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Maize yield stability under organic and conventional farming systems in sub-humid agro-ecozones of Central Kenya

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ABSTRACT

Maize (*Zea mays L.*) is the main staple crop and is important to the food security and livelihoods of people globally. We evaluated the effects of organic and conventional farming systems on maize grain yield and temporal yield stability under different external input levels in a long-term experiment (2007–2022) at two sites in Kenya. We implemented four farming systems: organic high (Org-High), conventional high (Conv-High), organic low (Org-Low), and conventional low (Conv-Low) in a randomized complete block design. Growth indicators for maize, height, stem diameter, and grain yield were higher in high input systems, but grain yield stability was not. At the onset of the experiments, grain yields of conventional systems were higher compared to the organic systems, whose yield levels gradually increased over time, reaching the yield levels of conventional systems. With regard to grain yield stability, the site (Chuka) with better soil fertility, the Conv-High system had the least residual variance (0.28 Mg ha^{-2}), followed by Org-Low, Conv-Low, and Org-High showing the highest residual variance (0.67 Mg ha^{-2}). Contrary, in the site (Kandara) with low soil fertility, Org-Low had the lowest residual variance in grain yield (0.16 Mg ha^{-2}), followed by Conv-Low and Org-High, while Conv-High (4.15 Mg ha^{-2}) had the highest residual variance. We observed that applying higher nutrient input levels did not necessarily lead to yield stability. Our findings suggest promoting long-term implementation of organic farming practices, especially in regions with degraded soils, for improved yield and resilience.

1. Introduction

The global population is estimated to surge to 9.7 billion by 2050 (United Nations Environment Programme (UNEP), 2019), with around 30 % of the population in Africa exposed to food insecurity (FAO et al., 2018). Thus, meeting the escalating food demand remains a global challenge and is more severe in the tropics, Kenya included (FAO et al., 2020; FiBL, 2024). Sufficient and stable crop yields are the basis for feeding a growing world population. Besides high population growth, food insecurity in Africa is also promoted by land degradation coupled with low soil fertility due to limited or non-use of external soil inputs, unaffordable fertilizers, and adverse climate change events (González-Sánchez et al., 2018; Jellason et al., 2021). In addition, food production in Africa is mainly done by smallholder farmers who practice rain-fed agriculture (Rajala et al., 2021). Mainly, the agricultural practices by the smallholders include continuous mono-cropping and tilling on the same piece of land, use of synthetic fertilizers and non-biodegradable pesticides, and crop residue removal (Mupangwa and Jewitt, 2011; Jellason et al., 2021; Kampermann et al., 2024). These practices lead to negative nutrient balances, exacerbating the efforts to sustainably enhance food production in smallholder farm systems. According to Gebre and Rahut (2021), the East Africa region faces an increased prevalence of food insecurity mainly due to climate change, compared to other parts of the world. Thus, the need to feed the current and future projected population triggers the importance of agricultural transformation towards sustainable and resilient practices such as conservation agriculture, agroecological farming, or organic farming.

Organic farming is key to food security and agricultural sustainability, especially in the tropics (Blockeel et al., 2023; Meena et al., 2023). It addresses the food production challenges by excluding the use of synthetic external inputs and integrating several environment-friendly and affordable practices, for example, the use of local renewable resources (animal manure, biomass transfer), prohibition of synthetic chemical pesticides (Jahantab et al., 2023) and crop-rotation. Additionally, it involves terraforming processes, such as the addition of organic matter (Barnwal et al., 2021), enhancing soil

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ecosystem services (Blanco-Canqui et al., 2017), soil microbial biomass (Das et al., 2017), and integration of organic matter-fixing crops in crop rotation systems, (Robertson et al., 2014). From their meta-analysis, Mondelaers et al. (2009) reported that soils in organic farming systems have, on average, a higher content of organic matter, which is important for good agricultural productivity and environmental soil status. A study in Kenya by Ndung'u et al. (2021) also concluded that the long-term application of organic inputs has a dual effect: improved soil fertility and maize yields.

Cereals, particularly maize (*Zea mays L.*), are the main staple crops and of great importance to food security and livelihoods of the people globally (Daryanto et al., 2017; Zhao et al., 2020) and more so in Africa (Bedeke et al., 2019; ten Berge et al., 2019). However, maize yields have been declining (Wang et al., 2014; Liang-bing et al., 2021) due to climate change events such as droughts, and poor soil conditions, i.e., low soil fertility, crop varieties and planting dates, amongst others. In Kenya, similar observations have been widely reported by several authors, e.g., Kihara et al. (2016), Ochieng et al. (2016), Macharia et al. (2020), and Musafiri et al. (2020). Therefore, effective and sustainable agricultural management practices and strategies are needed to enhance maize growth and yield, e.g., locally adapted and high-yielding varieties (FiBL), 2024). The primary goals of both conventional and organic agricultural systems are increased productivity and long-term yield stability, considering worst-case scenarios to reduce the risk of crop failure (Niether et al., 2023). Yield stability and attainment of a minimum 'guaranteed' grain yield each year should also be a considered goal during nutrient replenishment (Kisaka et al., 2016). Thus, yield stability (i.e., yield variability across years) is an important objective for enhanced food security.

