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Closing the crop yield gap between organic and conventional farming systems in Kenya: Long-term trial research indicates agronomic viability

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ABSTRACT

The production gap between current and attainable yields is highest on Africa's smallholder farms, and some studies indicate that they might not benefit from the yield gains offered by conventional farming. Simultaneously, alternative farming systems like organic provide biodiversity and soil fertility advantages, but their ability to produce sufficient food is still under debate. Additionally, comparative data on the productivity of organic versus conventional in tropical regions are scarce or short-term. We investigated the crop productivity of organic and conventional farming systems using 15 years in two long-term systems comparison trials in Kenya. The trials were established in 2007 at two sites in the Central Highlands of Kenya. At each site, conventional and organic systems were compared at high input levels. The trial involved a three-year crop rotation cycle of maize, vegetables, legumes, and potatoes, repeated five times since its establishment. Management practices were kept similar in the first four rotations and revised in the fifth to improve systems representing best practices. Our results showed that while maize and baby corn had relatively low yield gaps (−13 to +12 %) between organic and conventional systems, cabbage, French beans, and potato had high yield gaps (−50 to −30 %). We attributed this to nutrient limitations and higher pest and disease damage. The yield gap could partially be closed by adopting best practices in the organic system, including system diversification and effective soil fertility, nutrient, and integrated pest management.

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1. Introduction

The global population is estimated to reach over 9 billion people by 2050, and in parallel, the wealth and purchasing power likely will increase, leading to higher demand for food in general and for processed food, meat, dairy, and fish, specifically [1,2]. The current forecast shows that the global crop calories and protein demand could increase by 100 % and 110 %, respectively, by 2050 [3]. However, increasing crop production and following the current trend of intensification in high-yielding regions while extensification in low-yielding regions could lead to further increases in land clearing, GHG emissions, and nitrogen use [3]; thus affecting the resources and livelihoods of future generations. The enormous challenges of increasing food production, reducing food waste and loss, controlling greenhouse gas emissions, conserving water supplies and biodiversity, and ending hunger simultaneously draw a grim picture regarding the status and future development of food systems [1,4].

While drastic reductions in food waste and diet shifts with reduced meat consumption would enable meeting the nutrition demands [5,6], food insecurities also need to be met by closing the yield gap between current and attainable yields (i.e., a yield that can be achieved under good management conditions; [7]). The yield gap is highest on African smallholder farms. This is due to limited access to agricultural inputs, lack of mechanization, small and fragmented farm size, and insufficient investment in soil fertility management [8]. In addition, limited knowledge, institutional support, formalized training, and information about environmental factors also limit crop yield [9]. Studies show that small farms (<2 ha) in sub-Saharan Africa still operate a greater share of the land and, consequently, a greater share of the food production [10]. However, their low yields pose a problem with the projected rapid population growth in Africa [8]. Some studies argue that closing the yield gap on these farms will not be enough to achieve food security and a sufficient living income from farming [11]. For example, Tittonell and Giller [8] argued that smallholder farmers might not benefit from the yield gains offered by plant genetic improvement because cropping without sufficient nutrient input addition and organic matter leads to soil degradation. Additionally, available fertilizers have a low response on these soils [12–14], keeping poor farmers confined within recurrent poverty traps.

The question of whether the current agricultural development approach can boost African farms' productivity is crucial. Conventional farming practices that rely on intensified external synthetic resource use to increase yields have raised concerns about their negative environmental impacts. This has brought up a discussion about alternative, possibly more sustainable, and safe farming options, such as organic farming [15,16] or regenerative agriculture [17,18]. In the debate about whether organic agriculture can produce sufficient food to feed the world, the lower yields compared to conventional farming are a major concern to global food security [6,19]. On average, worldwide, organic farming yield is 9–25 % lower than conventional farming, depending on the crop and management practices [20–22]. In addition, critics point out that organic agriculture needs more land area to substitute for production losses, produce required nutrient inputs, and maintain optimum levels of biodiversity [23,24] whereas, at the same time, it increases output price, making food less affordable to consumers in developing countries [25].

Still, organic farming is often considered a more sustainable option, as there is clear evidence of higher biodiversity [26–33], improved energy efficiency [34,35], and improved soil and water quality [31,36–39]. The need for more sustainable and agroecological adapted food systems, as highlighted by Food and Agriculture Organization [40], presents an opportunity for organic farming systems to improve food security and nutrition and enhance the livelihoods of smallholders.

Despite the potential benefits of organic agriculture in developing countries, data on its productivity in tropical regions are scarce [22]. Additionally, most comparisons between organic and conventional agriculture are often limited to a single crop level, and short-term studies fail to capture the performance at a systems level and in the long-term. This is a significant gap for stakeholders and policymakers when making decisions for sustainable development. In our research, we investigated crop productivity of organic and conventional farming from maize crops, legumes, leafy vegetables, and potatoes cultivated over 15 years in two long-term farming systems comparison trials in Kenya. We evaluated the absolute economic (marketable) yields and the yield gap between high-input farming systems (using the farming system definition of Gómez-Macpherson et al. [41]). We hypothesized that crop productivity could be similar in high-input organic and conventional farming systems if best management practices are applied in organic.

2. Methodology

2.1. Sites description

The long-term trials were established in 2007 within the research program «Farming Systems Comparisons Trials in the Tropics» (SysCom) [42] at two trial sites: Chuka (Tharaka Nithi county) and Kandara (Murang'a county) in the sub-humid zones of the Central Highlands of Kenya (Fig. 1). Both sites are characterized by a bimodal rainfall pattern (long and short rain seasons). Chuka is situated in the upper midland 2 agro-ecological zone (UM2) at 1458 m above mean sea level with a mean annual rainfall of 1050 mm (Fig. 2). Kandara is situated in the upper midland 3 agroecological zone (UM3), at 1500 m above mean sea level and with a mean annual rainfall of 900 mm. Both sites have a mean annual temperature of 20 °C, ranging from 15 to 27 °C. However, temperature and rainfall have fluctuated over the years and months (Supplementary Tables A1 and A2 for rainfall and dry spell data). The main catchment river for both trial sites is the Tana River (named river Sagana at the source) with rivers Chania, Mathioya, Maragua, Tula, and Gura as the main tributaries.

