1). While in the first year the harvest index was around 0.35–0.4 across all sites (Fig. B2), it dropped to around 0.2 in Embu in all treatments after 16 years (Fig. 3). In contrast, Sidada and Aludeka did not experience a decline in harvest index, whilst a significant reduction over time occurred in Machanga for only the CT-N, MS1.2 ± N, SD1.2-N and TD4-N treatments that also all had a harvest index of around 0.2 towards year 16. In Machanga, the strong trends of yield decline led to very poor yields, as low as 1.7 t ha^{-1} per season towards year 16, even for the highest yielding TD4+N and FYM4+N treatments. In contrast, high yields towards year 16 occurred in Sidada, with 8.1 and 7.8 t ha^{-1} per season for FYM4+N and FYM4-N, respectively.

3.3. *Agronomic efficiency of applied N*

The AE_{totN} generally increased over time, but was highly site specific. In Aludeka for example, AE_{totN} towards year 16 was between 8 and 30 kg kg^{-1} N, while in Embu, AE_{totN} was between − 3 and 15 kg kg^{-1} N. An increasing differentiation of treatments over time in Sidada and decreasing differentiation in Machanga of AE_{totN} was observed (Table 4). The CT+N treatment had the lowest AE_{totN} in Embu and was among the treatments with lowest AE_{totN} values in Sidada. This was not the case in Aludeka and Machanga. In general, both types of AE_N values were considerably higher in Aludeka and Sidada than in Embu and Machanga (Table 4 and Table A1). For example, in Aludeka and Sidada more than half of the treatments had an AE_{totN} above 15 kg kg^{-1} N, while all but one treatment in Embu had an AE_{totN} below 10 kg kg^{-1} N, and all treatments in Machanga had an AE_{totN} below 8 kg kg^{-1} N towards year 16. Despite these differences between sites, there were some similarities across all sites, such as that the FYM1.2-N treatment was among the treatments with highest AE_{totN} values.

4. Discussion

This study reports on the maize yield performance in response to different types of organic resources with medium to very high (1.2 and 4 t C ha^{-1} yr^{-1}) input rates, and without or with high (120 kg ha^{-1} per season) mineral N fertilizer at four sites in Kenya. The time frame is almost two decades of continuous maize monocropping, with two cropping seasons per year. It is important to note that due to basal P and K fertilization, the results apply to conditions where P and K were not limiting.

4.1. Differences in the long-term suitability between the treatments

The analyses of long-term data showed that in contrast to significant yield losses in the CT-N treatment, the FYM4+N and FYM1.2+N treatments across sites could sustain their relatively high maize yields, indicated by the absence of significant yield declines over time (Fig. 1, Table B1). The results from this study also highlight that long-term studies are necessary for capturing the dynamics that determine the sustainability of organic resource and mineral fertilizer applications used in ISFM. For example, Mucheru-Muna et al. (2014) found in a 3-year experiment that *Tithonia* and *Calliandra* led to higher maize yields than farmyard manure; also Kimiti et al. (2021) concluded from a 2-year experiment that the application of 60 kg N ha^{-1} and 60 kg P ha^{-1} in the form of mineral fertilizer led to higher maize yields than manure application of around 2 t C ha^{-1}. In fact, when looking only at the short-term results of our study across sites, we would come to the same conclusions. In the long term, however, the sole mineral fertilizer (CT+N) did no longer have a significant yield difference compared to low rate of farmyard manure without fertilizer (FYM1.2-N).