However, most studies on the performance of agricultural systems focus on crop yield and neglect yield stability of production across years (Knapp and van der Heijden, 2018). Stability is conceptualized differently, with specific meanings including resilience, invariability, and resistance (Reckling et al., 2021). Thus, we used yield stability in our study, defined as the ability of a crop to perform consistently, whether at high or low yield, across a range of environments (Vita et al., 2010), as influenced by the farming system and input level.

Our study area, the Central region, is among Kenya's main food basket areas (Esilaba et al., 2023). Several studies in Kenya have reported maize yield and stability (Kiboi et al., 2017; Kiboi et al., 2023) under mono-cropping in organic versus conventional systems with similar input levels in short-term studies. However, whether maize yield and stability differ in organic and conventional systems in crop rotation with different input levels has not been tested. Thus, our study aimed to investigate the effects of organic and conventional farming systems on maize sole crop yield and temporal yield stability with different external input levels in a long-term experiment.

2. Materials and methods

2.1. Sites description

We carried out the research in the sub-humid agro-ecozones of the tropics in Central Kenya. The research was part of the long-term farming systems comparison trials (LTE) established in 2007 (https://systems-comparison.fibl.org/). The experiments were conducted at Kiereni primary school in Chuka, within Tharaka-Nithi County, and at the Kenya Agricultural and Livestock Research Organization (KALRO) farm in Kandara, Murang'a County. Chuka is located in the upper midland agro-ecozone two and lies at 1458 m above sea level (a.s.l.), while Kandara is at the upper midland agro-ecozone three and lies at 1518 m a.s.l. The two regions are part of Central Kenya and experience an average annual temperature of 20 ℃. Also, they receive bi-modal rainfall, thus two cropping seasons yearly, with the long rains (LR) season occurring from March to June and the short rains (SR) season from October to December. The mean annual rainfall in Chuka is 1500–2400 mm (Jaetzold et al., 2006c), while Kandara receives 900–1100 mm (Jaetzold et al., 2006b). The predominant soils at the experimental sites are *Humic Nitisols* in Chuka and *Rhodic Nitisols* at Kandara (Musyoka et al., 2017). The initial physicochemical properties of the soils in the Chuka (Kiereni primary school farm) and Kandara (KALRO farm) sites are shown in Table 1.

Maize sole-crop (maize variety was H513) was cultivated during the long rains seasons at the start of each crop-rotation cycle (Table 2). We used the H513 maize variety as it is recommended for the trial sites in Kenya, tolerant to most leaf diseases, and matures at 100–110 days (https://www.simlaw.co.ke/product-details/21/11). We recorded daily rainfall amounts using a rain gauge installed within the experimental site. From our observations, the LTE sites experienced rainfall variation over the years and within seasons (Fig. 1), as also observed by Adamtey et al. (2016) and Kiboi et al. (2023).

2.2. Experimental setup

We set the experiment in a randomized complete block design (RCBD) in 8 by 8 m plots and a central monitoring area of 6 by 6 m. The experiment consisted of four farming systems replicated four times at Chuka and five times at Kandara. We defined a farming system as a nutrient management strategy to sustain agricultural production and attain economic needs to meet some household requirements (Gómez-Macpherson et al., 2016). At each site, conventional (Conv) and organic (Org) were implemented in two input levels: high input (High) and low input (Low) (Table 2). The high-input level characterized crop production for commercial purposes, while the low-input level characterized production mainly for consumption. The experiment was based on a three-year crop rotation (Table 2; Musyoka et al., 2017). Since the start of the experiment in 2007, the crop rotation has been fully repeated five times, and the 6th is ongoing [(1st to 4th cycle: 2007–2018 and 5th / 6th cycle: 2019–2022) (Table 2)]. To enhance productivity and profitability (Wezel et al., 2014) and combat weed challenges with less herbicide use (Melander et al., 2013), it is essential to redesign a system including a crop rotation system. Thus, during the 5th cycle we had changes in the systems, and the push-pull technology was incorporated (Khan et al., 2011). Additionally, there was a variation increase in the amount of fertilizers applied in the farming systems during the 1st to 4th cycle (2007–2018) and the 5th / 6th cycle (2019–2022) during maize cropping seasons. The farming systems in the 1st to 4th cycle represented common management practices in Kenya (Adamtey et al., 2016), with the 1st cycle as a conversion period, the usual duration required to achieve organic certification. Management practices were adapted in the 5th cycle (adaptation period) after evaluating past results from long-term trials (Musyoka et al., 2019) to accommodate advances in crop management and improve systems to best management practices. We focused on the maize sole crop, the main staple food crop, which is continuously cultivated by most farmers in Kenya and our study areas (Muthoni and Nyamongo, 2010).

Table 1
Average soil physicochemical properties in the field experimental sites (Source: Musyoka et al., 2017; von Arb et al., 2020).

Parameter	Chuka	Kandara
Soil texture		
Clay (g kg^{-1})	740	805
Silt (g kg^{-1})	166	141
Sand (g kg^{-1})	94	54
pH (H_2O)	5.77	5.42
Total N (g kg^{-1})	2.08	1.60
Olsen P (mg kg^{-1})	28.85	7.21
Potassium	487.5	497.3
Soil organic carbon (g kg^{-1})	25	20

Table 2
Crop rotation from the 1st to the 4th cycle and the 5th /6th cycle under the conventional and organic farming systems in two input levels in the long-term experiments between 2007 and 2022 at Chuka and Kandara sites.