The soils at Chuka are *Humic Nitisols*, while those at Kandara are *Rhodic Nitisols* [43–45]. The experimental plots measured 8 × 8 m (net

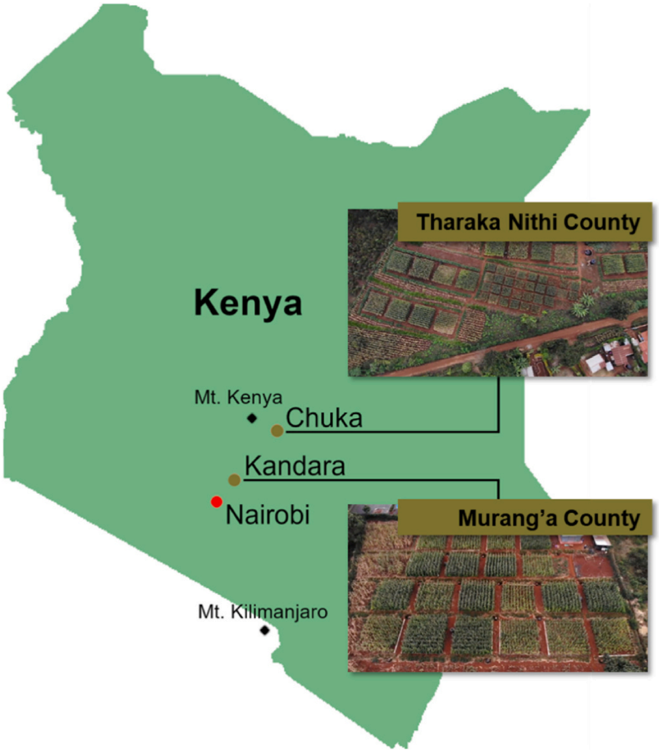

Fig. 1. Locations of the long-term farming system experiment trial sites Chuka and Kandara in the Central Highland of Kenya.

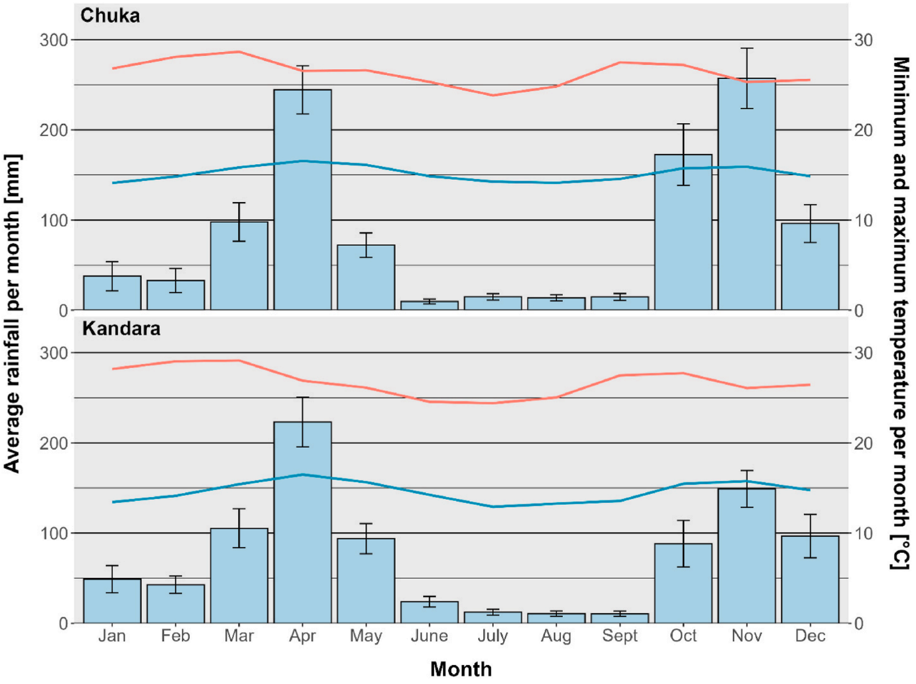

Fig. 2. Average rainfall (blue bar), maximum and minimum temperature (red and blue line) per month in the long and short season (Mar–Sep; Oct–Feb) at Chuka and Kandara (data from long season 2007 to short season 2021). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

plot size of 6 × 6 m for data collection) each. We set up the experiments in a Randomized Complete Block Design (RCBD) with four replications at Chuka and five at Kandara [36].

2.2. Farming system management

At each site, conventional (Conv) and organic (Org) systems were compared at high and low input levels. For this study, we focused on the high input systems (High) representing commercial production in smallholder farms with crops produced for regional and export markets receiving sufficient supply of nutrients, water, and pest control. The farming system design followed two studies conducted at the site location [46,47] analyzing current production patterns and making recommendations for potential systems. The three-year-six-season long crop rotation in the high-input systems was designed as shown in Table 1. In all systems, maize, a staple food crop in Kenya grown on around 2.1 Million ha [48] of the existing 5.8 Million ha arable land [49], was planted every year during the long rain season. The cereal was grown as a sole maize crop or as babycorn (young cobs used as a vegetable). For the maize sole crop, the variety H513 was used in all seasons, whereas for babycorn, we used Pannar 14 in all seasons except in 2008 (variety BC-2) and 2015 (variety G18). In the short rain seasons, cabbage (variety Gloria F1), French beans (variety Star 2052 in 2008, variety Serengeti in all other seasons), and potatoes (variety Asante in 2009 and 2012, variety Shangi in all other years) were grown. These crops are less common in Kenya (production area: around 30 000 ha, 8000 ha, and 115 000 ha, respectively) but with a greater share of total production value [48,50] as they can achieve higher prices.

