Agronomy for Sustainable Development (2025) 45:63
https://doi.org/10.1007/s13593-025-01054-x

RESEARCH ARTICLE

Maize yield responses to soil organic carbon under integrated soil fertility management in tropical environments

Moritz Laub[1] · **Marc Corbeels**[2,3] · **Chloe MacLaren**[4,5] · **Samuel Mathu Ndungu**[3] · **Monicah Wanjiku Mucheru-Muna**[6] · **Daniel Mugendi**[7] · **Bernard Vanlauwe**[3] · **Wycliffe Waswa**[3] · **Rebecca Yegon**[7] · **Johan Six**[1]

Received: 3 February 2025 / Accepted: 14 August 2025 /

Abstract

To ensure the sustainable management of tropical cropping systems, tracking changes in soil fertility and distinguishing long-term crop yield trends from season-to-season fluctuations are essential. However, a scarcity of long-term datasets for tropical systems has left a gap in understanding how soil organic carbon (SOC, used as a proxy for soil fertility) and yield co-evolve in these systems. Here, we present a unique analysis of maize yield and SOC trends in four long-term experiments in Kenya, conducted under contrasting pedo-climatic conditions. Experimental treatments consisted of yearly applications of organic resources with different C:N ratios (12 to 200) at two quantities (1.2 and 4 t C ha^{-1} yr^{-1}), with and without mineral nitrogen fertilizer (240 kg ha^{-1} yr^{-1}). At sites with adequate rainfall (475-600 mm in-season rainfall), long-term maintenance of maize yields and SOC were strongly correlated. Specifically, 74% of the variation in long-term yield trends across sites was explained by the interaction between site and the trend in SOC, increasing to 84% when adding the interaction with the mineral nitrogen fertilizer treatment. In contrast, no significant correlation between yield and SOC trends existed at the driest site (300 mm in-season rainfall). Differences in the strength of the SOC-yield relationships between treatments with and without mineral N fertilizer were significant at only one of the four sites. In addition, seasonal maize yield variability at three of the four sites was strongly influenced by seasonal mean temperature and total rainfall, overriding the effect of site fertility and SOC in any given season. However, the strength of climate effects varied between sites. We conclude that maintaining SOC is important for sustaining maize yields, but this potential can only be fully realized under favorable climatic conditions, particularly sufficient rainfall.

Keywords Sustainability of maize cropping · Maize yield loss · Soil organic matter · Organic resource addition · Organic amendments · Farmyard manure · Carbon sequestration

---

✉ Moritz Laub
moritz.laub@usys.ethz.ch

[1] Department of Environmental Systems Science, ETH Zurich (Swiss Federal Institute of Technology), 8092 Zürich, Switzerland

[2] AIDA Research Unit, University of Montpellier, CIRAD (French Agricultural Research Centre for International Development), Avenue Agropolis, F-34398 Montpellier, France

[3] International Institute of Tropical Agriculture (IITA), c/o ICIPE Compound, P. O. Box 30772-00100, Nairobi, Kenya

[4] Department of Crop Production Ecology, Swedish University of Agricultural Science, Almas Alle 8, 750 07 Uppsala, Sweden

[5] International Maize & Wheat Improvement Centre (CIMMYT), Southern Africa Regional Office (SARO), P.O. Box MP163, Harare, Zimbabwe

[6] Department of Environmental Sciences and Education, Kenyatta University, P.O. Box 43844-00100, Nairobi, Kenya

[7] Department of Water and Agricultural Resource Management, University of Embu, P.O. Box 6-60100, Embu, Kenya

1 Introduction

Sub-Saharan Africa has a high per capita maize consumption, yet it has the lowest maize crop yields and food self-sufficiency (Sanchez 2015; Erenstein et al. 2022) as well as the strongest population growth of all continents (Lutz et al. 2018). Most agricultural soils in sub-Saharan Africa are highly weathered (von Fromm et al. 2021; Reichenbach et al. 2023) and are characterized by low nutrient levels and organic matter status (Kihara et al. 2020). This severely limits crop productivity under current management and has led to stagnating crop yields (FAO 2023). As a potential solution to these challenges, integrated soil fertility management (ISFM; Vanlauwe et al. 2010) has been postulated to simultaneously increase crop yields and soil fertility by enhancing soil organic matter and nutrient supply. Since soil organic carbon (SOC) constitutes about half of soil organic matter (Berryman et al. 2020), it serves as a reliable proxy for assessing the overall status of soil organic matter.

While several field experiments have demonstrated the crop yield benefits of ISFM or similar practices (Chivenge et al. 2009; Mutuku et al. 2020; Cardinael et al. 2022; MacLaren et al. 2022; Laub et al. 2023b), long-term experiments in sub-Saharan Africa have also revealed instances where these practices led to a decline in SOC over time (Sommer et al. 2018; Cardinael et al. 2022; Laub et al. 2023a), even when yields were increasing (Laub et al. 2023b). This prompts the question of whether SOC is indeed a driving factor of long-term crop yield increases. Studies that show evidence of the long-term yield benefits of sustainable intensification practices are scarce, with even fewer assessing the underlying mechanisms of crop yield benefits. However, such research is essential to corroborate or refute the frameworks of sustainable intensification, as well as the hypothesized long-term relationships between SOC and yields (Vanlauwe et al. 2010).

Sustainable intensification of crop production in a changing climate can only be achieved if we understand the factors that determine the long-term productivity of crops, identify those controllable by humans, and adjust crop management practices accordingly. While many studies have indicated the importance of changes in both SOC (Tully et al. 2015; Ndung'u et al. 2021; Cardinael et al. 2022; Thierfelder et al. 2022; Ma et al. 2023) and weather patterns (Block et al. 2021; Jägermeyr et al. 2021) for maize productivity, there are few studies with datasets of sufficient duration to determine the effect of gradual changes in SOC on crop yield, especially in sub-Saharan Africa. Usually, relationships between yield and SOC are established through large-scale correlations (Oldfield et al. 2019; Ma et al. 2023), which may be confounded by factors such as net primary productivity, influencing both SOC levels and crop yields. Therefore, such studies cannot inform about the influence that SOC-altering management practices have on yields. Similarly, studies examining the effects of weather patterns on crop yield usually have limited information on soil fertility, relying either on aggregated county-level data (Schlenker and Roberts 2009) or on short-term field trials, often taking soil fertility as a given (Lobell et al. 2011). There is therefore a need for comprehensive analyses of the relative importance of weather patterns versus soil-quality-improving management practices on crop yield.

This study first examined the relationship between management induced changes in SOC and changes in maize crop yield. Our experimental approach, which controls for variations in soil and climatic properties, provides more robust insights into the SOC-yield relationship compared to global large-scale correlation studies. We focused on continuous maize cropping systems because demand for maize is high across sub-Saharan Africa (Erenstein et al. 2022), and it is the main staple food in eastern Africa (Ngeno 2024); consequently, cultivation of maize on the same land year after year is widespread (Badu-Apraku and Fakorede 2017). Second, we assessed the relative importance of controllable (i.e., management practices) versus uncontrollable (i.e., weather variability) factors that determine maize yield in any given season. We analyzed a dataset comprising maize yield records and SOC data from four experiments in Kenya, conducted over 16 to 19 years, covering a range of soil types (sandy to clayey) and climates (semi-arid to humid). These experiments investigated ISFM practices involving different combinations of organic amendments and mineral N fertilizer. Two recent studies (Laub et al. 2023a, b) reported the long-term trends in maize yields and SOC in these experiments. Interestingly, the treatments that best maintained or increased SOC across all sites were also associated with higher maize yields. Yet, the magnitude of treatment effects was site specific, and these studies did not analyze the relationship between maize yield and SOC changes, nor the relationship between yield and weather variability. Therefore, in the current study, we specifically wanted to explore: (1) to what extent do ISFM-induced SOC trends affect long-term maize yield trends, and how consistent are effects across different sites, and (2) what is the relative contribution of ISFM management practices compared to season-to-season weather variability in explaining maize yield variation?

To address these questions, we conducted two types of analyses. First, we investigated whether long-term trends in maize yields were correlated with treatment-related long-term trends in SOC within each site. We further explored how this relationship differed in response to mineral N fertilizer application and how it was affected by the long-term trends in rainfall, temperature, and soil pH. Second, we evaluated the extent to which fluctuations in maize yields between the seasons at each site could be attributed to ISFM treatment factors, in comparison to seasonal weather variability. In this analysis we used the ISFM treatment factors as covariates instead of SOC, because SOC measurements were only available every few years. Furthermore, we examined significant interactions between treatment factors and primary weather patterns (rainfall, temperature, and season length).