Cycle	Season	Conv-High	Org-High	Conv-Low	Org-Low
1st to 4th cycle	LR	Maize	Maize/Mucuna	Maize	Maize
	SR	Cabbage	Cabbage	Swiss chard/Kale	Swiss chard/Kale
	LR	Babycorn	Babycorn/Mucuna	Maize/Common bean	Maize/Common bean
	SR	French bean	French bean	Common bean	Common bean
	LR	Babycorn	Babycorn/Mucuna	Maize/Common bean	Maize/Common bean
	SR	Potato	Potato	Potato	Potato
5th cycle.6th cycle	LR	Maize	Maize/Mucuna	Maize	Maize
	SR	Cabbage	Swiss chard	Swiss chard/Kale	Swiss chard/Kale
	LR	Babycorn/Desmodium	Babycorn/Desmodium	Maize/Common bean	Maize/Common bean
	SR	French bean/ Coriander/Desmodium	French bean/ Coriander/Desmodium	Common bean	Common bean
	LR	Babycorn/Desmodium	Babycorn/Desmodium	Maize/Common bean	Maize/Common bean
	SR	Potato/Dolichos/ Desmodium	Potato/Dolichos/ Desmodium	Potato/Dolichos	Potato/Dolichos

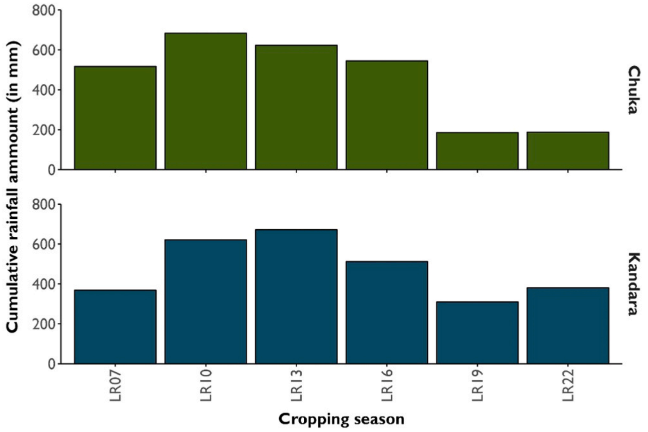

Fig. 1. Total rainfall amounts in mm during maize sole crop growing seasons.

2.3. *Field trial management*

Composting and heaping fresh farmyard manure for application during maize sole crop seasons was done three months before planting. Minimum tillage was done between March and April using a machete during land preparation in all plots. Planting was done at the onset of the rains. Three maize seeds were planted per hill and thinned out to remain with two plants after emergence to ensure maximum plant population. Weeding was done twice per season using a machete in each farming system. Maize harvesting was done at crop physiological maturity. The nutrient application rate for the high-input systems was in line with the recommendations of the Kenyan Ministry of Agriculture, while for the low-input systems was in line with the practices of farmers in the region (Adamtey et al., 2016; Musyoka et al., 2017). Organic systems received compost, decomposed FYM, rock phosphate, and plant residues, while conventional systems received fresh/decomposed farmyard manure (FYM), Triple-Super phosphate (TSP), and Di-ammonium phosphate (DAP) as soil nutrient inputs (Table 3). Topdressing was done with tithonia plant tea (*Tithonia diversifolia*) in organic farming systems, while calcium ammonium nitrate (CAN) was used in the conventional systems. Farmyard manure and compost were sourced from farms close to the sites, while tithonia was harvested from hedges around the trial sites. These organic inputs are locally available in most smallholder farms in Central Kenya (Kiboi et al., 2019). Organic inputs were analyzed for N and P to determine the nutrients applied in each system. The range of N and P concentration in each organic input was shown in the supplementary table A1. Mulch was surface applied in the organic farming systems in all crops at 2 Mg ha^{-1} in the first to fourth cycle and 4 Mg ha^{-1} during the Fifth/Sixth cycle. In cases of a prolonged dry spells, and when soil moisture dropped below a set threshold, supplementary irrigation was done in high-input systems, while the low-input systems were fully rainfall-dependent (Musyoka et al., 2017). Soil moisture monitoring was done using a Time Domain Reflectometer.

Fortnight scouting reports were utilized to manage pests and diseases in the experimental sites. In the organic farming systems, commercial biological pesticides (supplementary material A3) (Kampermann et al., 2024) were used during the first to fourth cycle, while in the fifth cycle, companion cropping, sticky traps, and homemade plant-based biopesticides were used. In conventional farming systems, synthetic pesticides and fungicides (supplementary material A3) were used to manage pests and diseases.

2.4. *Crop growth indices and yield measurement*

We used a non-destructive sampling method to determine maize height and stem diameter. Ten (10) maize plants were randomly selected from four quadrants within the net plot (6 by 6 m). We used a measuring tape to determine plant height, which is the distance from the base of the plant to the uppermost extended leaf tip, and a vernier caliper for diameter measurement. The measurements were taken during the reproductive stage, i.e., tasseling/silking. The tasseling stage occurs 2–3 days before silking (the emergence of silk marks the first stage of the reproductive period) (Nleya et al., 2019), with the plant having achieved full height. However, height and diameter measurements were not recorded during the LR10 season.