Table 1
Crop rotation in the 1st to 4th (conversion and stable period) and the 5th cycle (adaptation period) of the organic and conventional farming systems in the long-term experiments between 2007 and 2021 at Chuka and Kandara, Central Highland of Kenya.

Cycle	Year	Season	Conv-High	Org-High
1st to 4th	1st	Long	Maize	Maize/Mucuna
		Short	Cabbage	Cabbage
	2nd	Long	Babycorn	Babycorn/Mucuna
		Short	French bean	French bean
	3rd	Long	Babycorn	Babycorn/Mucuna
		Short	Potato	Potato
5th	1st	Long	Maize	Maize/Mucuna
		Short	Cabbage	Cabbage
	2nd	Long	Babycorn/Desmodium	Babycorn/Desmodium
		Short	French bean/ Desmodium	French bean/ Desmodium
	3rd	Long	Babycorn/Desmodium	Babycorn/Desmodium
		Short	Potato/Dolichos/ Desmodium	Potato/Dolichos/ Desmodium

Since the establishment of the trials in 2007, the crop rotation has been repeated five times (1st cycle: 2007–2009; 2nd: 2010–2012; 3rd: 2013–2015; 4th: 2016–2018; 5th: 2019–2021). The farming systems in the 1st to 4th cycle represented common management practices in Kenya (see Adamtey et al. [36] for further details), with the 1st cycle as a conversion period, which is the usual duration required to achieve organic certification. However, management practices were adapted in the 5th cycle (adaptation period) after evaluating past results from long-term trials (e.g., Musoka et al. [51]) and to accommodate advances in crop management and improve systems to best management practices. The crop rotation was diversified by incorporating the push-pull technology [52], changing from sole cropping to intercropping in babycorn (+desmodium), maize (+desmodium), French beans (+desmodium), and potatoes (+dolichos/desmodium). In addition, the cabbage variety was changed to Pruktor F1 in both systems.

Nutrient management followed similar approaches in the farming systems during the conversion and stable period (Table 2). At planting, the conventional system received fresh/decomposed farmyard manure (FYM), Triple-Super phosphate (TSP), or Di-ammonium phosphate (DAP), while organic systems received compost, rock phosphate, and plant residues. Topdressing during vegetative and reproductive crop stages was done with Calcium ammonium nitrate (CAN) in the conventional system or tithonia plant tea (*Tithonia diversifolia*) in the organic farming system. Tithonia was also applied as mulch two weeks after crop emergence/transplanting in the organic system. The farming

Table 2

Nutrient management in the conventional and organic farming systems in the long-term experiment at Chuka and Kandara, Central Highlands of Kenya; Total N and P are shown as given before and during the adaptation period (separated by "/").

System	Year	Season	Main crop	Nutrient management	Total N (kg ha^{-1})	Total P (kg ha^{-1})
Conv-High	1st	Long	Maize	Decomposed FYM, 200 kg ha^{-1} DAP, 100 kg ha^{-1} CAN	96/113	54/68
		Short	Cabbage	Decomposed FYM, 200 kg ha^{-1} TSP, 300 kg ha^{-1} CAN	145	64
	2nd	Long	Babycorn	Decomposed FYM, 200 kg ha^{-1} DAP, 100 kg ha^{-1} CAN	113	60
		Short	French bean	Decomposed FYM, 200 kg ha^{-1} DAP, 100 kg ha^{-1} CAN	113	60/68
	3rd	Long	Babycorn	Decomposed FYM, 200 kg ha^{-1} DAP, 100 kg ha^{-1} CAN	113	60
		Short	Potato	Decomposed FYM, 300 kg ha^{-1} TSP, 200 kg ha^{-1} CAN	103/90	83/100
Org-High	1st	Long	Maize	Compost, 364 kg ha^{-1} Rock phosphate, Tithonia mulch and tea	96/113	54/68
		Short	Cabbage	Compost, 400 kg ha^{-1} Rock phosphate, Tithonia mulch and tea	145	64
	2nd	Long	Babycorn	Compost, 364 kg ha^{-1} Rock phosphate, Tithonia mulch and tea	113	60
		Short	French bean	Compost, 364 kg ha^{-1} Rock phosphate, Tithonia mulch, and tea	113	60/68
	3rd	Long	Babycorn	Compost, 364 kg ha^{-1} Rock phosphate, Tithonia mulch and tea	113	60
		Short	Potato	Compost, 581 kg ha^{-1} Rock phosphate, Tithonia mulch	103/90	83/100

FYM, Farm-yard manure; DAP, Di-Ammonium Phosphate; CAN, Calcium Ammonium Nitrate; TSP, Triple Super Phosphate.

Note: All input were applied during planting, except CAN and Tithonia tea which were applied as topdressing during vegetative and reproductive crop stages.

systems received different amounts of fertilizer in the adaptation period compared to the conversion and stable periods: We increased the total N applied in the sole maize crop and decreased in potato (see Table 2 for further details).

Pests and diseases were managed based on bi-weekly scouting reports. In the conventional farming system, synthetic pesticides and fungicides were used to manage pests and diseases, respectively, while in the organic farming system, commercial biological pesticides were used during the 1st to 4th cycle (Supplementary material A3). In the 5th cycle, companion cropping, sticky traps, and homemade plant-based biopesticides were introduced into the organic farming system. In all systems, hand hoeing was done during planting in each season up to a depth of 20 cm, followed by two weeding times with a matchet within the season. Mulching in the organic farming system was also done on all crops at the rate of 2 Mg ha^{-1} in the 1st to 4th cycle, and later, it was adapted to 4 Mg ha^{-1} in the 5th cycle. In addition, drip irrigation was done in both systems after rainfall ceased during the planting season.