The high N loads of treatments (i.e. FYM4+N, FYM4-N and FYM1.2+N; all above 300 kg N ha^{-1} yr^{-1}) may explain part of their stable yield performance over time. For example, yearly exports of N through maize biomass in the western Kenya sites were estimated between 50 and 100 kg N ha^{-1} $year^{-1}$ for CT-N, and up to 280 kg N ha^{-1} $year^{-1}$ for FYM4+N (data not shown here). The amounts were somewhat lower in central Kenya than in western Kenya, due to lower yields. Yet, in both regions a negative N balance in CT-N is to be expected, while in FYM4+N maximally half of the applied N is exported. However, the form and the rate by which N is supplied to the crop clearly also played an important role in the maintenance of yields over time. For example, FYM4+N achieved significantly higher yields in year 18 than the CC4+N and TD4+N treatments, despite the similar N loads of around 550 kg N ha^{-1} yr^{-1} in the three treatments. Farmyard manure is known to provide mineral N to crops beyond the year of its application, the so-called residual effect (e.g. typically only about 30% of its N is released in the first year; Silva et al., 2014; Sileshi et al., 2019). Organic resources of low C/N ratios, such as *Tithonia* and *Calliandra*, in contrast, usually decompose within a few months (Palm et al., 2001a; Puttaso et al., 2011). The better synchronisation of N release with plant N demand from farmyard manure than from *Tithonia* and *Calliandra* may thus partly explain the superior yield with farmyard manure in the long term. In fact, Muema et al. (2016) observed at the Embu site that the N supply of the CC4-N and TD4-N treatments was rather transient, as they only had significantly higher levels of soil mineral N than CT-N up to about 60 days after maize planting (unfortunately, no measurements were done in the farmyard manure treatment).

The findings on agronomic efficiency of total N applied (Table 4) show that FYM1.2-N in year 16 had the highest efficiency in all sites except Machanga. Furthermore, the efficiency of FYM4-N in Embu and Sidada were high as well. These two findings also support the notion of a good synchronisation between N release from farmyard manure and crop demand. In clayey soils, i.e. Embu and Sidada, this may even hold for high loads of N, as indicated by the significantly higher agronomic efficiency of total N applied of FYM4+N compared to TD4+N and CC4+N. Yet, apart from a good synchronisation of N supply and demand, the good yield performance of the FYM treatments may be also due to improvements in soil structure (Blair et al., 2006), increased soil pH and alleviation of multiple (micro)nutrient limitations as is often observed with farmyard manure applications (Mucheru-Muna et al., 2014; Rusinamhodzi et al., 2013; Xiao et al., 2021).

In contrast to the observed yield difference between farmyard manure, *Tithonia* and *Calliandra*, our results provided no evidence for the suggestion by Palm et al. (2001a) that organic resources of class 2 (slow release) should be amended with mineral N, and class 1 (fast release) not: there were no significant yield differences between *Calliandra* and *Tithonia* with +N treatments, despite the significantly higher polyphenol content in *Calliandra* residues (Table 2). Another interesting finding was the increasing differentiation of yields between +N and -N treatments towards year 18 (e.g. no significant yield difference for CC4, FYM4, TD4 in year 1 but significant differences towards year 18). This could be due to a decreasing N supply from soil organic matter (SOM) over time, resulting from depleting soil total N (and C) stocks. Due to high organic matter mineralization rates in tropical conditions, SOM is usually lost in long-term agronomic trials, even with high loads of organic resource additions (Kihara et al., 2020). Interestingly, the *Tithonia* and *Calliandra* treatments with their low C/N ratio could not maintain yields, despite the notion that such material efficiently forms new SOM through microbial decomposition and assimilation (Cotrufo et al., 2013; Denef et al., 2010; Sinsabaugh et al., 2016). Recent results from another long-term experiment in western Kenya also showed that it is nearly impossible to maintain initial levels of SOM, even with high input rates of organic resources (Sommer et al., 2018; Nyawira et al., 2021; Kihara et al., 2020), probably because soils at the sites in the region were still fairly close to their high natural SOM levels at the onset of the experiments. In the same experiments than those of this study, it was further found that, except in Aludeka, the addition of *Calliandra* and *Tithonia* residues, even at high rates, did not counterbalance soil carbon losses (Laub et al., 2022), so their main benefit might be to supply N to crops. The absence of significant differences in maize yields between the CC4-N, TD4-N and CT+N treatments across sites towards year 18 is an indication of this beneficial N effect, as all these treatments supply similar amounts of N (about 300 kg N ha^{-1} yr^{-1}). This finding is in line with results from a 2-year experiment in western Kenya: Opala et al. (2015) found that when organic resource application rates were chosen to provide the exact same amount of 60 kg N ha^{-1} yr^{-1}, yields from the application of farmyard manure and *Tithonia* were the same as those from N fertilizer application in the form of urea. Yet, Mucheru-Muna et al. (2014) found that without a basal P and K fertilization, applying the same rate of N through either *Tithonia, Calliandra* or farmyard manure led to significantly higher maize yields than applying the same amount of N in the form of mineral fertilizer. The fact that in our study only farmyard manure had significantly higher yields across sites than the mineral fertilizer only treatment in year 18, could thus be a result of the basal P and K fertilization in our study.