All maize grain yield was harvested from net plots to reduce the edge effects. Grain moisture content was determined using the PM-600 seed and grain moisture meter. Maize grain weight was corrected based on the measured moisture content, determined to 12.5 % equivalence, and converted to a per-hectare basis. (dry grain weight).

2.5. *Statistical analyses*

As a first step in the analysis, we carried out diagnostic checks on potentially influential and outlying random and residual effects on the data using a studentized residual approach. This allowed for quick graphical checks of fitted residuals in assessing distributional assumptions such as variance homogeneity and lack/presence of serial correlation and assessing the need to add or transform fixed model effects. Diagnostic plots suggested heterogeneity of variances, that is, the variability of the data changed according to one or more factors. Then, the crop growth indices and yield data were subjected to analysis of variance (ANOVA) using the Mixed Procedure Model in SAS 9.3 software (SAS, 2013) to obtain an F value of the effect of the model. Differences between the farming systems were evaluated using least significance difference (LSD) at $p \leq 0.05$.

We calculated the residual variance using the mixed procedure in

Table 3
Nutrient application rate in the conventional and organic farming systems at both input levels in the LTE at Chuka and Kandara sites.

System	Year	Season	Crop	Nutrient load	Total **N** (kg ha^{-1})	Total **P** (kg ha^{-1})
Conv-High	1st	LR	Maize	D-FYM, 200 kg ha^{-1} DAP, 100 kg ha^{-1} CAN	96/113	54/68
		SR	Cabbage	D-FYM, 200 kg ha^{-1} TSP, 300 kg ha^{-1} CAN	145	64
	2nd	LR	Babycorn	D-FYM, 200 kg ha^{-1} DAP, 100 kg ha^{-1} CAN	113	60
		SR	French bean	D-FYM, 200 kg ha^{-1} DAP, 100 kg ha^{-1} CAN	113	60/68
	3rd	LR	Babycorn	D-FYM, 200 kg ha^{-1} DAP, 100 kg ha^{-1} CAN	113	60
		SR	Potato	D-FYM, 300 kg ha^{-1} TSP, 200 kg ha^{-1} CAN	103/90	83/100
Org-High	1st	LR	Maize/Mucuna	Compost, 364 kg ha^{-1} Rock phosphate, Tithonia mulch & tea	96/113	54/68
		SR	Cabbage	Compost, 400 kg ha^{-1} Rock phosphate, Tithonia mulch & tea	145	64
	2nd	LR	Babycorn/Mucuna	Compost, 364 kg ha^{-1} Rock phosphate, Tithonia mulch & tea	113	60
		SR	French bean	Compost, 364 kg ha^{-1} Rock phosphate, Tithonia mulch & tea	113	60/68
	3rd	LR	Babycorn / Mucuna	Compost, 364 kg ha^{-1} Rock phosphate, Tithonia mulch & tea	113	60
		SR	Potato	Compost, 581 kg ha^{-1} Rock phosphate, Tithonia mulch	103/90	83/100
Conv-Low	1st	LR	Maize	Fresh FYM, 50 kg ha^{-1} DAP	31/45	18/27
		SR	Swiss chard/Kale	Fresh FYM, 50 kg ha^{-1} TSP, 60 kg ha^{-1} CAN	20	13
	2nd	LR	Maize/Common bean	Fresh FYM, 50 kg ha^{-1} DAP	31/45	18/27
		SR	Common bean	No fertilizer application	na	na
	3rd	LR	Maize/Common bean	Fresh FYM, 50 kg ha^{-1} DAP	31/45	18/27
		SR	Potato	Fresh FYM, 100 kg ha^{-1} DAP	27/45	25/50
Org-Low	1st	LR	Maize	D-FYM, 100 kg ha^{-1} Rock phosphate, Tithonia mulch	31/45	18/27
		SR	Swiss chard/Kale	D-FYM, 90 kg ha^{-1} Rock phosphate, Tithonia mulch & tea	20	13
	2nd	LR	Maize/Common bean	D-FYM, 100 kg ha^{-1} Rock phosphate, Tithonia mulch	31/45	18/27
		SR	Common bean	No fertilizer application	na	na
	3rd	LR	Maize/Common bean	D-FYM, 100 kg ha^{-1} Rock phosphate, Tithonia mulch	31/45	18/27
		SR	Potato	D-FYM, 200 kg ha^{-1} Rock phosphate, Tithonia mulch	27/45	25/50

Total N and P are shown as supplied during 1st to 4th Cycle and 5th Cycle (separated by "/")
LR = Long rains season, SR =Short rains season, D-FYM = Decomposed Farmyard manure, na = not applicable