2.3. *Data collection and analysis*

2.3.1. *Productivity*

We collected all yield data of the economic yields (edible crop parts for consumption or marketing) from the net plot. Baby corn cobs, cabbage heads, French bean pods, and potato tubers were measured as fresh weight, whereas maize grain was determined at a moisture content of 13 % (dry weight). All economic yields were sorted into marketable and unmarketable yields (i.e., damaged, physiologically deformed, or below-marketable-sized crop products). Absolute marketable yield data were separately prepared, and we analyzed them using the statistical software R version 4.2.1 [53] for each trial site and crop. Therefore, we used a linear mixed effect model analyzing the marketable crop yield with the farming system and sampling year as fixed factors, block as a random factor, and an interaction between the fixed factors. The model was applied using the function *lmer* from the package *lme4* [54]. The model was checked for outliers with the function *cooks.distance* from the *stats* package [53] and they were removed if reasonable. In addition, residuals of the model were checked for normal distribution and heteroscedasticity graphically and with hypothesis test using the *shapiro.test* and *bartlett.test* from the *stats* package. In case normal distribution or heteroscedasticity was not given, data were transformed using the *transformTukey* function from the *rcompanion* package [55]. The significant difference between fixed factors was checked with an ANOVA using the *anova* function from the *lmerTest* package [56]. In addition, a pairwise comparison was made, computing the estimated marginal means with the *emmeans* function from the *emmeans* package [57] and using the *pairs* function from the same package.

In addition to absolute marketable crop yields, we calculated the yield gap between organic and conventional systems (%) to describe farming systems differences within each site and crop. The yield gap was the relative difference between the average organic system's yield to the average conventional system's yield per season and crop within the same input level (Equation (1)) expressed as a negative or positive percentage (negative: yield higher in conventional; positive: yield higher in organic). The yield gap illustrates the data, and no statistical analysis was performed as the sample size per season and crop was small (n = 4 at Chuka and n = 5 at Kandara).

$$\mathit{Relative\ yield\ difference}\ (\%) = \left(\frac{\mathit{Organic\ yield}}{\mathit{Conventional\ yield}} * 100\right) - 100 \qquad \text{Equation 1}$$

3. Results

At Chuka, the organic high-input system produced significantly higher yields of **maize under sole cropping** compared to the conventional high-input systems, with an average yield gap of +12 % (Figs. 3 and 4, Table 3). At Kandara, yields of maize under sole cropping performed similarly in both systems with an average yield gap of −13 % between Org-High and Conv-High (Figs. 3 and 5, Table 4).

Yield gaps for **babycorn** ranged from about −32 % to +22 %, with year-specific significant different yields between Org-High and Conv-High at Chuka. Yields were significantly higher in Org-High compared to Conv-High in 2012 and 2020, and significantly higher in Conv-High than Org-High in 2015, 2018, and 2021, whereas, in all other years, they were similar. The yield gaps of babycorn at Kandara were generally

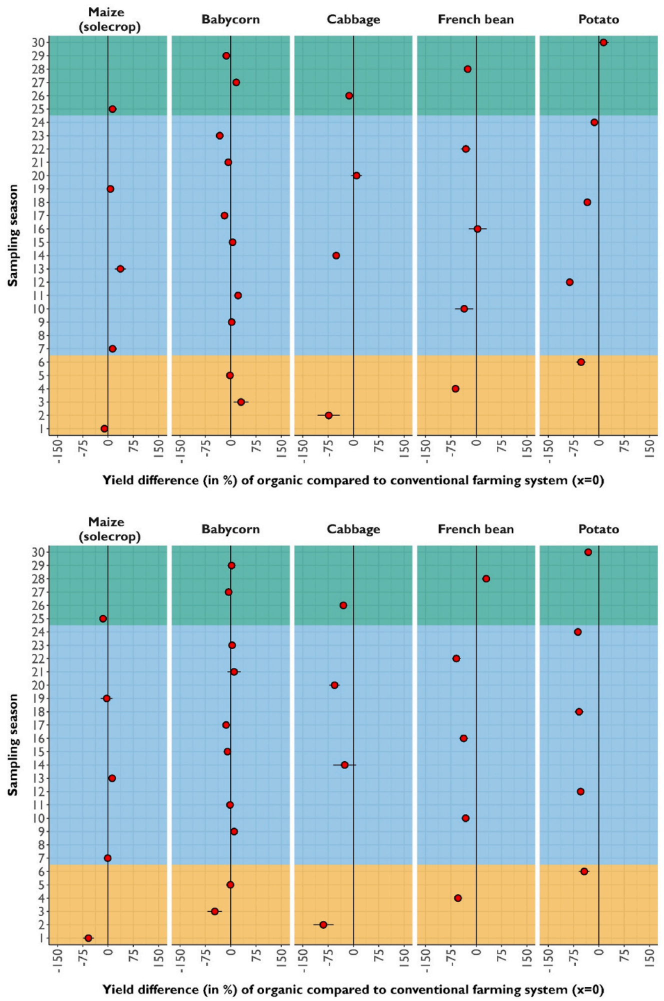

Fig. 3. Yield gap of organic (dots) compared to the conventional farming system (black line at x = 0) at Chuka (top) and Kandara (bottom) during the conversion period (yellow background; season 1 to 6 [2007–2009]), stable period (blue background; season 7 to 24 [2010–2018]), and the adaptation period (green background; season 25 to 30 [2019–2021]). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

lower than at Chuka, ranging between −14 % and +17 % from Org-High to Conv-High between 2011 and 2021 (after the conversion period). Significant differences between systems at this site were only found in 2015, with Conv-High yielding significantly higher than Org-High, whereas, during other years, the yields were similar.

Cabbage yields at Chuka showed an increase over time and a decrease in the yield gap from −73 % in the conversion period (2007) to −13 % in the adaptation period (2019) between Org-High and Conv-High. However, statistics showed that cabbage yields in Conv-High were significantly higher than in Org-High at Chuka. Increasing cabbage yields over time were also recorded at Kandara. However, cabbage yields were still significantly higher in Conv-High compared to Org-High, showing yield gaps of −30 % between Org-High and Conv-High even in the adaptation period.