Consequently, our initial hypothesis that organic resources are more important for maintaining crop yields than the addition of mineral N only holds for farmyard manure applied at a rate of 4 t C ha^{-1} yr^{-1}. However, 4 t C ha^{-1} yr^{-1} is not an amount that most smallholder farmers can supply of any organic resource. For example, the amount of manure that can be sourced from farms in Kenya typically ranges between 0.2 and 1 t C ha^{-1} yr^{-1} (Tittonell et al., 2008a; Onduru et al., 2008). This means that even the low rate in our study is in the upper range of what typically can be applied under current conditions in Kenya. Thus, a decline of maize yields under continuous maize monocropping in farming conditions of smallholders may not be avoidable in most maize-growing regions in Kenya, unless farmyard manure is combined with mineral N fertilizer. The fact that the agronomic efficiency of total N of the combined mineral fertilizer-farmyard treatment at 1.2 t C ha^{-1} yr^{-1} was amongst the highest towards year 16 (Table 4), suggests that the combined use of organic and mineral inputs is a N efficient strategy. The general high values of agronomic N efficiency with farmyard manure treatments further indicates a high efficiency of N recycling in mixed croplivestock farming systems. Yet, farmyard manure already represents a condensed and partly decomposed C and N resource. Thus, on-farm N losses as well as how much feedstock C is needed to produce manure should be considered. For sheep and goats for example, only 25–35% of the C and N they take in is recovered in their excrement (de Azevedo et al., 2021; Dickhoefer et al., 2021; Hossain, 2021). This means that the biomass needed to produce 1.2 t C of farmyard manure is equivalent to about 4 t C of other organic resources. On top of that, on-farm storage losses of nutrients in manure can be up to 40% for N (Castellanos-Navarrete et al., 2015), underlining the need for proper management of this resource. In this context, the most realistic option for smallholder farmers is the combined application of farmyard manure with mineral N, but at lower rates than 120 kg N $^{-1}$ per season and 1.2 t C $^{-1}$ yr^{-1} of farmyard manure (equivalent to about 5 t dry matter). In fact, lower additions of mineral N usually result in higher N use efficiencies (Vanlauwe et al., 2011). Thus, the combined application of lower amounts of fertilizer N with organic resources is most likely even more beneficial than the results of our study suggest.

4.2. Yield trends are site specific, so the order of ISFM practice adoption needs to consider soil responsiveness

The notion that crop yield responses to sustainable intensification practices, such as ISFM, are site-dependent (Prestele and Verburg, 2020) is fully corroborated by our study. Yet, the order of organic resource treatments in terms of their yield effects after 16 years was roughly the same across sites (i.e. FYM4+N had the highest yields, MS4+N had intermediate yields, and CT-N was in the group with the lowest yields). The site-specificity was more revealed in the absolute maize yield levels and in the responsiveness to mineral N fertilizer. In Aludeka and Sidada, yield responses to mineral N fertilizer were large for most treatments, and yields increased over time for the treatments with high N loads. In contrast, in Embu no significant difference between +N and -N for any organic resource treatment was observed in year 16, despite the significant difference in yields between the organic resource treatments. Interestingly, Embu had the highest initial SOM content of all four sites, and may therefore be classified as high fertility soil, unresponsive to mineral N addition (Vanlauwe et al., 2015; Kihara et al., 2016). On the other hand, the fact that Embu was responsive to organic resource treatments may be related to better soil structure and its positive effects on the soil water balance (Bashir et al., 2021), and thus not only to the N supply from the organic resources. The non-responsiveness to mineral N in Embu is possibly because other factors than N are limiting crop growth. For example, the significant decline of harvest index for all treatments in Embu points to factors inhibiting proper grain formation in the later years of the experiment, such as soil water availability towards the end of the cropping season. Yet, above-ground biomass did not experience the same reduction in time (data not shown).