SAS 9.3 to assess grain yield stability. The data were first analyzed with a mixed model ANOVA in which the factors cropping seasons (6 levels) and farming systems (4 levels) and their interactions were considered as fixed effects, while the replications were considered as the random effect (block effect). Diagnostic plots and Levene's test were performed by subjecting the absolute values of the residuals from the basic mixed model to a regular analysis of variance, which showed heterogeneity between sites ($p < .0001$), maize cropping seasons ($p < .0001$), site × cropping season ($p = 0.02$), between the farming systems ($p < .0001$), systems × site ($p = 0.003$), season× system ($p < .0001$), cropping season × site ($p < .0001$) and cropping season × systems × site (0.01). The mixed model was then improved by specifying that the residual variance differed between the cropping seasons or between the cropping seasons × farming systems (using a 'REPEATED' statement procedure). The smallest score for Akaike's information criterion was used to select the best model (Akaike, 1974) to show the difference in residual variance between the farming systems. The mean (fixed effect) and the variance (random effect) were the two main factors used in describing the response pattern of the grain yields under the implemented systems. Differences between factor-level means were examined using the least significant difference at $p \leq 0.05$.

3. Findings and discussion

3.1. Rainfall characteristics during the maize cropping (long rains) seasons

We observed declining total rainfall amounts during the maize sole-cropping (LR) seasons over the experimental period in both sites (Fig. 1).

The onset and cessation dates were generally similar in both sites except during the LR19 and LR22 seasons (Table 4). Dry spells of 5–10 days were highly recurrent in all the seasons compared to those of more than 10 days in the two sites.

The onset and cessation of a rainy season, length of the season, precipitation amounts, and frequency of dry spells within a season are essential for crop growth and productivity (Ngetich et al., 2014; Patrick et al., 2019). According to MacLeod (2018), unpredictability in the timing of the rains, onset, and cessation significantly impact agriculture and is a frequent request from farmers in East Africa to manage potential risks during planting and harvesting activities. Our observations corroborated the study by Ngetich et al. (2014), who reported a high frequency of dry spells of at least 5 days during long rain seasons in the Central Highlands of Kenya, including the Chuka area. Each season experienced a dry spell, a similar observation to the studies of Rockström et al. (2010) and Kiboi et al. (2023). A study by Nathan et al. (2020) in the Central Highlands of Kenya also reported similar observations on frequent dry spells, onset, and cessation dates.

3.2. Maize crop growth indices

The farming systems significantly affected maize crop height during the reproductive stage in both sites. At Chuka, the systems had a significant effect on height ($p \leq 0.05$) during all the cropping seasons except during LR07 and LR16 (Table 5). Crop height between the low input systems had significant differences during the LR13, LR16, and LR19 seasons. There were no crop height differences between the high input systems throughout the research period at Chuka. At the Kandara site, we observed significant differences in crop height in all systems throughout the experimental period ($p \leq 0.05$). Crop height in the Org-High system was significantly different during LR22, while under low input systems, the difference was significant during LR07 and LR16 seasons (Table 5).

Table 4
Rainfall characteristics during sole maize cropping seasons (LR07, LR10, LR13, LR16, LR19 & LR22) at Chuka and Kandara sites.

Rainfall distribution	LR07	LR10	LR13	LR16	LR19	LR22
Chuka						
Onset	19th March, 2007	26th Feb, 2010	08th March, 2013	03rd March, 2016	11th March, 2019	26th March, 2022
Cessation	31st July, 2007	31st July, 2010	31st July, 2013	30th July, 2016	11th May, 2019	12th July, 2022
Length of the season	135	156	146	150	62	109
Dry spells						
5 – 10 days	3	2	5	4	1	1
11 – 14 days	2	0	0	1	0	1
> 14 days	2	2	1	1	2	1
Kandara						
Onset	19th March, 2007	27th Feb, 2010	08th March, 2013	01st March, 2016	05th March, 2019	28th March, 2022
Cessation	31st July, 2007	27th July, 2010	29th July, 2013	23rd June, 2016	30th July, 2019	31st July, 2022
Length of the season	135	151	144	115	148	126
Dry spells						
5 – 10 days	6	2	0	5	3	0
11 – 14 days	2	1	0	1	0	1
> 14 days	0	1	2	1	2	3

During the reproductive stage, maize crop diameter significantly differed between the systems during the LR13, LR16, and LR19 seasons at the Chuka site (Table 5). At the Kandara site, the crop diameter was significantly different under the farming systems during all the cropping seasons, similar to crop height. There was a significant difference in the crop diameter between the high input systems in the LR22 season (similar to crop height) and between the low input systems during the LR07 and LR19 seasons.

Maize plant height (Guo et al., 2022) and diameter (Schepers et al., 2017; Zhou et al., 2023) are important agricultural indicators for monitoring physiological-related traits such as grain yields and biomass. We attributed high plant height and diameter under high input levels to the high nitrogen and moisture levels (due to supplementary irrigation). In Chuka, we attributed the greater plant height and diameter under the high input systems to the soil type, *Humic Nitisols* that are already higher in nitrogen content and soil organic carbon (Table 1) compared to *Rhodic nitisols* at Kandara (Musyoka et al., 2017; von Arb et al., 2020). At Kandara, Conv-High had the greater plant height and diameter during the earlier years but greater in the later years under Org-High. This could be due to the build-up of soil organic carbon from the organics enhancing soil moisture retention, leading to better nutrient mineralization (Fließbach et al., 2013). A significant increase in maize plant height due to high soil N content was also reported by Amanullah et al. (2010), Iqbal et al. (2015), and Bao et al. (2024). Consequently, increased plant height due to supplemental irrigation was observed by Chinasho et al. (2023) in maize and Dugje et al. (2023) in sorghum. Similar to our findings at Kandara, Bayoh et al. (2024) also observed organic inputs had a positive effect on plant growth traits of maize crops after the research period.