The four experimental sites had identical treatments, with organic amendments of low to high C:N ratios, i.e., farmyard manure, two types of green manures (*Tithonia diversifolia* and *Calliandra calothyrsus*), maize stover and sawdust, at application rates of 1.2 and 4 t C ha^{1} yr^{1}. Using a split plot design, half of each plot received 120 kg N ha^{1} of mineral fertilizer per growing season (+N and -N treatments; see Methods for further details). Two sites, Aludeka and Sidada, were situated in humid western Kenya, comprising 16 years of data. Two other sites, Embu and Machanga, were in the sub-humid and semi-arid areas of the central region of Kenya, respectively, comprising 19 years of data. All four sites were characterized by two maize growing seasons per year, corresponding to the long and the short rainy season.

2 Materials and methods

2.1 Study sites

The four experimental sites, located in central and western Kenya, were under continuous maize monocropping with two growing seasons per year. The long rainy season lasts from March until August/September and the short rainy season from September/October until January/February. The two experiments at Embu and Machanga (central Kenya) were initiated in 2002, while those at Sidada and Aludeka (western Kenya) started in 2005. The four sites were selected to represent different temperatures, levels of rainfall, and soil conditions. With a higher amount of annual rainfall, the sites at Sidada (1730 mm, 675 mm in season; 22.6°C) and Aludeka (1660 mm, 600 mm in season; 24.4°C) represent a more favorable climate for maize than the sites in central Kenya, Embu (1175 mm, 475 mm in season; 20.1°C) and Machanga (795 mm, 290 mm in season; 23.7°C). The soils at all four sites are heavily weathered, with the Aludeka and Machanga sites having coarse-textured soils with low SOC contents (both had < 15% clay, and 7 and 8 g SOC kg^{1} soil, respectively, at the start of the experiment), while the soils at Sidada and Embu are fine-textured with relatively high clay and SOC contents (both had > 55% clay, with 26 and 31 g SOC kg^{1} soil, respectively, at the start of the experiment). Initial soil pH in water was 5.3 at Machanga, 5.5 at Aludeka and 5.4 at the other two sites. The soils were classified according to the World Reference Base for Soil Resources (IUSS Working Group 2015) as a Humic Nitisol at Embu, a Humic Ferralsol at Sidada, a Haplic Acrisol at Aludeka and a Ferric Alisol at Machanga. All sites have an almost flat surface, but at the Embu site this has been achieved by terracing the field (5% slope). More details on the sites have recently been published (Laub et al. 2023a).

2.2 Experimental setup

All four experiments were set up with an identical experimental design. This was a split plot design with three replicates. The main treatments (i.e., main plots) consisted of the addition of five different types of organic resources, each applied at two different rates: 1.2 t C ha^{1} yr^{1} and 4 t C ha^{1} yr^{1}. Besides, a control treatment without any input of organic resources was established, leading to 11 main plots. The plots had a size of 12 × 6 m (12 × 5 m at Embu). The subplots consisted of the application of 120 kg of mineral fertilizer N ha^{1} per season in the +N treatment (calcium ammonium nitrate) compared to the absence of mineral N input in the -N treatment, leading to 22 treatments (i.e., split plots) tested over three replicates per site. The mineral N application was split; 40 kg N ha^{1} was applied at planting and the rest as top dressing about 1.5 months later. 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 in each growing season. Organic resources were applied only once a year, specifically at planting in the long rainy season. They were incorporated to about 15 cm soil depth with a hand hoe. Maize residues were removed at harvest, so the roots of maize were the only source of C input apart from external C inputs related to the treatments. The applied organic resources were chosen in a way to include all four quality classes of organic resources as defined by Palm et al. (2001). They represented a gradient of C:N ratios, lignin and polyphenol contents: pruned leaves including stems of <2 cm thickness from *Tithonia diversifolia*- (C:N of 12, 9% lignin, 2% polyphenols), pruned leaves including small stems from *Calliandra calothyrsus* (C:N of 14, 11% lignin, 11% polyphenols), stover of *Zea mays* (C:N of 59, 5% lignin, 1% polyphenols), sawdust from *Grevillea robusta* trees (C:N of 199, 17% lignin, 1% polyphenols), and locally available farmyard manure (C:N of 12, 20% lignin, 1% polyphenols; Figure 1). The initial assumption behind the organic resource selection was that organic resources with a low C:N ratio would be best for supplying plant nutrients, while those rich in lignin and polyphenols would be better for maintaining SOC (Woomer and Swift 1994). However, this proved

Figure 1 Illustration of the effect of soil fertility on maize growth. Pictures display the treatment receiving 4 t C organic resource inputs ha^{-1} year^{-1} and 120 kg N ha^{-1} season^{-1} (left) versus the control receiving no organic inputs and no mineral N fertilizer (right). Pictures were taken at the Machanga experimental site in July 2023, Marking the 20th year since the start of the experiment (Photocredit: Moritz Laub).

incorrect, because low C:N resources were most effective at maintaining both maize yield and SOC, while high C:N, lignin- and polyphenol-rich organic resources neither maintained yield nor SOC (Laub et al. 2023a).

2.3 Datasets A and B

We used two different types of datasets in this study: dataset A to study the determinants of the seasonal maize yields, and dataset B to study the determinants of the long-term maize yield trends. Dataset A consists of the maize grain yields recorded in each season at the subplot (mineral N × organic resource treatment × block) level. Dataset B comprises the long-term trends in maize grain yields and SOC at the mineral N × organic resource treatment level, derived from linear mixed models applied to dataset A in earlier studies (Laub et al. 2023a, b). Dataset B also includes the long-term trends in soil pH, temperature, rainfall, and the number of dry days per season, while dataset A incorporates aggregated weather data per season as described in the following section. The dependent variable in dataset A is the maize yield recorded in each season in each subplot at each site, while in dataset B, it is the modelled long-term trend of maize yield of each treatment at each site.

2.4 Seasonal covariate data in dataset A

The climate data used as explanatory covariates in this study were recorded with weather stations at each of the sites, but some data gaps had to be filled. At Embu and Machanga, daily minimum and Maximum temperature and rainfall were available from 2002 until the end of 2007 and after 2017. From 2008 until 2017, only recorded rainfall was available. Embu had further gaps in rainfall data in 2008 to 2012, 2014 and 2016. At Aludeka and Sidada, manual recordings of daily minimum and maximum temperature and rainfall were available for all years from 2005 to 2017, but Sidada had no temperature data in 2019 and 2020, and Aludeka had data gaps from July 2017 to April 2018 and after July 2019. The data gaps were filled using the NASA POWER product (https://power.larc.nasa.gov/docs/methodology/) after bias correction. For this, a linear regression with measured data as dependent variable (y) and NASA POWER data as independent variable (x) was conducted. For temperature, the slopes were not different from 1, but intercepts for maximum temperature (−0.3°C, −0.4°C, +3°C, and +6°C for Embu, Machanga, Sidada and Aludeka, respectively) and minimum temperature (−0.25°C, −0.5°C, −3°C and +1°C for Embu, Machanga, Sidada, and Aludeka, respectively) were applied. The final covariate used was the daily mean temperature, calculated from minimum and maximum temperature. No bias correction for rainfall was done because of nonsignificant slopes and intercepts.

The daily primary covariates were then aggregated to the season-specific covariates, based on the recorded planting and harvesting dates of maize at each site. Those were seasonal mean temperature, cumulative rainfall, and season length. Secondary weather covariates were calculated from the primary ones. Those were maximum consecutive dry days in each season, the cumulative growing degree days, number of days without rainfall, and the standardized precipitation index (Svoboda and Fuchs 2017). Further, ratios of rainfall and growing degree days in the first month of the growing season (i.e., the first 30 days after planting) were calculated as proxies for abnormal rainfall and temperature distributions within the season. Finally, dataset A contained site, block, and treatment as covariates. They can be seen as covariates that represent the SOC state of each treatment, because SOC was only assessed once every few years and thus not available at seasonal resolution.

2.5 Long-term trend data in dataset B

Trends in soil pH, temperature, rainfall, and the number of dry days per season were determined by linear regression on the seasonal averages per site, with year as covariate. The long-term trends in SOC and maize yield per site and experimental treatment were from two recent publications (Laub et al. 2023a, b). In brief, mixed linear models were fitted to maize yield data of all seasons across all years or all available measurements for SOC. Maize grain yield data was available from every season across all years, and were standardized to 12% moisture content. SOC data was obtained from 2 mm-sieved soil samples taken with a gauge auger at 0-15 cm soil depth and analyzed by dry combustion using an elemental analyzer (CHN628; LECO Corporation, Michigan, USA). SOC measurements were done in the first experimental year, and in the years 2017, 2018, 2019, and 2021. In Embu and Machanga, additional soil sampling was conducted every two to three years between 2002 and 2017, while in Sidada and Aludeka, budget constraints did not allow sampling from 2005 to 2017.