The **French bean** yields at Chuka during the first two cropping cycles were significantly higher in Conv-High compared to Org-High, showing a yield gap of −61 to −35 %. Both systems achieved similar yields in 2014 and 2017. The trend changed in the adaptation period, whereby Org-High showed a significant increase in yield. The conventional system still achieved significantly higher yields compared to Org-High in 2021, and the yield gap at Chuka could only be closed to - 25 %. The French beans yield at Kandara showed a similar trend: high yield gaps between Org-High and Conv-High (−53 to −31 %) and significantly higher yields in Conv-High compared to Org-High during the first cropping years. The yield decreased in Conv-High in the subsequent year, leading to similar yields in 2014. In the adaptation period, Org-High showed a significant increase in yield, leading to a significantly higher yield compared to Conv-High in 2021. Thus, yield gaps for French beans at Kandara were positive, showing a yield gap of +30 % between Org-High and Conv-High.

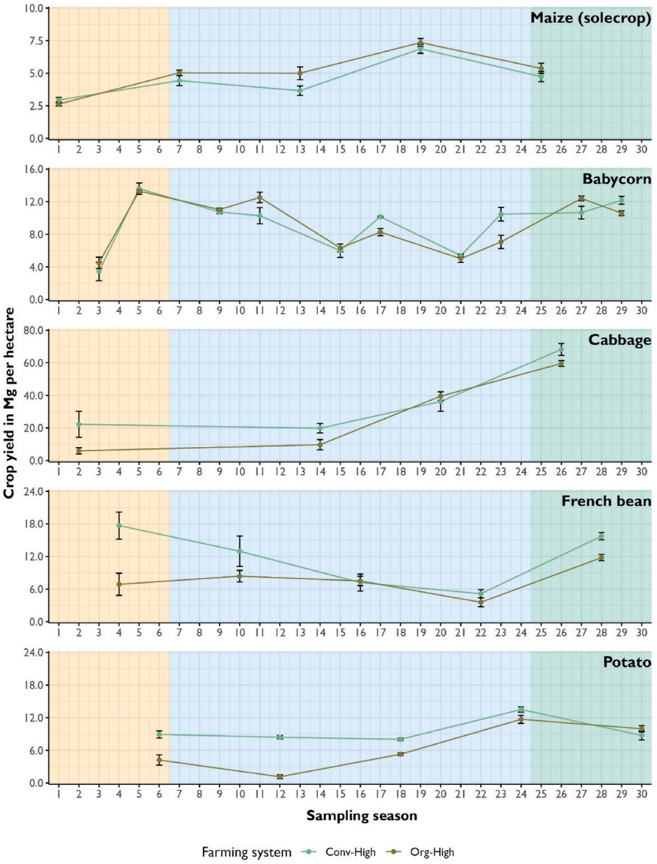

Fig. 4. Absolute marketable crop yield of the organic and conventional farming system at **Chuka** during the conversion period (yellow background; season 1 to 6 [2007–2009]), stable period (blue background; season 7 to 24 [2010–2018]), and the adaptation period (green background; season 25 to 30 [2019–2021]). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

The **potato** tuber yields under Conv-High at Chuka were significantly higher than Org-High up to the year 2018. As a result, the yield gaps to Org-High were high, showing values between −86 to −13 %. However, the Org-High system increased yield over the years and yielded higher to Conv-High in 2021, reducing the yield gap to +14 % (the difference was statistically not different). The potato tuber yields at Kandara were significantly higher in Conv-High compared with Org-High in the stable period, with yield gaps ranging from −63 to −43 %. The Org-High system increased yield in the adaptation period. Contrary to Chuka, the yield gap could not be closed and only decreased to −31 % between Org-High and Conv-High in 2021.

4. Discussion

Generally, the average yield gaps from our study in the two sites under high input management (−19 %) were smaller than previously reported yield gaps between organic and conventional systems [20,22,58,59]. However, our results show that while cereals, maize, and

Table 3
Means, standard error of means, and statistics output (ANOVA) for crop yields (in Mg ha^{-1}) in conventional and organic farming systems in all sampling seasons at Chuka.

				Rotational Cycle[a]														
Season	**System**	**Crop**		One			Two			Three			Four			Five		
				2007 (1/2)			*2010 (7/8)*			*2013 (13/14)*			*2016 (19/20)*			*2019 (25/26)*		
1st	Conv-High	Maize	b	2.94 ± 0.21		γ	4.43 ± 0.39		β	3.66 ± 0.36		β	6.87 ± 0.34		α	4.74 ± 0.39		β
	Org-High	Maize	a	2.63 ± 0.15			5.03 ± 0.21			5.00 ± 0.49			7.35 ± 0.31			5.37 ± 0.39		
2nd	Conv-High	Cabbage	a	22.24 ± 7.93		γ	na			19.83 ± 2.94		γ	36.18 ± 5.93		β	68.19 ± 3.65		α
	Org-High	Cabbage	b	19.83 ± 2.94						9.72 ± 3.12			39.51 ± 2.62			59.51 ± 1.75		
				2008 (3/4)			*2011 (9/10)*			*2014 (15/16)*			*2017 (21/22)*			*2020 (27/28)*		
3rd	Conv-High	Babycorn		3.45 ± 1.15	a	ε	10.73 ± 0.22	a	βγ	5.99 ± 0.83	a	δ	5.39 ± 0.17	a	δ	10.66 ± 0.78	b	βγ
	Org-High	Babycorn		4.50 ± 0.70	a	ζ	11.04 ± 0.18	a	βγ	6.33 ± 0.49	a	εζ	5.01 ± 0.46	a	ζ	12.40 ± 0.28	a	αβγ
4th	Conv-High	French bean		17.69 ± 2.48	a	α	12.97 ± 2.80	a	α	7.20 ± 1.57	a	β	5.14 ± 0.76	a	β	15.74 ± 0.67	a	α
	Org-High	French bean		6.88 ± 2.05	b	αβ	8.38 ± 1.06	b	αβ	7.50 ± 0.87	a	αβ	3.57 ± 0.82	a	β	11.79 ± 0.57	b	α
				2009 (5/6)			*2012 (11/12)*			*2015 (17/18)*			*2018 (23/24)*			*2021 (29/30)*		
5th	Conv-High	Babycorn		13.60 ± 0.69	a	α	10.28 ± 0.99	b	γ	10.15 ± 0.08	a	γ	10.47 ± 0.84	a	βγ	12.17 ± 0.48	a	αβ
	Org-High	Babycorn		13.30 ± 0.16	a	α	12.52 ± 0.64	a	αβ	8.27 ± 0.44	b	δ	7.06 ± 0.81	b	δε	10.59 ± 0.29	b	γ
6th	Conv-High	Potato		8.92 ± 0.65	a	β	8.40 ± 0.31	a	β	8.03 ± 0.23	a	β	13.50 ± 0.49	a	α	8.75 ± 0.85	a	β
	Org-High	Potato		4.22 ± 0.94	b	β	1.15 ± 0.36	b	γ	5.28 ± 0.26	b	β	11.70 ± 0.73	b	α	9.97 ± 0.56	a	α