Nevertheless, Maintang et al. (2021) reported improved maize growth parameters, including height and diameter, under the combination of organic and inorganic fertilizers. We attributed the lower plant height and diameter under the Org-Low system to the low N content, reduced soil moisture content, and low plant nutrient demand synchronization in the two sites, which are fully rain-fed. Also, plant height and diameter were low during the LR19 season compared to other seasons, which we ascribed to the least amount of rainfall received (Fig. 1).

3.3. Maize grain yield

The maize grain yields during seasons significantly differed among the farming systems throughout the experimental period in both sites (Table 6). However, there was no significant difference in grain yields within high-input systems and within low-input systems except during LR22 at Chuka. At Chuka, Org-High generally had higher grain yields except in LR07 and LR22, while at Kandara, the Org-High system had the highest yields during the LR13, LR16, and LR22 seasons. During the LR19 and LR22 seasons, the Conv-Low system had the lowest grain yields in the two sites. Generally, the Chuka site had more grain yields compared to the Kandara site.

Our observations confirm the long-term experiment findings by Boomsma et al. (2010) that plant height variability can be an indicator or predictor of maize grain production. In our study sites, Adamtey et al. (2016) and Bautze et al. (2024) had similar observations for marketable maize grain yields. Despite the high rainfall amounts during the LR13 season (Fig. 1), the low input systems had low yield, which we attributed to the poor rainfall distribution and high dry spell frequency at Chuka (Fig. 1 and Table 4) (Adamtey et al., 2016; Kiboi et al., 2019). We ascribed low grain yields under the low input systems during LR19 to early rainfall cessation than expected in Chuka and comparably low total rainfall amounts in both sites (Table 4), as also observed for the crop growth indices.

Table 5
Effect of the different farming systems on maize height and diameter during reproductive stage (the LR07, LR13, LR16 and LR19 cropping seasons) at Chuka and Kandara sites.

	Chuka									
Farming	**Height (cm)**					**Diameter**				
System	**LR07**	**LR13**	**LR16**	**LR19**	**LR22**	**LR07**	**LR13**	**LR16**	**LR19**	**LR22**
Org-High	187.23^{a}	188.07^{a}	144.88^{a}	217.70^{a}	250.88^{a}	21.76^{a}	25.57^{a}	23.05^{a}	21.88^{a}	22.95^{a}
Conv-High	194.31^{a}	176.97^{a}	154.73^{a}	210.40^{a}	243.45^{ab}	24.39^{a}	22.66^{b}	20.70^{a}	19.62^{a}	23.95^{a}
Org-Low	186.24^{a}	110.74^{c}	83.13^{b}	79.45^{c}	223.43^{b}	22.97^{a}	20.69^{c}	17.13^{b}	12.90^{b}	23.12^{a}
Conv-Low	173.05^{a}	154.19^{b}	136.90^{a}	119.75^{b}	247.95^{ab}	20.17^{a}	22.36^{bc}	20.63^{a}	15.14^{b}	23.73^{a}
p value	ns	< .0001	0.004	< .0001	0.05	ns	0.0009	0.03	0.001	ns
	Kandara									
	LR07	**LR13**	**LR16**	**LR19**	**LR22**	**LR07**	**LR13**	**LR16**	**LR19**	**LR22**
Org-High	98.60^{b}	213.33^{a}	202.02^{a}	242.04^{a}	283.64^{a}	19.60^{b}	22.21^{a}	22.77^{a}	24.64^{a}	29.92^{a}
Conv-High	126.38^{ab}	222.58^{a}	235.65^{a}	252.13^{a}	256.84^{b}	22.60^{ab}	21.57^{a}	22.64^{a}	25.77^{a}	25.43^{b}
Org-Low	113.98^{b}	110.31^{b}	102.49^{b}	121.15^{b}	208.70^{c}	21.60^{b}	18.23^{b}	17.51^{b}	14.54^{c}	19.60^{c}
Conv-Low	159.16^{a}	125.65^{b}	204.09^{a}	156.01^{b}	210.34^{c}	28.10^{a}	18.49^{b}	19.95^{b}	17.87^{b}	20.01^{c}
p value	0.001	< .0001	0.003	0.0001	< .0001	0.01	0.01	0.001	< .0001	< .0001

Org-High =Organic High system, Conv-High = Conventional High, Org-Low =Organic Low, Conv-Low = Conventional Low. Same superscript letters in the same column denote no significant difference between farming systems means in a season at a given site

Table 6
Maize grain yield (Mg ha^{-1}) under the different farming systems during the LR07, LR10, LR13, LR16 and LR19 cropping seasons at Chuka and Kandara sites.