Mixed linear models were applied to account for autocorrelation in the data, with a random effect for the main plot nested in block, each growing season and site in the yield model, and a random effect for the main plot nested in block, sampling campaign, and site in the SOC model. The initial fixed effects were organic resource treatment, mineral fertilizer N treatment, site and time (years since the start of the experiment), all possible interactions (to four-way interactions) were initially included and then eliminated, until only significant effects and interactions remained (Zuur et al. 2009). From this model, the treatment- and site-specific slopes of the time effect were extracted to derive the treatment-specific temporal trends in maize yield and SOC.

2.6 Statistical analyses

We used the R software version 4.0.5 (R Core Team 2021), standard linear regressions, and the nlme package (Pinheiro et al. 2016) for mixed linear effects models to conduct the statistical analyses of the two dependent variables in this study. For both datasets, we explored the importance of individual covariates and groups of covariates in explaining the variability in the dependent variable, by assessing the reduction in explanatory power (R^2 and Akaike Information Criterion) when removing them from the model.

Dataset B was analyzed with a simple linear effects model, since autocorrelation in the data had already been accounted for by the mixed models that the trends originated from. Dataset A was analyzed by two approaches. First, we used a mixed linear model across sites with the established autocorrelation structure of the model from which the long-term trends were derived (see section above; details are in Laub, et al. 2023b; for which the model was initially developed). To this model, all weather covariates were added to derive the fullest model, and then selected groups of covariates (i.e., temperature-related, rainfall-related, treatment-related) were removed to assess their explanatory power. The pseudo R^2 for the mixed model was calculated based on the likelihood (Nagelkerke 1991). In the second approach, linear models without random effects were constructed for each site individually to evaluate the site specificity of weather- vs. treatment-related covariates on maize yield. For these, we added a fixed intercept effect to account for the effects of the experimental blocks. In the site-specific models, the response variable was square root transformed to achieve normality and homoscedasticity of residuals. To delineate the individual effects of weather-related covariates, site-specific linear models with only the mineral N fertilizer treatment, organic resource treatment, time, and all possible two-way interactions between these three covariates, as well as the additional block effect were built (base model). To this base model, single weather-related covariates were added to estimate their overall effect. Finally, all possible two-way interactions between mineral N fertilizer treatment, organic resource treatment, and the primary weather-related covariates (seasonal mean temperature, in-season rainfall, season length) were tested to understand how one covariate affected the maize grain yield depending on the level of another covariate. For each possible combination of these five covariates, the significance of their interaction was assessed by comparing a base model that included the pair of covariates without interaction to a base model that included the pair of covariates and their interaction. For those interactions that were found to be significant, post-hoc estimates were conducted to understand the nature of their interactions. Specifically, the maize grain yields for the range of conditions of both factors were predicted and were displayed in plots, where maize grain yield was the y-axis, one covariate (e.g., rainfall) was the x-axis, and the other covariate (e.g., seasonal mean temperature) was displayed at several levels as the color coding. These post-hoc predictions were only produced for the observed range of each covariate at each site. This was done to avoid extrapolation beyond the data.

3 Results

3.1 Long-term trends in SOC and maize yield

A gain in SOC over time was only observed at one site (i.e., Aludeka) and only in the treatment with farmyard Manure at a rate of 4 t C ha^{-1} yr^{-1}. At all other sites, SOC either declined by up to 0.6 g kg^{-1} yr^{-1} at the clayey sites (which started at 26 to 31 g SOC kg^{-1} soil) and up to 0.2 g kg^{-1} yr^{-1} at the sandy sites (which started at only 7 to 8 g SOC kg^{-1} soil) or was maintained at best, depending on the treatment. Although both sites started with similarly low SOC levels, SOC at Machanga could, in contrast to Aludeka, not be increased by any treatment. The range of trends in maize grain yields were between increases of 0.2 t ha^{-1} yr^{-1} in the best treatment at Sidada and losses of 0.15 ha^{-1} yr^{-1} at Machanga. Maize yields declined in most treatments at Embu and Machanga, in about half of the treatments at Aludeka, and in some treatments at Sidada. However, only Machanga experienced a maize yield decline in all treatments, while at the other sites yields remained stable or even increased in the best treatments. The treatment that was the most effective in maintaining or increasing SOC and maize yields across sites was the combination of farmyard manure at a rate of 4 t C ha^{-1} yr^{-1} with mineral N fertilizer. On the other hand, the organic resources with high C:N ratio, i.e., maize stover and sawdust, hardly had any effect on both maize yield and SOC, whilst *Tithonia* and *Calliandra* residues had a limited positive effect on both.

3.2 Determinants of long-term trends in maize yields

At the humid sites in western Kenya, Aludeka and Sidada, treatment-specific long-term maize yield trends were significantly ($p < 0.01$) and positively correlated with the trends in SOC content. Experimental treatments that experienced the strongest SOC loss also exhibited the strongest yield loss, whilst those increasing or maintaining SOC showed increased yield (Figure 2). At the sub-humid site of Embu, the correlation between SOC loss and yield loss was weaker ($p < 0.05$) and only observed in the +N but not in the -N treatments. At the semi-arid site of Machanga, no significant ($p > 0.5$) relationship was found between the long-term trends in yield and SOC, despite significant differences in SOC content and maize yields between treatments (Laub et al. 2023a, b).

Overall, the strongest correlation between temporal trends in maize yield and SOC was observed at Aludeka, characterized by a humid climate and a coarse-textured soil. A mean loss of 0.1 g kg^{-1} SOC per year at Aludeka translated to a grain yield loss of 68 kg ha^{-1} per year in the +N treatment and 38 kg ha^{-1} per year in the -N treatment. In contrast, at Sidada, characterized by a humid climate and a clayey soil, the -N treatment experienced the strongest effect, and SOC losses of up to about 0.3 g kg^{-1} per year did not lead to grain yield losses. A loss (or gain) of 0.1 g kg^{-1} SOC per year translated to a grain yield loss (or gain) of 56 kg ha^{-1} in the -N treatment and 28 kg ha^{-1} in the +N treatment.

Overall, the interaction between site, trend in SOC, and mineral N fertilizer treatment explained 84% of the variability in maize yield trends across sites (Table 1). Trends in soil pH, while statistically significant ($p < 0.05$), added limited explanatory value (increase to 86% of variability explained). Temporal trends in seasonal rainfall were not significantly different from zero, while trends in temperature were significant at Embu and Aludeka ($p < 0.05$; Figure S1). Despite this, neither rainfall nor temperature trends were significant in explaining the maize yield trends. Notably, site alone explained 56% of the variability in the temporal maize yield trends, while the interaction between site and SOC trend explained 74% of variability (Table 1).

3.3 Determinants of season-to-season variability in maize yields

The significance of weather-related covariates in explaining the season-to-season maize yield variability across sites was high (Table S1). A model with site, organic resource treatments and mineral N fertilizer treatments explained only 51% of the season-to-season maize yield variability, which increased to 60% when adding only temperature-related covariates, to 69% when adding only rainfall-related covariates, and to 74% when adding both temperature- and rainfall-related covariates.

However, the degree to which season-to-season variability in maize yields was explained by each covariate depended strongly on the site (Table 2). Weather variability played a minor role at Aludeka, as indicated by the experimental treatments explaining 41% of the maize yield variability, a value close to that of the model with all covariates (49%). At Embu, in contrast, experimental treatments alone only explained 17% of the variability, while weather variability alone explained 47%, and all covariates combined 60%. Sidada was similar to Embu, with treatments alone explaining only 18%, weather alone