It is also important to consider that micronutrients may be limiting crop growth at our four sites. Low nutrient use efficiencies are often the result of nutrient imbalances (Aliyu et al., 2021); indeed, visual observations in our experiments suggested that Mg, Zn and/or S were limiting in the treatments with low amounts and qualities of organic resource inputs. This was much less in the FYM treatments as manures often contain substantial amounts of micronutrients (Sileshi et al., 2019; Mbatha et al., 2021). For example, Kihara et al. (2016) showed that the addition of micronutrients could significantly improve crop yields (in a range of 0.25–4 t ha^{-1}) in a third of the experimental sites across multiple countries in sub-Saharan Africa. Likewise, Rusinamhodzi et al. (2013) showed that farmyard manure addition alleviated micronutrient limitations in coarse textured soils in Zimbabwe and increased maize yields and use efficiency of macro-nutrients.

The high yield potential and responsiveness to mineral N in Aludeka and Sidada compared to the other sites may be the result of the relatively high amounts of rainfall and long growing seasons (Table 1) combined with a better overall soil nutrient status at these two sites. In stark contrast, Machanga experienced many crop failures in the later seasons of the experiment, which coincided with more erratic rainfalls and severe soil erosion. With low rainfall and high temperatures, Machanga is the least suitable site for maize cultivation. No experimental treatment could offset the decline of maize yields (i.e. all treatments that had initially acceptable yields experienced a significant decline in yield over time; Table 3). Yet, even in such conditions it might be possible to increase yields with ISFM, as demonstrated in a 50-years experiment using high loads of manure and a crop rotation of sorghum and cowpea in a coarse textured soil with about 800 mm of annual precipitation (Adams et al., 2020).

In general, the higher site-specificity of maize yield responses to mineral N fertilizer than to organic resource additions suggests that sustainable intensification should start with organic resource applications, ideally farmyard manure, and mineral N application should follow as soon as soil N fertility declines. As our data show, mineral N application alone put long-term yields at risk, despite providing good yields in the short term. Our results suggest that farmyard manure with the addition of mineral N is the most effective way to maintain crop yields in the longer term. Hence, the access to both farmyard manure and mineral fertilizer is pertinent and should be priority for sub-Saharan Africa instead of the recommendation of increasing only the access to mineral N fertilizer by Sanchez (2015). This highlights thus the importance of mixed crop-livestock systems for a sustained crop productivity in sub-Saharan Africa (Herrero et al., 2010). Yet, farmyard manure may never be available in sufficient quantities to farmers, so other ways to maintain soil fertility, such as crop rotations with legumes and forages (Namatsheve et al., 2020) are most likely also needed.

5. Conclusions

Based on the observed long-term trends, farmyard manure plus mineral N application is the most effective way to maintain maize yields in Kenya. Across sites, the use of farmyard manure with mineral N at both input rates of 4 t C ha^{-1} yr^{-1} and 1.2 t C ha^{-1} yr^{-1} prevented the decline of maize yields that was observed under sole mineral N fertilizer application over the 16+ experimental years. The addition of 4 t C ha^{-1} yr^{-1} high-quality *Tithonia* and *Calliandra* in contrast, could only prevent yield decline in two of the four sites. Furthermore, yields even increased with the use of farmyard manure in combination with mineral N fertilizer (i.e. full ISFM) in suitable agroecological zones for maize cultivation (i.e. western Kenya). The unresponsiveness to mineral N fertilizer in Embu, however, may have been related to other limitations, such as water and micronutrients. These differences in responses to mineral and organic fertilizers and the finding that maize yields were about double in western Kenya compared to central Kenya indicate that factors determining the site specificity of yield responses need to be studied in detail before more specific ISFM recommendations can be formulated. Finally, the fact that maize yields in many organic resource treatments of the central Kenya sites did not benefit from mineral N applications is a potentially detrimental outcome for poor farmers investing into mineral N fertilizer. We conclude that the combined application of 1.2 t C ha^{-1} yr^{-1} farmyard manure and mineral N seems to be the safest option: the treatment is N efficient, among the highest yielding ones and has a low risk of loosing yields over time. Due to this studies‘ the high rates of 120 kg ha^{-1} mineral N fertilizer per season, the N use efficiency of the combined application may even be higher at lower mineral N application rates. Hence, a more realistic and more efficient option would be to use less than 120 kg ha^{-1} mineral N fertilizer per season combined with yearly farmyard manure additions of up to 1.2 t C ha^{-1}.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Competing interests