Farming Systems	**LR07**	**LR10**	**LR13**	**LR16**	**LR19**	**LR22**
	Chuka					
Org-High	2.55^{ab}	4.87^{a}	5.00^{a}	7.42^{a}	5.33^{a}	4.19^{a}
Conv-High	2.85^{a}	4.30^{a}	3.70^{a}	6.82^{a}	4.67^{a}	4.97^{a}
Org-Low	2.04^{cb}	2.58^{b}	1.54^{b}	2.46^{b}	0.29^{b}	3.26^{b}
Conv-Low	1.46^{c}	2.77^{b}	1.69^{b}	3.21^{b}	0.26^{b}	2.18^{c}
p value	0.003	0.001	0.001	< .0001	< .0001	0.001
	Kandara					
Org-High	0.47^{b}	5.16^{a}	5.74^{a}	6.92^{a}	3.68^{a}	4.83^{a}
Conv-High	1.11^{a}	5.20^{a}	5.26^{a}	6.10^{a}	4.39^{a}	3.59^{a}
Org-Low	0.41^{b}	2.01^{b}	0.10^{b}	1.20^{b}	0.22^{b}	1.28^{b}
Conv-Low	1.08^{a}	2.33^{b}	0.11^{b}	1.91^{b}	0.19^{b}	0.71^{b}
p value	0.03	< .0001	< .0001	0.001	0.0004	0.0004

Org-High =Organic High system, Conv-High = Conventional High, Org-Low =Organic Low, Conv-Low = Conventional Low.
Note: Same superscript letters in the same column denote no significant difference between farming systems means in a season at a given site

There was a gradual (not significant) increase in crop growth parameters and grain yield under the Org-High system in Kandara seasonally (LR07 -LR16) compared to Conv-High. Similar findings of gradual increase in crop yields due to soils readapting to organic inputs were reported from a long-term experiment by Fließbach et al. (2007) and Fließbach et al. (2013). Also, in a 26-year study, Borrelli et al. (2014) found that maize grain yield in rotation with ryegrass, barley, white clover, and tall fescue in two levels of agronomic inputs increased steadily. Also, the Org-Low systems gradually increased grain yields within seasons compared with the Conv-Low in the two sites. Despite the low rainfall amounts, the organic low systems had more yields in the LR19 and LR22 seasons (later years) than the conventional low systems. We ascribed this to the transition period whereby soil biological parameters need to be readapted for enhanced nutrient release. Higher grain yields and crop growth indices during the earlier seasons under conventional systems were due to the readily available nutrients from the mineral fertilizers.

Additionally, higher yields during LR22 were ascribed to the management practices adapted in the fifth cycle, including the use of push-pull technology and an increase in the amount of fertilizers applied in the farming systems (Bautze et al., 2024). We ascribed the higher grain yields in Chuka to better soil fertility in the *Humic Nitisols* than the *Rhodic Nitisols*. Additionally, Chuka is categorized as a higher agricultural potential area (Okeyo et al., 2014).

3.4. Maize grain yield stability

The grain yield residual variance was heterogeneous, indicating that the farming systems influenced grain yield stability during the experimental period (Fig. 2). In Chuka, the Conv-High system had the least residual variance of 0.28 Mg ha$^{-2,}$ followed by the Org-Low system (0.45 Mg ha^{-2}), then the Conv-Low system (0.46 Mg ha^{-2}), while the Org-High system (0.67 Mg ha^{-2}) had the highest residual variance. At the Kandara site, the Org-Low system had the lowest grain yield residual variance (0.16 Mg ha^{-2}), followed by the Conv-Low system (0.47 Mg ha^{-2}), then Org-High (1.53 Mg ha^{-2}) and Conv-High (4.15 Mg ha^{-2}) had the highest residual variance (Fig. 2). We used the mean (fixed, i.e., systematic effect) and the variance (random element) to describe the response of the maize yields under the different farming systems. The smaller variance implied a more stable yield.

The average maize grain yield was high under high input systems (Fig. 3), which corresponds with the observed seasonal yield (Table 6) in Chuka and Kandara sites. Also, the average grain yields were higher in high input systems compared with low input systems (Fig. 3). Generally, the most stable farming systems had the lowest average grain yields except for Conv-High in Chuka.

Generally, grain yields were more stable in the low input systems at Kandara (Fig. 2), whereas, at Chuka, the Conv-High system had more stable yields than the low input systems. Comparing both sites, we observed better maize grain yield stability at Chuka compared with

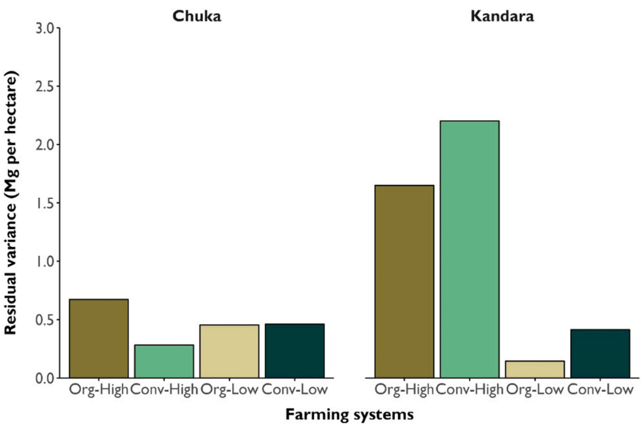

Fig. 2. Residual variance of grain yields in Mg ha^{-2} under different farming systems in Chuka and Kandara sites over six long rains cropping seasons. Org-High =Organic High system, Conv-High = Conventional High, Org-Low =Organic Low, Conv-Low = Conventional Low.