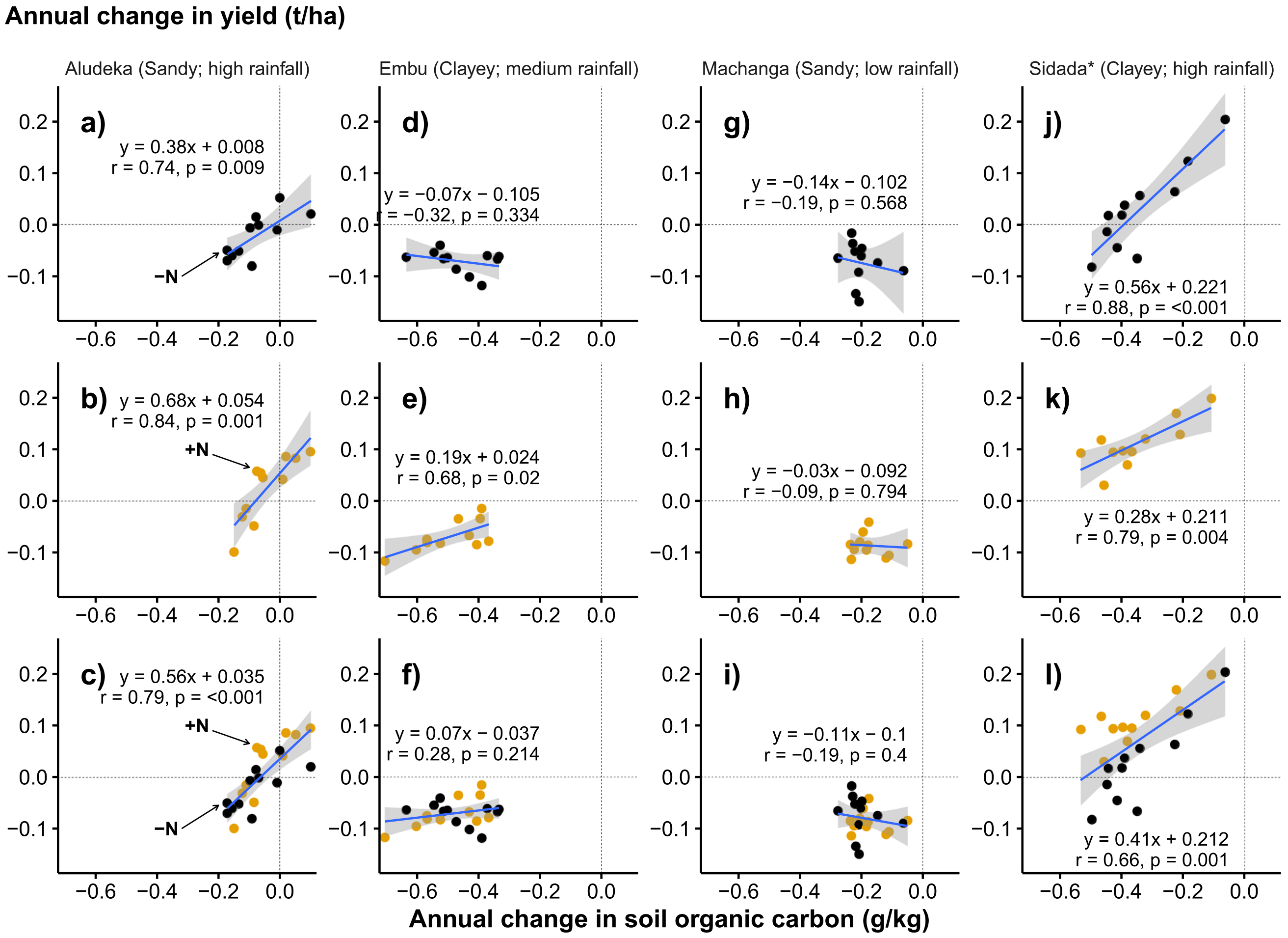

Figure 2 Relationship between the long-term changes in soil organic carbon (SOC) and long-term trends in maize yields at the four experimental sites in Kenya, displayed as mean annual change estimated by a linear mixed model per site and N fertilizer treatment. The cropping system in the experiment is monoculture of maize with two cropping cycles per year and different treatments of addition of organic resources and mineral nitrogen (N) fertilizer (see text for details). Further displayed are the regression of SOC changes on yield trends, its formula, correlation coefficient and significance level. The yellow dots represent treatments with the addition of 120 kg mineral N ha^{-1} per season, the black dots represent treatments without N fertilizer. An asterisk behind the site of Sidada indicates a significant difference between the regression estimates for the +N and -N treatment of that site. Panels correspond to Aludeka in the -N (**a**), +N (**b**), and +/-N treatments combined (**c**), Embu in the -N (**d**), +N (**e**), and +/-N treatments combined (**f**), Machanga in the -N (**g**), +N (**h**), and +/-N treatments combined (**i**), and Sidada in the -N (**j**), +N (**k**), and +/-N treatments combined (**l**).

explaining 37% and all covariates combined explaining 57% of the variability in maize yield. At Machanga, treatments (32%) and weather alone (28%) held similar importance, while 59% of maize yield variability was explained by all covariates combined.

Individual assessment of weather-related covariates was conducted by adding each one to the model with only organic resource and mineral N fertilizer treatments and their interactions with time. In-season rainfall, standardized precipitation index, and growing degree days per season had significant positive effects ($p < 0.01$) on maize yield at all sites (Table 3), with the length of the growing season showing significance ($p < 0.001$) at all sites, except Aludeka. As an indicator of unusually cold or hot mid- and/or late-season conditions, the ratio of growing degree days in the first 30 days of the season to the total of the entire season had a significant ($p < 0.01$) negative effect at all sites. Interestingly, some weather-related covariates had a positive or insignificant effect at the sites in western Kenya but a negative effect at the sites in central Kenya. Seasonal mean temperature had a significant negative effect at the drier sites, Embu and Machanga, but a significant positive effect at the more humid site, Aludeka. Similarly, the ratio of rainfall in the first 30 days of the season to the total of the entire season had a significant negative effect at the drier sites, Embu and Machanga, but a significant positive effect at the more humid site, Sidada. The total number of days without rain had a significant positive effect at the drier sites, Embu and

Table 1 Explanatory strength of different linear models across all sites with the trend in maize yield as the dependent variable and with different covariates used. Displayed are the adjusted R^2, the Akaike Information Criterion (AIC) and the reduction in R^2 compared to the model with the highest R^2. Abbreviations: SOC: soil organic carbon; N TRT: mineral nitrogen fertilizer treatment; dry days: number of dry days per season.

Model of yield trend	Adjusted R^2	AIC	Reduction in adjusted R^2 compared to model with highest R^2
Site only	0.56	−262	−0.3
SOC trend only	0.04	−194	−0.82
N TRT only	0.02	−193	−0.84
pH trend only	0.00	−183	−0.86
Temperature trend only	0.01	−191	−0.85
Rainfall trend only	0.07	−198	−0.79
Dry days trend only	0.00	−190	−0.86
Site × SOC trend	0.74	−304	−0.12
Site × SOC trend × N TRT	0.84	−341	−0.02
Site × SOC trend × N TRT + pH trend	0.86	−335	0
Site × SOC trend × N TRT + temperature trend	0.84	−341	−0.02
Site × SOC trend × N TRT + rainfall trend	0.84	−341	−0.02
Site × SOC trend × N TRT + dry days trend	0.84	−341	−0.02

Table 2 Explanatory strength of different linear models by experimental site, with maize yield per season, treatment and block as the dependent variable and with different covariates used. Displayed are the adjusted R^2, the Akaike Information Criterion (AIC) and the reduction in R^2 compared to the full model with all covariates (highest R^2). Treatment covariates here refer to both the organic resource and mineral nitrogen fertilizer treatments.

Site	Model of yields in all years by site	Adjusted R^2	AIC	Reduction in adjusted R^2 compared to fullest model
Aludeka	Model with only treatment and time	0.41	3346	−0.08
	Full model with all covariates	0.49	3009	
	Model with treatment, time, and temperature	0.43	3235	−0.06
	Model with treatment, time, and rainfall	0.44	3198	−0.05
	Model with weather covariates only	0.04	4460	−0.45
Embu	Model with only treatment and time	0.17	4882	−0.43
	Full model with all covariates	0.60	3044	
	Model with treatment, time, and temperature	0.26	4526	−0.34
	Model with treatment, time, and rainfall	0.54	3334	−0.06
	Model with weather covariates only	0.47	3669	−0.13
Machanga	Model with only treatment and time	0.32	4479	−0.27
	Full model with all covariates	0.59	3160	
	Model with treatment, time and temperature	0.48	3742	−0.11
	Model with treatment, time, and rainfall	0.53	3490	−0.06
	Model with weather covariates only	0.28	4496	−0.31
Sidada	Model with only treatment, and time	0.18	3316	−0.39
	Full model with all covariates	0.57	1623	
	Model with treatment, time, and temperature	0.32	2786	−0.25
	Model with treatment, time, and rainfall	0.49	2061	−0.08
	Model with weather covariates only	0.37	2589	−0.2

Machanga, but a significant negative effect at Sidada. Additionally, the effect of in-season rainfall and the standardized precipitation index on maize yield was greater at the drier sites in central Kenya compared to the more humid sites in western Kenya, despite the fact that maize yields were generally higher in western Kenya. For example, the effect of in-season rainfall on maize grain yield at Embu (2.7 kg ha^{-1} mm^{-1}) and Machanga (1.9 kg ha^{-1} mm^{-1}) was higher than at Sidada (1.6 kg ha^{-1} mm^{-1}) and much higher than at Aludeka (0.2 kg ha^{-1} mm^{-1}; note that all values were back-transformed from their square root, applying the mean in-season rainfall level of each site).