The authors declare, that they have no competing interests.

Appendix A. AE_{minN} and it's development over time

A1 Results

Both AE_{minN} and AE_{totN} generally increased over time, but were highly site specific. In Aludeka for example, AE_{totN} towards year 16 was between 8 and 30 kg kg^{-1} N and AE_{minN} between 11 and 25 kg kg^{-1} N, while in Embu, AE_{totN} was between − 3 and 15 kg kg^{-1} N and AE_{minN} between − 3 and 8 kg kg^{-1} N. Interestingly, the order of treatments regarding the effects on AE_{minN} changed between sites. For example, the CT treatment towards year 16 was not significantly different from the treatments with highest AE_{minN} values in Aludeka (18.7 kg kg^{-1} N) and Sidada (23.8 kg kg^{-1} N). In Embu, CT showed lowest and even negative values (−2.7 kg kg^{-1} N), whilst in Machanga no significant differences in AE_{minN} occurred between any of the treatments towards year 16 (Table A1). Both SD treatments were initially among the treatments with highest AE_{minN} at all sites, but towards year 16, SD1.2 in Aludeka and both SD1.2 and SD4 treatments in Embu and Machanga were among treatments with lowest AE_{minN}. Yet, in Sidada, where initially no significant differences existed between treatments, both SD treatments were in the group with the highest AE_{minN} values.

The increased differentiation of treatments in Sidada and reduced differentiation in Machanga observed for AE_{minN} was also observed for AE_{totN} (Table 4). The CT+N treatment had the lowest AE_{totN} in Embu and was among the treatments with lowest AE_{totN} values in Sidada, which was not the case in Aludeka and Machanga. In general, both types of AE_N values were considerably higher in Aludeka and Sidada than in Embu and Machanga. In Aludeka and Sidada, for example, more than half of the treatments had an AE_{totN} above 15 kg kg^{-1} N, while all but one treatment in Embu had an AE_{totN} below 10 kg kg^{-1} N and all treatments in Machanga had an AE_{totN} below 8 kg kg^{-1} N towards year 16. Despite these differences between sites, there were some similarities, such as that the FYM1.2-N treatment was among treatments with highest AE_{totN} values across all sites.

A2 Discussion: Increases in AE_{totN} and AE_{minN} point to reduced N supply from soils

Overall, the AE_{totN} and AE_{minN} values observed in this study were low compared to their theoretical maximum of 70 kg kg^{-1} N applied. In Embu and Machanga, they were also considerably lower than typical values (25–30 kg kg^{-1} N applied; Vanlauwe et al., 2011; Mutuku et al., 2021), which is likely related to the high N application rates in our experiments, aiming for non-N limited conditions in +N treatments (N loads up to 250 kg N ha^{-1} per season). Despite this, the increasing responsiveness to mineral N in the sites with clayey soils, Embu and Sidada, as indicated by significant AE_{minN} increases over time in several treatments, suggests that N became increasingly limiting with experiment duration, probably linked to a decrease of soil N supply through mineralization. This is also indicated by the significant decline of yields in the CT-N treatment (with the same trend for CT+N; Table B1). On the clayey soils in Embu and Sidada, FYM1.2-N towards year 16 (with 14.6 and 40.3 kg kg^{-1} N, respectively) showed also more than double the values of AE_{totN} of CT+N (−2.5 and 15.6 kg kg^{-1} N, respectively), while having similar or even higher yields. This is in alignment with Pincus et al. (2016), who found that at high N rates of 200 kg ha^{-1}, treatments combining manure and mineral N to supply the same amount of total N had significantly higher yields than the mineral N only treatment.