	Farming system		Sampling season		System x season	
Crop	F value	p-value	F value	p-value	F value	p-value
Maize sole crop	**11.32**	**0.002**	**72.89**	**<0.001**	2.60	0.052
Babycorn	1.06	0.305	**118.81**	**<0.001**	**8.99**	**<0.001**
Cabbage	**9.36**	**0.004**	**82.51**	**<0.001**	2.50	0.077
French bean	**23.66**	**<0.001**	**16.19**	**<0.001**	**4.94**	**0.003**
Potato	**90.51**	**<0.001**	**72.24**	**<0.001**	**19.53**	**<0.001**

[a] Year and the cumulative cropping season numbers (in brackets) are also indicated; Latin letters (abc) show differences between systems or differences for systems within a season; Greek letters (αβγ) show differences between seasons or differences for seasons within a system; na, not applicable.

babycorn had relatively low yield gaps between organic and conventional systems, cabbage, French beans, and potatoes had high yield gaps when not managed with best practice.

4.1. Reasons for the yield gap between the high input systems

Maize grain or babycorn yields showed that comparable yields are attainable in Org-High and Conv-High. In the conversion period, the initial low yields for these crops were attributed to low soil fertility status, unfavorable weather conditions, and low soil moisture [36]. These factors slowed down the decomposition of compost, resulting in slowed release of nutrients to meet the crop's requirements. However, supplementary irrigation was introduced in the second season of 2009, and *Mucuna pruriens* was established as an intercrop in Org-High over time, which could supply adequate nitrogen from fixation and biomass addition [51,60] to augment the nitrogen from compost. In a study by Barthès et al. [61], they reported the benefits of relay-cropping maize with *Mucuna pruriens* to control weeds and soil erosion, maintain soil organic matter, and increase maize productivity. Thus, the high yields in the two systems with low or no yield gaps between them. Even with the invasion of the Fall armyworm in Kenya during the stable period of the trials [62,63] and corresponding drops in yield, Org-High yields were sustained through the implementation of the push-pull approach. To suppress Fall armyworm and stemborer incidence [62,64,65] and consequently, increase maize grain and baby corn yields, *Desmodium uncinatum* was introduced in 2020 to replace Mucuna, combined with the border crop *Brachiaria ruziziensis*. Other studies suggest that organic systems can reach a certain pest control level by enhancing natural enemies, similar to the pesticide use in conventional systems [66,67]. However, introducing *Desmodium* led to competition for nutrients and water. For instance, when there was profuse growth of desmodium in Org-High in 2021 at Chuka, the babycorn yield was low. Effective management of *Desmodium* is therefore necessary to avoid competition for space, nutrients, and water in maize systems under organic high-input management.

The cabbage, French bean, and potato crop grown in the high-input systems brought out the challenges of managing crops in organic systems. In contrast to maize, these crops had higher yield gaps between the Org-High and Conv-High, which we attributed to nutrient limitations and higher pest and disease damage. The use of phosphate rock (PR) in organic systems, which has a very low solubility [68,69], and a low phosphorous recovery efficiency [70], affected the crop's development at early growth stages. However, in 2019, phosphorous availability in organic systems from phosphate rock (PR) was improved by dissolving PR with acidic liquids (e.g., citric acid) before application on top of compost [71]. We also observed pest and disease damage contributed to