Table 3 Effect size of individual weather-related covariates by experimental site, when added to a model that only contains the organic resource and mineral nitrogen fertilizer treatments, time and their two-way interactions as covariates. The effect sizes are the β coefficients of the respective numerical covariates from linear models built by site, with the square root of maize yield per season as the dependent variable. Only covariates that were significant when adding them to the treatments-only model are displayed. Abbreviations: ^{x}response variable is the square root of yield (t ha^{-1} season^{-1})$^{0.5}$, p <0.05; **, p <0.01; ***, p <0.001; ^{ns}not significant.

Covariate	Unit^{x}	Aludeka	Embu	Machanga	Sidada
Seasonal mean temperature	°C	0.080***	−0.082***	−0.339***	0.008^{ns}
Season length	Days	0.001^{ns}	0.012***	0.014***	0.020***
Cumulative rainfall	mm	0.0004***	0.002***	0.002***	0.001***
Maximum consecutive dry days	Days	−0.007***	0.002^{ns}	−0.005***	−0.011***
Cumulative growing degree days	°d	0.0001**	0.0013***	0.0008***	0.0004***
Ratio of rainfall in 1st 30 days	-	0.093^{ns}	−2.100***	−0.536***	1.041***
Ratio of GDD in 1st 30 days	-	−0.252**	−7.106***	−4.325***	−3.008***
Days without rainfall	Days	−0.0001^{ns}	0.0041***	0.0084***	−0.0015***
Standardized precipitation index	-	0.083***	0.408***	0.384***	0.069***

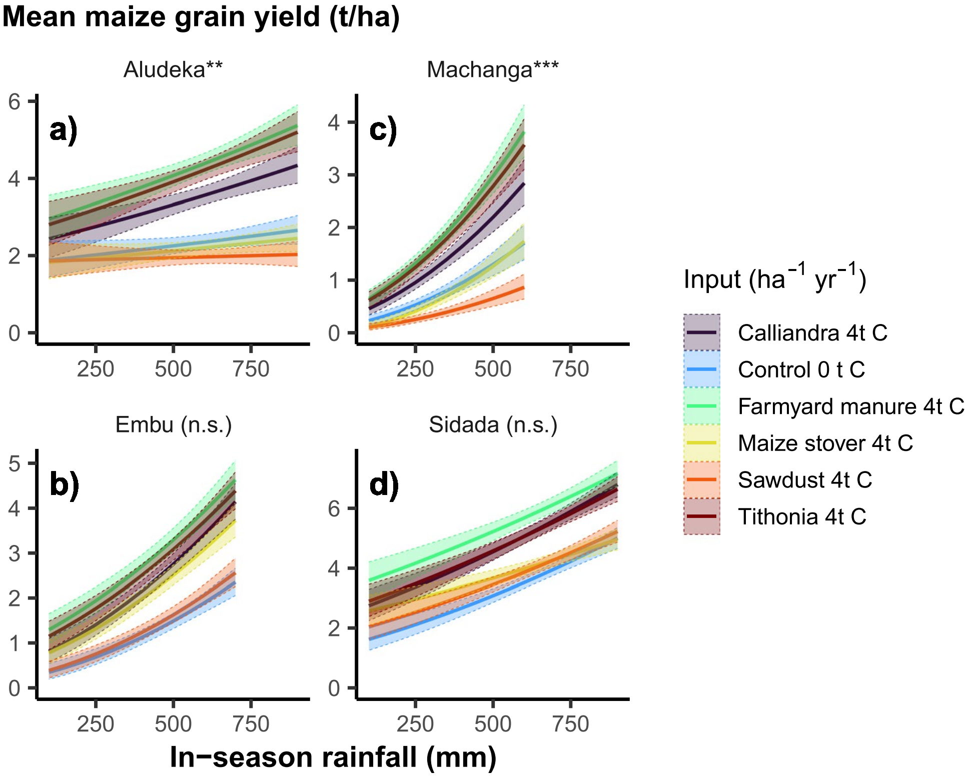

Figure 3 Interactive effects between in-season rainfall and organic resource input treatment on maize yield per season for the sites Aludeka (**a**), Embu (**b**), Machanga (**c**), and Sidada (**d**). Treatments were the additions of 4 t C ha^{-1} yr^{-1} of either farmyard manure, *Calliandra* leaves, *Tithonia* leaves, maize stover, saw dust, compared to a control treatment with no inputs. Displayed are the post-hoc predictions using a base linear models per site to which the in-season rainfall and its interaction with organic resource treatments were added. The base linear models consisted of the organic resource treatment, mineral N fertilizer treatment, time since experiment start and their interactions, as well as a block effect. Note that the response variable in the linear model was root-transformed and post-hoc predictions were transformed back. Ribbons indicate the 95% confidence interval. Abbreviations: **/***, interaction significant at that site (at $p < 0.01/p < 0.001$); n.s., interaction not significant at that site.

Several significant interactions were identified between the primary explanatory covariates, namely seasonal mean temperature, in-season rainfall, and season length. These interactions were observed both between individual covariates and treatments, and between covariates. Interactions between in-season rainfall and seasonal mean temperature were significant at all sites ($p < 0.001$; Figure S2). At Aludeka and Machanga, the effect of in-season rainfall on maize yield was negative at seasonal mean temperatures up to 22°C, turning positive at 23 °C and above. At Embu and Sidada, the effect of in-season rainfall on maize yield was consistently positive. However, the impact of in-season rainfall increased with higher seasonal mean temperatures at Embu while it weakened at Sidada. The effect of in-season rainfall also interacted significantly with organic resource treatment at Aludeka and Machanga ($p < 0.01$; Figure 3). It was pronounced in the farmyard manure, *Calliandra*, and *Tithonia* treatments (at 4 t C ha^{-1} yr^{-1}), but much weaker in the maize stover, sawdust, and control treatments. A significantly stronger effect of in-season rainfall in the +N treatment than in the –N treatment ($p < 0.001$) was only observed at Embu and Machanga (Figure S3). Finally, site-specific significant interactions at all sites also existed between season length and seasonal mean temperature ($p < 0.001$; Figure S4) and between the season length and in-season rainfall ($p < 0.001$; Figure S5).

4 Discussion

4.1 Long-term maize yield trends are strongly linked to SOC trends

With the interaction of site characteristics and temporal trends in SOC predominantly explaining the long-term trends in maize yield, our study provides clear evidence of the strong association between maintaining SOC and sustaining maize yields under tropical conditions, but only under conditions generally suitable for maize cultivation. This corroborates the validity of the principles behind ISFM (Vanlauwe et al. 2010), namely that SOC serves as an indicator of soil fertility (Lal 2004; Janzen et al. 2021) and is effective in sustaining crop yields (Tully et al. 2015; Mhlanga et al. 2022; Thierfelder et al. 2022). Higher levels of SOC imply higher amounts of mineralizable soil nutrients for plant uptake (Bashir et al. 2021). They further enhance the soil cation exchange capacity (Soares and Alleoni 2008), particularly in clay-poor soils (Bashir et al. 2021), which may explain the stronger relationship between long-term trends of SOC and yield in the +N compared to the -N treatment at the clay-poor Aludeka site. The lack of a significant regression intercept at Aludeka for both the -N and +N treatments, unlike at the Sidada and Embu sites that are characterized by clayey soils (Figure 2), further underscores the site-specific nature of the effect of SOC on maize yields (Vanlauwe et al. 2015). It supports the notion that SOC plays a more critical role in coarse-textured soils that inherently have limited nutrient (and water) holding capacities (Bashir et al. 2021; Thierfelder et al. 2022).

It is important to acknowledge in this context that correlation does not guarantee causation, and, therefore, it cannot be excluded that other factors besides SOC may have contributed to changes in maize yields in the long term. For example, additional micronutrients provided by organic inputs (Mucheru-Muna et al. 2014; Xiao et al. 2021), or organic N, P, K and other essential nutrients that are co-stabilized with SOC (Manzoni et al. 2012; Sinsabaugh et al. 2016) may have also played an important role. Furthermore, positive feedback loops between increased SOC and increased crop biomass productivity may exist (Couëdel et al. 2024).

In general, our study aligns with two recent global studies, showing that higher levels of SOC are associated with higher maize yields, and vice versa. However, the SOC levels at which the highest yields were estimated differed considerably between these two studies, with estimates being 20 g C kg^1 soil (Oldfield et al. 2019) and 43 g C kg^1 soil (Ma et al. 2023). This difference, together with the site-specific effects of SOC trends on yield trends observed in our study, as well as the interactions with mineral N fertilizer, suggests that the effect of SOC on yield should ideally be determined independently for contrasting site conditions, such as varying rainfall regimes or soil textures. For example, the decrease in average maize yield related to decreasing SOC was primarily observed at Aludeka and Sidada, sites with favorable climatic conditions for maize production (an average of about 600 mm of in-season rainfall). This finding suggests a clear benefit of increasing or maintaining SOC under such conditions. In contrast, at the Machanga and Embu sites, characterized by in-season rainfall ranging from 300 to 450 mm and frequent dry spells, SOC changes had little to no associations with long-term maize yield trends. This indicates a limited benefit of additional SOC under such rainfall-limited conditions, somewhat contradicting recent claims that SOC universally enhances climate change adaptation (Rumpel et al. 2020).