Trends found for AE_{totN}, that N is used most efficiently when it is available in medium quantities, are also partly observed for AE_{minN}. Usually, the treatments that received little N from organic resources achieved highest AE_{minN} (e.g. in year 16, MS4 with 24.6 kg kg^{-1} N in Aludeka, FYM1.2 with 8.1 kg kg^{-1} N in Embu, and SD4 with 24.3 kg kg^{-1} N in Sidada). Yet, the strong site specificity of AE_{minN} shows that, in contrast to applying high-quality organic resources, applying mineral N does not have a guaranteed benefit, as in Machanga the AE_{minN} for all treatments in year 16, except CT, CC1.2 FYM1,2 and TD4, was not significantly different from 0. Hence, applying mineral N can be considered a higher risk for farmers than the use of organic resources. Our results align with Sileshi et al. (2019), who found higher AE_N for low compared to high rates of manure application, lowest AE_N for coarse textured soils, and that treatments that partly substituted mineral fertilizer N by manure N had highest AE_N. The combination of farmyard manure with mineral N was also highly efficient in our trials, as FYM1.2 +N could achieve the same yields as *Tithonia* and *Calliandra* +N at 4 t C ha^{-1} yr^{-1} at only about half of the total N applied. However, while manure and mineral fertilizer application are well adopted in e.g. central Kenya, their combined application is not commonly practiced (Mucheru-Muna et al., 2021), potentially due to missing knowledge of the additional benefits. Hence it should be a priority to communicate the advantages of the combined use (Tittonell et al., 2008b).

Appendix B. Additional least square means and seasonal plots

B1 Computed probabilities of obtaining low or high yields

To assess the risk in maize production under the different ISFM combinations, probabilities of obtaining poor, medium and good yields were computed from the Random Site model. It has been argued that the likelihood of obtaining a poor yield may be as suitable to estimate the yield stability compared to assessing the variability of yields (Piepho, 1998; Reckling et al., 2021). For example, low variability could also result from a stable but very low yield. Probabilities to obtain at least a predefined yield were assessed, based on the likelihood given by the statistical model. In this study, the thresholds for a poor, medium/-acceptable, and above average yield were chosen as 1.5, 3 and 6 t ha^{-1}, respectively. The lower threshold was defined based on the mean national yields in Kenya (1.5 t ha^{-1}; Anon, 2021), the upper as "attainable yields" by farmers, for which we chose a conservative 60% of the maximum yield potential of maize in Kenya (up to 10 t ha^{-1} under rainfed conditions in the high-potential agroecological; Ittersum et al., 2016, https://www.yieldgap.org/), because 80% are probably too optimistic (Ittersum et al., 2016). The 3 t ha^{-1} is roughly the target yield to achieve for food self-sufficiency of Kenya at the country scale (Sileshi et al., 2019; Sanchez, 2015). In calculating the probabilities to outyield these thresholds, we followed the recommendations of Reckling et al. (2021), i.e. we did not delete any outliers, had random effects for each season, a fixed temporal trend, which initially was allowed to have a random deviation (removed due to no improved AIC) in our mixed linear model. Furthermore we tested for variance heterogeneity between different treatments by including variance heterogeneity per treatment in the model (as a random effect) and standard error based confidence intervals for each treatment are reported. The reason that we did not use a variance based approach (e.g. Shukla's stability variance; Shukla, 1972), was that with the mixed model we found no convincing evidence of variance heterogeneity (Zuur et al., 2009) between treatments: due to issues with model convergence it was only possible to allow for either variance heterogeneity between sites or between treatments, and according to AIC, the variance heterogeneity between sites was more important (AIC of 27,443.52) than between treatments (AIC of 27, 714.26) (Table B1).

The probability of having a yield greater than the threshold was computed with the 'pnorm()' function of R, using the standard errors and least square means provided by the statistical model with site as a random effect, while adjusting the probability distribution for the degrees of freedom (3, due to 4 sites).

B2 Analysis of variance tables

See Tables B2 and B3.

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