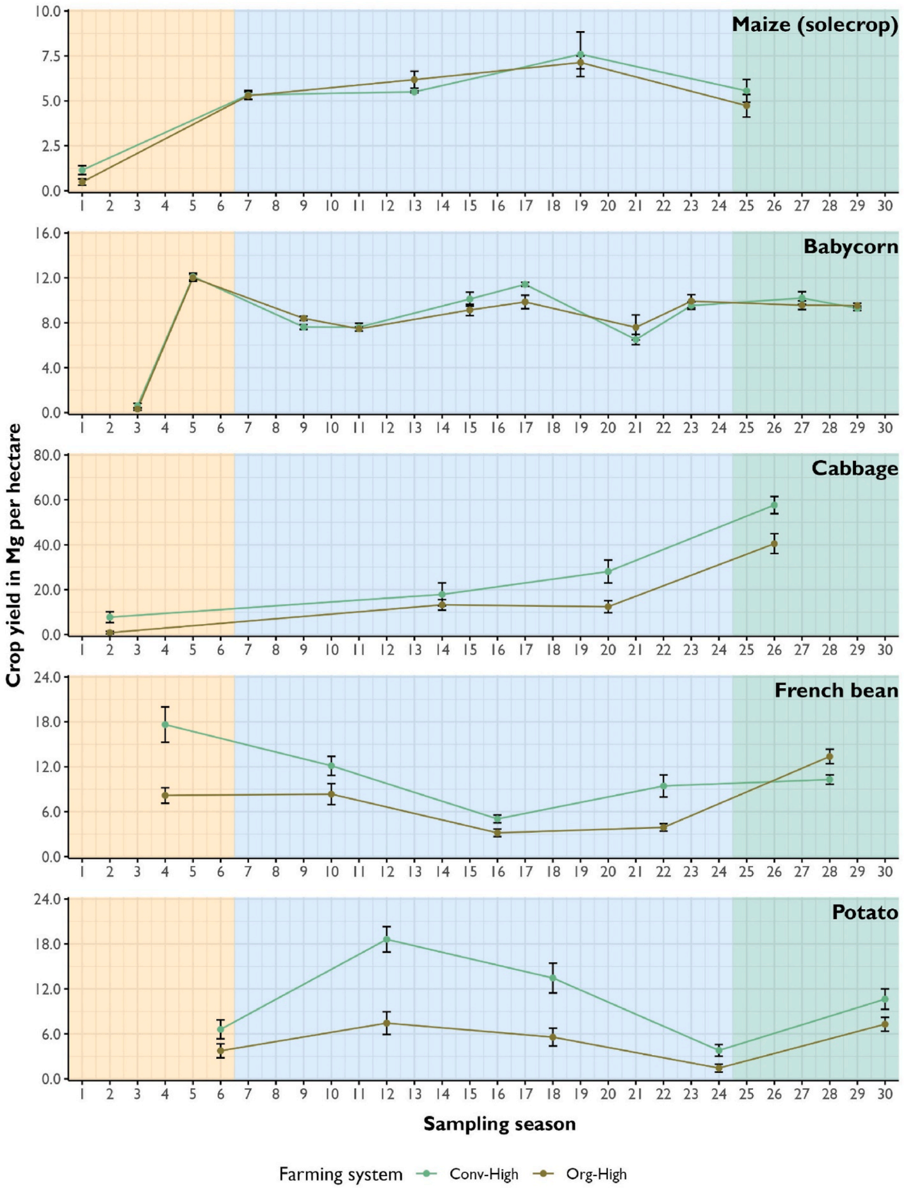

Fig. 5. Absolute marketable crop yield of the organic and conventional farming system at **Kandara** during the conversion period (yellow background; season 1 to 6 [2007–2009]), stable period (blue background; season 7 to 24 [2010–2018]), and the adaptation period (green background; season 25 to 30 [2019–2021]). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

a higher percentage of unmarketable yield in cabbage, French bean, and potato in Org-High compared to Conv-High. For instance, Late blight (a foliar disease) in potatoes was observed in our trials and was managed by repeated application of various fungicides in conventional systems. However, the scope of fungicides available for use in organic systems was narrow, leading to higher potato damage. Late blight has been shown to lower potato yield by up to 70 % if not controlled properly [72–74]. Additionally, the biopesticides used in the organic systems were initially applied at the same frequency and time intervals as synthetic pesticides in conventional systems. This method was ineffective because biopesticide efficacy on pests was low under the climatic conditions of the study area. However, in 2019, the above challenge was addressed by changing the crop variety (in the case of cabbage), where a pest-resistant cabbage variety was adopted. In addition, we conducted efficacy trials to identify suitable biopesticides and botanicals, their optimal dosage and frequency of application to effectively manage the pests in the organic systems [75]. Introducing companion crops (known to have pest repellency) and sticky traps in cabbage, French beans, and potatoes was another approach used to manage pests and diseases, thus improving yields. These approaches helped reduce the yield gaps by reducing unmarketable yield in Org-High, which we attributed to a reduction in pest damage. Similar to other authors [21,22,76], this shows that yield gaps between organic and conventional systems can be closed if best-practice approaches are used. In addition, companion crops can produce additional food or income sources through additional products from the same plot (e.g., see supplementary material for Dolichos yield).

4.2. *The potential of organic agriculture in Sub-Saharan Africa*

Our study demonstrated that the yield gap between organic and conventional farming systems in the tropics could be closed by adopting best management practices in the organic systems that include diversification of farming systems through inter- and companion cropping, effective soil nutrient replenishment, and integrated pest management. However, productivity alone is not a viable parameter to judge the

Table 4
Means, standard error of means, and statistics output (ANOVA) for crop yields (in Mg ha^{-1}) in conventional and organic farming systems in all sampling seasons at Kandara.

				Rotational Cycle[a]														
Season	**System**	**Crop**		One			Two			Three			Four			Five		
				2007 (1/2)			*2010 (7/8)*			*2013 (13/14)*			*2016 (19/20)*			*2019 (25/26)*		
1st	Conv-High	Maize		1.14 ± 0.21		γ	5.33 ± 0.25		β	5.50 ± 0.06		β	7.59 ± 1.24		α	5.55 ± 0.64		β
	Org-High	Maize		0.48 ± 0.17			5.28 ± 0.21			6.18 ± 0.47			7.13 ± 0.36			4.73 ± 0.63		
2nd	Conv-High	Cabbage	a	7.76 ± 2.45		γ	na			17.89 ± 5.12		β	28.08 ± 5.14		α	57.67 ± 3.82		β
	Org-High	Cabbage	b	0.85 ± 0.59						13.25 ± 2.36			12.41 ± 2.70			40.47 ± 4.39		
				2008 (3/4)			*2011 (9/10)*			*2014 (15/16)*			*2017 (21/22)*			*2020 (27/28)*		
3rd	Conv-High	Babycorn		0.60 ± 0.21	a	ζ	7.63 ± 0.21	a	δε	10.11 ± 0.62	a	βγ	6.51 ± 0.46	a	ε	10.20 ± 0.55	a	βγ
	Org-High	Babycorn		0.32 ± 0.11	a	δ	8.40 ± 0.19	a	βγ	9.14 ± 0.50	a	βγ	7.59 ± 1.12	a	γ	9.57 ± 0.38	a	β
4th	Conv-High	French bean		17.62 ± 2.36	a	α	12.13 ± 1.27	a	β	5.04 ± 0.52	a	γ	9.44 ± 1.48	a	β	10.29 ± 0.63	b	β
	Org-High	French bean		8.17 ± 1.04	b	β	8.35 ± 1.40	b	β	3.18 ± 0.52	a	γ	3.90 ± 0.51	b	γ	13.37 ± 0.98	a	α
				2009 (5/6)			*2012 (11/12)*			*2015 (17/18)*			*2018 (23/24)*			*2021 (29/30)*		
5th	Conv-High	Babycorn		12.11 ± 0.31	a	α	7.61 ± 0.34	a	δε	11.42 ± 0.42	a	αβ	9.53 ± 0.33	a	γ	9.29 ± 0.20	a	γδ
	Org-High	Babycorn		12.00 ± 0.32	a	α	7.46 ± 0.19	a	γ	9.86 ± 0.59	b	β	9.93 ± 0.57	a	β	9.53 ± 0.22	a	β
6th	Conv-High	Potato		6.61 ± 1.26	a	γδ	18.61 ± 1.70	a	α	13.46 ± 1.98	a	β	3.80 ± 0.78	a	δ	10.64 ± 1.36	a	βγ
	Org-High	Potato		3.75 ± 0.93	a	αβ	7.44 ± 1.51	b	α	5.58 ± 1.18	b	αβ	1.44 ± 0.52	a	β	7.30 ± 0.93	b	α