Although SOC can to some extent enhance soil water holding capacity (Ussiri and Lal 2019), the overall effect is limited and often negligible at realistic rates of SOC change (Minasny and McBratney 2018). Thus, changes in SOC likely have limited effects on long-term maize yield trends in regions with poor rainfall conditions where water, rather than nutrients, is the main limiting factor for crop growth. In that sense, our results provide one possible explanation for the strong spatial variability in the effectiveness of ISFM practices in sub-Saharan Africa (Mhlanga et al. 2021).

Nevertheless, this should not be interpreted as evidence that ISFM is only effective under high rainfall conditions, but rather as a crop-specific limitation related to maize. For example, a study on sorghum showed that even in arid conditions, an increase in yields over time is possible with ISFM applied to the right cropping system (Adams et al. 2020). Further, a meta-analysis showed that sites with arid conditions and sandy soils had among the strongest relative increase in maize yield from ISFM compared to control treatments (Chivenge et al. 2011), most likely because of the water retention by the freshly added organic materials that allowed plant growth and fertilizer uptake. These points demonstrate that our results should not be generalized to crops other than maize, or to situations where complementary management strategies, such as water harvesting, are used. ISFM may, therefore, still be a valuable component for improving crop yields across diverse environmental conditions, including those with limited rainfall.

4.2 Effects of weather on season-to-season maize yield variability are site specific

The importance of weather-related covariates in explaining seasonal maize yield across the sites in our study is consistent with findings from a recent global study (Ma et al. 2023) and several other studies suggesting in-season rainfall as a main limiting factor for maize yield in sub-Saharan Africa (Lobell et al. 2008; Madembo et al. 2020; Mhlanga et al. 2021; Simanjuntak et al. 2023; Rezaei et al. 2023). However, our site-specific analyses revealed a more nuanced picture. Because the crop growth-defining factors, i.e., solar radiation and genotypes, were near optimal at all four sites and all received best-practice pest management, the differences in the relative importance of treatments and weather covariates reflect the dominant growth-limiting factors for maize productivity at each site (van Ittersum and Rabbinge 1997). At Aludeka, which has favorable weather conditions but poor soil fertility, nutrients are the main growth-limiting factor (Mubanga and Steyn 2020). ISFM treatments therefore have the strongest effects on maize yields, fostering a strong relationship between long-term yield and SOC trends. The positive maize yield response to temperature and the low effect of rainfall at this site are likely due to generally sufficient soil moisture availability. Additionally, as Aludeka has low soil clay content, excessive rainfall may lead to nutrient leaching and thus yield losses (Weil and Brady 2016). These complex interactions could also be an explanation for the overall low importance of weather covariates in the linear models for this site. At Machanga, where both weather and soil fertility are growth-limiting, ISFM treatments and weather covariates hold similar importance. However, because Machanga is at the rainfall margin for maize cultivation, long-term SOC trends are not significantly related to yield trends. The treatment effects may instead reflect the short-term benefits of added organic resources, which can improvewater holding capacity, especially from those with high C:N ratio and high lignin content (Zhang et al. 2022). At sites with clay-rich soils, such as Embu and Sidada, soil fertility is not the major limitation to plant growth if soil acidity is properly managed (Zhang et al. 2023). Thus, weather becomes the main limiting factor. Nevertheless, the strong correlation between yield trends and SOC trends at Sidada suggests that SOC remains important for achieving maximum maize yields when weather conditions are favorable. This is especially the case when no mineral N is applied, as evidenced by the higher slope in the –N treatment (Figure 1).

The more pronounced positive effect of rainfall on maize yields at Embu and Machanga (e.g., effect sizes; Table 3) aligns with the fact that these sites are near or below the rainfall margin (about 450 mm of seasonal rainfall) for maize cultivation. Embu, with an average seasonal rainfall of 476 mm, is close to the lower threshold required for viable maize yields, while Machanga, with just 290 mm, is well below it (Ngetich et al. 2014; Tayel et al. 2015). Low maize yields at these sites are thus primarily driven by moisture limitations. This interpretation is further corroborated by the significant interactions between ISFM inputs and rainfall at both sites. Specifically, in seasons with adequate rainfall, maize yields responded positively to the application of organic resources with a low C:N ratio (at Machanga; Figure 3) and mineral N fertilizer (at both sites; Figure S3).

Additional evidence for this response comes from the significant negative effect of a high ratio of rainfall in the first 30 days to the total in-season rainfall at Embu and Machanga. Field observations by the site manager, confirmed that early rainfall followed by dry spells led to premature germination and subsequent severe drought stress or even plant death.

Regarding the effect of temperature, we initially wanted to explore whether daily temperatures above 30 °C would negatively influence maize yields, as shown in the study by Lobell et al. (2011), conducted using over 20.000 historical maize trials in sub-Saharan Africa. However, such temperatures occurred in only two seasons (both at Aludeka), making it impractical to include this covariate in our analysis. Still, we found significant negative effects of seasonal mean temperatures on maize yield at Embu and Machanga, likely due to interactions with water stress. This is supported by the greater sensitivity of maize yields to in-season rainfall under higher temperatures (at all sites except Sidada; Figure S2). This finding is thus consistent with the finding of Lobell et al. (2011), that high temperatures have 1.7 times stronger negative effects on maize yields under drought conditions than under adequate moisture conditions. Given the projected increases in temperature in Kenya without increases in rainfall (Mumo et al. 2021; Ojara et al. 2021), coping strategies such as irrigation (Rezaei et al. 2023) may become necessary to sustain maize yields in the future.

4.3 Local adaptation and targeting of ISFM must address the site-specific limitations

By combining the results of the long-term trends analysis and the season-to-season yield variations, our study demonstrates that addressing growth-limiting factors in maize production has both a long-term aspect, i.e., maintaining or improving soil fertility, and a short-term aspect, i.e., ensuring sufficient water availability, especially under high temperatures. Long-term SOC changes translated into maize yield changes only at Aludeka and Sidada, where rainfall is not a growth-limiting factor. In contrast, at the rainfall-constrained sites of Embu (in the -N treatment) and Machanga, there was no clear association between SOC and long-term yield changes, showing a more complex relationship under water-limited conditions. Consequently, we posit that the main benefit of maintaining or increasing SOC through sustainable intensification practices (e.g., ISFM) lies in relieving nutrient limitations. Importantly, in environments, where water is the main limiting factor, SOC improvements alone may not increase crop yields, making water management the priority. Effective local adaptation of ISFM (Vanlauwe et al. 2015) therefore requires targeting site-specific constraints. For example, applying low C:N ratio organic resources together with mineral nitrogen fertilizer under rainfed conditions appears beneficial only where in-season rainfall exceeds approximately 475 mm. In drier areas, several strategies could enable effective use of ISFM: implementing water harvesting (Kebenei et al. 2021), or irrigation, which also significantly reduces the effect of temperature stress and increases the yield per amount of N applied (Lobell et al. 2011; Vanlauwe et al. 2015), transitioning to more drought-tolerant crops such as sorghum (Adams et al. 2020), or applying lignin-rich organic resources with a high C:N ratio (Zhang et al. 2022), that enhance water retention. These approaches may allow ISFM to be effective even in moisture-constrained environments.

A practical challenge to ISFM is the limited availability of manure, the most effective external organic resource for maintaining SOC (Laub et al. 2023a). In many farming systems, crop and livestock production are not well integrated. As a result, pastoral areas often have surplus manure, while cropping areas may face shortages or lack proper manure collection due to free-roaming livestock (Sileshi et al. 2025). Therefore, promoting better integration of crop-livestock systems, either on the same farms, or through the development of value chains for manure trade, could help address this imbalance. Together with further research on adapting ISFM to regions with rainfall-limited conditions, these efforts could unlock the potential of ISFM for a wider range of agroecological conditions.

5 Conclusion

We presented a unique assessment of the relation between long-term trends in soil organic carbon and maize yield, along with season-to-season yield variability, in four long-term experiments conducted in Kenya, with the goal of providing nuanced insights into the interacting factors that affect maize yield in tropical cropping systems. Significant positive correlations between temporal trends in maize yield and soil organic carbon showed the benefits of maintaining soil organic carbon for sustaining maize yields, but only at sites with adequate seasonal rainfall (475-600 mm in-season rainfall). In contrast, in regions, such as Machanga, with around 300 mm in-season rainfall, moisture is a major limiting factor (especially under rising temperatures), and maintaining soil organic carbon has less influence on maize yield outcomes. Next to the long-term trends, seasonal variability of maize yields was strongly influenced by mean seasonal temperature and total seasonal rainfall at three of the four sites, but the magnitude of these weather effects varied between sites. Therefore, sustainable intensification strategies should be tailored to local climate conditions, particularly rainfall, and prioritize interventions based on the most limiting crop-growth factor.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s13593-025-01054-x.