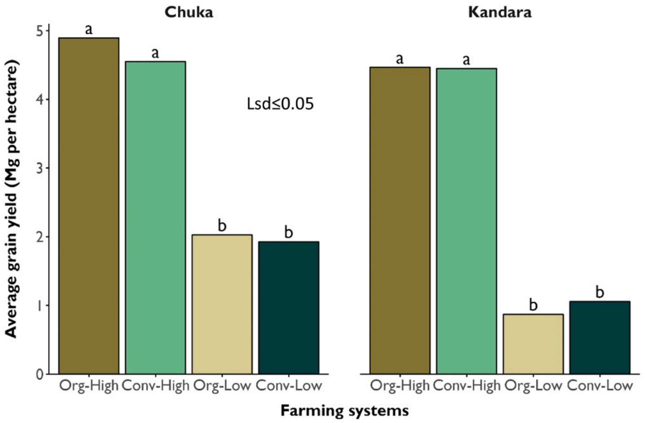

Fig. 3. Average grain yields in Mg ha^{-1} under different farming systems in Chuka and Kandara sites over six long rains cropping seasons. Org-High =Organic High system, Conv-High = Conventional High, Org-Low =Organic Low, Conv-Low = Conventional Low. Same superscript letters in the same column denote no significant difference between farming systems means in a season at a given site.

Kandara. We attributed this to better soil fertility status at Chuka (von Arb et al., 2020). In our two sites, Kiboi et al. (2020) showed better responses of the Humic Nitisols to organic amendments in soil physical-chemical properties at Chuka than the soils in Kandara. Zhang et al. (2021) concluded that improvement in soil organic matter, total N, available N, available P, and available K as a result of straw incorporation led to increased rice yield stability. Our attribution also agrees with several other researchers who reported that higher soil fertility, especially soil organic carbon and organic matter, enhances yield stability (Pan et al., 2009; Sileshi et al., 2010; Shrestha et al., 2013; Chen et al., 2022).

At Chuka, we observed better grain yield stability under Conv-High. In their meta-analyses, Knapp and van der Heijden (2018) demonstrated that conventional agriculture had higher relative yield stability than organic agriculture due to the nutrient load and crop species. Knapp et al. (2023) also reported better relative yield stability in conventional than in organic systems. Generally, yield stability in low farming systems was more stable than the high input systems except Conv-high in Chuka, which could be attributed to the likelihood of nutrient imbalance, e.g., leaching due to supplementary irrigation in the high input systems (Musyoka et al., 2017). Also, the low-input systems had lower average yields throughout the experimental period. From their long-term experiment, comparing conventional and organic farming with different fertilizer levels and crop rotation, Knapp et al. (2023) also observed that treatments with low fertilizer levels showed to be more stable in absolute stability for maize crop. In long-term simulations, Kisaka et al. (2016) reported that applying low rates of N showed low inter-seasonal variations in maize yields compared to using high N rates. Contrary to our findings, Schrama et al. (2018) reported no difference in temporal stability between the organic and conventional farming systems. Nevertheless, in their study on maize grain yield stability at Chuka, Kiboi et al. (2023) concluded that adding soil inputs did not suddenly lead to stable yields.

4. Conclusion

Based on the findings of our study, organic farming systems have the potential to achieve yields that match or exceed those of conventional farming systems, particularly in the long term when given adequate time for soil adaptation and improvement in soil fertility. Given the region's susceptibility to climate variability, it is crucial to consider yield stability alongside average yield performance. Low-input farming systems demonstrated greater yield stability, suggesting that they could play an essential role in mitigating risks associated with fluctuating climates and input availability. To sustainably enhance maize productivity and stability, the study recommends focusing on improving soil fertility through sustainable organic practices, including crop rotation, organic inputs application, and mulching, all of which can be practically implemented by smallholder farmers in Central Kenya or any other regions of similar agro-ecological conditions in the tropics.

Potential limitations

This study has a number of limitations that should be considered while interpreting the results. First, unmeasured covariates such as specific pest and disease pressures, farmer-specific management practices, and variations in pest management strategies could have influenced maize yields and stability. Second, climate variability factors beyond rainfall, such as humidity and temperature extremes, were not comprehensively assessed and could affect yield stability interpretations. Lastly, economic and labor-related covariates, including the costs, and availability, were not evaluated. These factors can significantly influence the practical adoption and sustainability of recommended organic farming practices, thus the need to be adjusted to the agroecological and socioeconomic environment.

CRediT authorship contribution statement

Milka Kiboi: Conceptualization, Methodology, Validation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Project administration. **David Bautze:** Conceptualization, Validation, Formal analysis, Data curation, Writing – review & editing, Visualization, Funding acquisition. **Felix Matheri:** Investigation, Visualization, Writing – review & editing. **Amritbir Riar:** Writing – review & editing, Resources, Funding acquisition. **Andreas Fliessbach:** Writing – review & editing, Supervision, Visualization, Funding acquisition.

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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.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2025.127746.

Data availability

The datasets generated during and/or analyzed during the study have been presented in the article

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