	Farming system		Sampling season		System x season	
Crop	F value	p-value	F value	p-value	F value	p-value
Maize solecrop	0.96	0.333	**69.94**	**<0.001**	1.037	0.398
Babycorn	0.54	0.466	**146.24**	**<0.001**	**2.56**	**0.025**
Cabbage	**25.37**	**<0.001**	**74.74**	**<0.001**	2.01	0.130
French bean	**50.84**	**<0.001**	**44.55**	**<0.001**	**17.65**	**<0.001**
Potato	**66.29**	**<0.001**	**27.69**	**<0.001**	**6.00**	**<0.001**

[a] Year and the cumulative cropping season numbers (in brackets) are also indicated; Latin letters (abc) show differences between systems or differences for systems within a season; Greek letters (αβγ) show differences between seasons or differences for seasons within a system; na, not applicable.

performance of a farming system. Especially in high-input systems, which primarily focus on production for a local or export market, economic competitiveness is essential. An analysis of the combined low and high-input organic systems in our trials revealed that production costs and revenue were higher under organic compared to conventional systems [77]. Consequently, the gross margins were comparable. This is in contrast with earlier studies that showed higher profits in organic agriculture [76,78,79]. Next to the potential economic benefits of organic agriculture, we also recorded other benefits in our trials: reduced pesticide contamination in plants and soil [80], increased biodiversity [26,81,82] and improved soil organic carbon [39].

We want to emphasize that a generalization of our results for the performance of organic agriculture in Kenya or even Sub-Saharan Africa is challenging. The management practices adopted in our trials are site-specific and might work on one site but fail on another due to unfavorable climatic conditions, unsuitable crop choices, lack of seeds, or knowledge of how to manage the crops. Our systems represent a potential for how smallholder farming systems in Sub-Saharan Africa could be ecologically intensified to achieve good performance using organic and agroecological principles and site-specific innovations, decreasing the use of synthetic inputs. The critique that boosting yield and improving food availability without increasing mineral fertilizers [83] is therefore only partially valid as it neglects the potential of innovations to adapt current agroecological and organic practices. Nonetheless, this approach is knowledge-intensive as these innovations are not one-fits-all solutions. In every case, research and extension through governmental or private institutions is necessary. That also means that funding schemes for research, either through governments or philanthropic investors, need to shift from funding industrial agriculture to agroecological approaches like organic agriculture. This is rarely the case because donors often either reduce agroecological approaches to the biophysical dimension or avoid it because it does not fit into the existing investment modalities looking for quick, tangible returns on investment [84]. Lastly, as other authors stated, a narrow focus on production alone is unlikely to eradicate global hunger and poverty: increasing the access of farmers to land, water, seeds, and fair markets, empowering local communities, fostering knowledge exchange, reducing food waste and post-harvest losses, and reconsider consumption patterns is of fundamental importance [85].

5. Conclusion

After 15 years of continuous monitoring in the two long-term systems comparison trials, we found that both organic and conventional farming systems can be equal in crop productivity, despite crops like cabbage and potatoes still showing yield gaps. The study also demonstrated that the yield gap could be closed by adopting best management practices that include crop diversification and enhanced pest and disease management. However, these adaptations need to be adjusted to the agroecological and sociocultural environment. Research and extension through governmental or private institutions are necessary as these approaches are knowledge-intensive. Famers and society could benefit from the potential of such farming systems for the environment and human health. A detailed economic study with seasonal trends for our high-input farming systems still needs to be done.

CRediT authorship contribution statement

David Bautze: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Edward Karanja:** Supervision, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Martha Musyoka:** Methodology, Investigation, Data curation, Conceptualization. **Johanna Rüegg:** Writing – review & editing. **Eva Goldmann:** Writing – review & editing. **Milka Kiboi:** Writing – review & editing, Project administration. **Ivonne Kampermann:** Writing – review & editing, Formal analysis, Data curation. **Marc Cotter:** Writing – review & editing, Project administration, Funding acquisition. **Amritbir Riar:** Writing – review & editing, Project administration. **Felix Matheri:** Investigation, Data curation. **Edwin Mwangi:** Investigation, Data curation. **Monicah Mucheru-Muna:** Supervision, Methodology, Conceptualization. **Hottensiah Wambui:** Supervision, Methodology. **John J. Anyango:** Supervision, Methodology, Conceptualization. **Samuel Ndung'u:** Supervision, Methodology. **Chrysantus Tanga:** Supervision, Project administration. **Komi K.M. Fiaboe:** Supervision, Project administration, Methodology. **Jesca Mbaka:** Supervision, Project administration. **Anne Muriuki:** Supervision, Project administration, Methodology, Conceptualization. **David Kamau:** Writing – review & editing, Supervision. **Noah Adamtey:** Writing – review & editing, Validation, Project administration, Methodology, Funding acquisition, Conceptualization.

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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. Supplementary data

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Data availability

Data will be made available on request.

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