Acknowledgements The AI language model “DeepL Write” has been used to improve the grammar of the manuscript.

Authors'contributions BV and DM established the long-term experiments that this research was conducted in. BV, JS, MC and ML designed this study. MWMM, DM, SMN, RY and WW managed and maintained the long-term experiment over the years. SMN, WW, BV, RY, JS, and ML were involved in the various sampling campaigns. MC, BV and JS acquired funding for the research. ML summarized the data, did the statistical analysis in collaboration with CML, and prepared the original draft. All co-authors contributed to the writing and editing of the final submitted article.

Funding Open access funding provided by Swiss Federal Institute of Technology Zurich. This research has been supported by the Schweizerischer Nationalfonds zur Förderung der Wissenschaftlichen Forschung (grant no. 172940), the European Union’s Horizon 2020 framework (LANDMARC; grant no. 869367), the DSCATT project “Agricultural Intensification and Dynamics of Soil Carbon Sequestration in Tropical and Temperate Farming Systems” (grant nos. AF 1802-001 and FT C002181), supported by the Agropolis Foundation (“Programme d’Investissement d’Avenir” LabEx Agro, grant no. ANR-10-LABX-0001-01), TOTAL Foundation (within a patronage agreement) and the CGIAR Excellence in Agronomy (EiA) Initiative.

Data availability The datasets used for the calibration of this study are available in the IITA data repository, available at https://doi.org/10.25502/wdh5-6c13/d for SOC and https://doi.org/10.25502/be9y-xh75/d for yields and biomass.

Code availability The data analyses applied the R software to create standard linear (mixed) models which are easily reproducible from the description in the text. No specialized software or code was used.

Declarations

Conflict of interest The authors declare no competing interests.

References

Adams AM, Gillespie AW, Dhillon GS, Kar G, Minielly C, Koala S, Ouattara B, Kimaro AA, Bationo A, Schoenau JJ, Peak D (2020) Long-term effects of integrated soil fertility management practices on soil chemical properties in the Sahel. Geoderma 366:114207. https://doi.org/10.1016/j.geoderma.2020.114207

Badu-Apraku B, Fakorede MAB (2017) Maize in Sub-Saharan Africa: Importance and Production Constraints. In: Badu-Apraku B, Fakorede MAB (eds) Advances in Genetic Enhancement of Early and Extra-Early Maize for Sub-Saharan Africa. Springer International Publishing, Cham, pp 3–10

Bashir O, Ali T, Baba ZA, Rather GH, Bangroo SA, Mukhtar SD, Naik N, Mohiuddin R, Bharati V, Bhat RA (2021) Soil Organic Matter and Its Impact on Soil Properties and Nutrient Status. In: Dar GH, Bhat RA, Mehmood MA, Hakeem KR (eds) Microbiota and Biofertilizers, vol 2. Ecofriendly Tools for Reclamation of Degraded Soil Environs. Springer International Publishing, Cham, pp 129–159

Berryman E, Hatten J, Page-Dumroese DS, Heckman KA, D'Amore DV, Puttere J, SanClements M, Connolly SJ, Perry CH (Hobie), Domke GM (2020) Soil Carbon. In: Pouyat RV, Page-Dumroese DS, Patel-Weynand T, Geiser LH (eds) Forest and Rangeland Soils of the United States Under Changing Conditions: A Comprehensive Science Synthesis. Springer International Publishing, Cham, pp 9–31. ISBN: 978-3-030-45216-2

Block S, Haile B, You L, Headey D (2021) Heat shocks, maize yields, and child height in Tanzania. Food Secur 14:93–109. https://doi.org/10.1007/s12571-021-01211-6

Cardinael R, Guibert H, Kouassi Brédoumy ST, Gigou J, N'Goran KE, Corbeels M (2022) Sustaining maize yields and soil carbon following land clearing in the forest–savannah transition zone of West Africa: results from a 20-year experiment. Field Crop Res 275:108335. https://doi.org/10.1016/j.fcr.2021.108335

Chivenge P, Vanlauwe B, Gentile R, Wangechi H, Mugendi D, van Kessel C, Six J (2009) Organic and mineral input management to enhance crop productivity in Central Kenya. Agron J 101:1266–1275. https://doi.org/10.2134/agronj2008.0188x

Chivenge P, Vanlauwe B, Six J (2011) Does the combined application of organic and mineral nutrient sources influence maize productivity? A meta-analysis. Plant Soil 342:1–30. https://doi.org/10.1007/s11104-010-0626-5

Couëdel A, Falconnier GN, Adam M, Cardinael R, Boote K, Justes E, Smith WN, Whitbread AM, Affholder F, Balkovic J, Basso B, Bhatia A, Chakrabarti B, Chikowo R, Christina M, Faye B, Ferchaud F, Folberth C, Akinseye FM, Gaiser T, Galdos MV, Gayler S, Gorooei A, Grant B, Guibert H, Hoogenboom G, Kamali B, Laub M, Maureira F, Mequanint F, Nendel C, Porter CH, Ripoche D, Ruane AC, Rusinamhodzi L, Sharma S, Singh U, Six J, Srivastava A, Vanlauwe B, Versini A, Vianna M, Webber H, Weber TKD, Zhang C, Corbeels M (2024) Long-term soil organic carbon and crop yield feedbacks differ between 16 soil-crop models in sub-Saharan Africa. Eur J Agron 155:127109. https://doi.org/10.1016/j.eja.2024.127109

Erenstein O, Jaleta M, Sonder K, Mottaleb K, Prasanna BM (2022) Global maize production, consumption and trade: trends and R&D implications. Food Secur 14:1295–1319. https://doi.org/10.1007/s12571-022-01288-7

FAO (2023) FAOSTAT Online Database. https://www.fao.org/faostat/en/#data/QCL. Accessed on 28 Apr 2023

IUSS Working Group (2015) World reference base for soil resources 2014, update 2015. International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106. FAO, Rome

Jägermeyr J, Müller C, Ruane AC, Elliott J, Balkovic J, Castillo O, Faye B, Foster I, Folberth C, Franke JA, Fuchs K, Guarin JR, Heinke J, Hoogenboom G, Iizumi T, Jain AK, Kelly D, Khabarov N, Lange S, Lin T-S, Liu W, Mialyk O, Minoli S, Moyer EJ, Okada M, Phillips M, Porter C, Rabin SS, Scheer C, Schneider JM, Schyns JF, Skalsky R, Smerald A, Stella T, Stephens H, Webber H, Zabel F, Rosenzweig C (2021) Climate impacts on global agriculture emerge earlier in new generation of climate and crop models. Nat Food. https://doi.org/10.1038/s43016-021-00400-y

Janzen HH, Janzen DW, Gregorich EG (2021) The 'soil health' metaphor: Illuminating or illusory? Soil Biol Biochem 159:108167. https://doi.org/10.1016/j.soilbio.2021.108167

Kebenei MC, Mucheru-Muna M, Muriu-Ng'ang'a F, Ndung'u CK (2021) Zai Technology and Integrated Nutrient Management for Improved Soil Fertility and Increased Sorghum Yields in Kitui County, Kenya. Front Sustain Food Syst 5:714212. https://doi.org/10.3389/fsufs.2021.714212

Kihara J, Bolo P, Kinyua M, Nyawira SS, Sommer R (2020) Soil health and ecosystem services: lessons from sub-Sahara Africa (SSA). Geoderma 370:114342. https://doi.org/10.1016/j.geoderma.2020.114342

Lal R (2004) Soil carbon sequestration to mitigate climate change. Geoderma 123:1–22. https://doi.org/10.1016/j.geoderma.2004.01.032

Laub M, Corbeels M, Couëdel A, Ndungu SM, Mucheru-Muna MW, Mugendi D, Necpalova M, Waswa W, Van de Broek M, Vanlauwe B, Six J (2023a) Managing soil organic carbon in tropical agroecosystems: evidence from four long-term experiments in Kenya. SOIL 9:301–323. https://doi.org/10.5194/soil-9-301-2023

Laub M, Corbeels M, Mathu Ndungu S, Mucheru-Muna MW, Mugendi D, Necpalova M, Van de Broek M, Waswa W, Vanlauwe B, Six J (2023b) Combining manure with mineral N fertilizer maintains maize yields: evidence from four long-term experiments in Kenya. Field Crop Res 291:108788. https://doi.org/10.1016/j.fcr.2022.108788

Lobell DB, Bänziger M, Magorokosho C, Vivek B (2011) Nonlinear heat effects on African maize as evidenced by historical yield trials. Nat Clim Change 1:42–45. https://doi.org/10.1038/nclimate1043

Lobell DB, Burke MB, Tebaldi C, Mastrandrea MD, Falcon WP, Naylor RL (2008) Prioritizing climate change adaptation needs for food security in 2030. Science 319:607–610. https://doi.org/10.1126/science.1152339

Lutz W, Stilianakis N, Stonawski M, Goujon A, Samir KC (2018) Demographic and human capital scenarios for the 21st century: 2018 assessment for 201 countries. Publications Office of the European Union. https://data.europa.eu/doi/10.2760/835878

Ma Y, Woolf D, Fan M, Qiao L, Li R, Lehmann J (2023) Global crop production increase by soil organic carbon. Nat Geosci 16:1159–1165. https://doi.org/10.1038/s41561-023-01302-3

MacLaren C, Mead A, van Balen D, Claessens L, Etana A, de Haan J, Haagsma W, Jäck O, Keller T, Labuschagne J, Myrbeck Å, Necpalova M, Nziguheba G, Six J, Strauss J, Swanepoel PA, Thierfelder C, Topp C, Tshuma F, Verstegen H, Walker R, Watson C, Wesselink M, Storkey J (2022) Long-term evidence for ecological intensification as a pathway to sustainable agriculture. Nat Sustain 5:770–779. https://doi.org/10.1038/s41893-022-00911-x

Madembo C, Mhlanga B, Thierfelder C (2020) Productivity or stability? Exploring maize-legume intercropping strategies for smallholder conservation agriculture farmers in Zimbabwe. Agr Syst 185:102921. https://doi.org/10.1016/j.agsy.2020.102921

Manzoni S, Taylor P, Richter A, Porporato A, Ågren GI (2012) Environmental and stoichiometric controls on microbial carbon-use efficiency in soils. New Phytol 196:79–91. https://doi.org/10.1111/j.1469-8137.2012.04225.x

Mhlanga B, Ercoli L, Pellegrino E, Onofri A, Thierfelder C (2021) The crucial role of mulch to enhance the stability and resilience of cropping systems in southern Africa. Agron Sustain Dev 41:29. https://doi.org/10.1007/s13593-021-00687-y

Mhlanga B, Pellegrino E, Thierfelder C, Ercoli L (2022) Conservation agriculture practices drive maize yield by regulating soil nutrient availability, arbuscular mycorrhizas, and plant nutrient uptake. Field Crop Res 277:108403. https://doi.org/10.1016/j.fcr.2021.108403

Minasny B, McBratney AB (2018) Limited effect of organic matter on soil available water capacity. Eur J Soil Sci 69:39–47. https://doi.org/10.1111/ejss.12475

Mubanga DKH, Steyn PMJ (2020) Rainfall is not the most limiting factor to maize (*Zea mays* L.) production in intermediate rainfall regions of Zambia. Lessons from Choma District. J Agric Policy 3:18–40. https://doi.org/10.47941/jap.377

Mucheru-Muna M, Mugendi D, Pypers P, Mugwe J, Kung'u J, Vanlauwe B, Merckx R (2014) Enhancing maize productivity and profitability using organic inputs and mineral fertilizer in central Kenya small-hold farms. Exp Agr 50:250–269. https://doi.org/10.1017/S0014479713000525

Mumo L, Yu J, Ojara M, Lukorito C, Kerandi N (2021) Assessing changes in climate suitability and yields of maize and sorghum crops over Kenya in the twenty-first century. Theor Appl Climatol 146:381–394. https://doi.org/10.1007/s00704-021-03718-6

Mutuku EA, Roobroeck D, Vanlauwe B, Boeckx P, Cornelis WM (2020) Maize production under combined conservation agriculture and integrated soil fertility management in the sub-humid and semi-arid regions of Kenya. Field Crop Res 254:107833. https://doi.org/10.1016/j.fcr.2020.107833

Nagelkerke NJD (1991) A note on a general definition of the coefficient of determination. Biometrika 78:691–692. https://doi.org/10.2307/2337038

Ndung'u M, Ngatia LW, Onwonga RN, Mucheru-Muna MW, Fu R, Moriasi DN, Ngetich KF (2021) The influence of organic and inorganic nutrient inputs on soil organic carbon functional groups content and maize yields. Heliyon 7:e07881. https://doi.org/10.1016/j.heliyon.2021.e07881

Ngeno V (2024) Profit efficiency among Kenyan maize farmers. Heliyon 10:e24657. https://doi.org/10.1016/j.heliyon.2024.e24657

Ngetich KF, Diels J, Shisanya CA, Mugwe JN, Mucheru-Muna M, Mugendi DN (2014) Effects of selected soil and water conservation techniques on runoff, sediment yield and maize productivity under sub-humid and semi-arid conditions in Kenya. CATENA 121:288–296. https://doi.org/10.1016/j.catena.2014.05.026

Ojara MA, Yunsheng L, Ongoma V, Mumo L, Akodi D, Ayugi B, Ogwang BA (2021) Projected changes in East African climate and its impacts on climatic suitability of maize production areas by the mid-twenty-first century. Environ Monit Assess 193:831. https://doi.org/10.1007/s10661-021-09547-4

Oldfield EE, Bradford MA, Wood SA (2019) Global meta-analysis of the relationship between soil organic matter and crop yields. Soil 5:15–32. https://doi.org/10.5194/soil-5-15-2019

Palm C, Gachengo CN, Delve RJ, Cadisch G, Giller KE (2001) Organic inputs for soil fertility management in tropical agroecosystems: application of an organic resource database. Agr Ecosyst Environ 83:27–42. https://doi.org/10.1016/S0167-8809(00)00267-X

Pinheiro J, Bates D, DebRoy S et al (2016) {nlme}: Linear and Nonlinear Mixed Effects Models. R package version 3.1-127. https://doi.org/10.32614/CRAN.package.nlme

R Core Team (2021) R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria

Reichenbach M, Fiener P, Hoyt A, Trumbore S, Six J, Doetterl S (2023) Soil carbon stocks in stable tropical landforms are dominated by geochemical controls and not by land use. Glob Change Biol 29:2591–2607. https://doi.org/10.1111/gcb.16622

Rezaei EE, Webber H, Asseng S, Boote K, Durand JL, Ewert F, Martre P, MacCarthy DS (2023) Climate change impacts on crop yields. Nat Rev Earth Environ 4:831–846. https://doi.org/10.1038/s43017-023-00491-0

Rumpel C, Amiraslani F, Chenu C, Garcia Cardenas M, Kaonga M, Koutika L-S, Ladha J, Madari B, Shirato Y, Smith P, Soudi B, Soussana J-F, Whitehead D, Wollenberg E (2020) The 4p1000 initiative: opportunities, limitations and challenges for implementing soil organic carbon sequestration as a sustainable development strategy. Ambio 49:350–360. https://doi.org/10.1007/s13280-019-01165-2

Sanchez PA (2015) En route to plentiful food production in Africa. Nat Plants 1(1):14014. https://doi.org/10.1038/nplants.2014.14

Schlenker W, Roberts MJ (2009) Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. P Natl Acad Sci USA 106:15594–15598. https://doi.org/10.1073/pnas.0906865106

Sileshi GW, Stewart ZP, Odhong J, Mhlanga B, Amede T, Aynekulu E, Thierfelder C, Marenya P, Dittmer KM, Aliyu KT, Chikowo R, Chiduwa M, Ngoma H, Snapp S (2025) A review of organic inputs to inform soil health advice for African smallholder farmers: localization matters. npj Sustain Agric 3:1–15. https://doi.org/10.1038/s44264-025-00063-3

Simanjuntak C, Gaiser T, Ahrends HE, Ceglar A, Singh M, Ewert F, Srivastava AK (2023) Impact of climate extreme events and their causality on maize yield in South Africa. Sci Rep 13:12462. https://doi.org/10.1038/s41598-023-38921-0

Sinsabaugh RL, Turner BL, Talbot JM, Waring BG, Powers JS, Kuske CR, Moorhead DL, Follstad Shah JJ (2016) Stoichiometry of microbial carbon use efficiency in soils. Ecol Monogr 86:172–189. https://doi.org/10.1890/15-2110.1

Soares MR, Alleoni LRF (2008) Contribution of soil organic carbon to the ion exchange capacity of tropical soils. J Sustain Agr 32:439–462. https://doi.org/10.1080/10440040802257348

Sommer R, Paul BK, Mukalama J, Kihara J (2018) Reducing losses but failing to sequester carbon in soils – the case of conservation agriculture and integrated soil fertility management in the humid tropical agro-ecosystem of Western Kenya. Agr Ecosyst Environ 254:82–91. https://doi.org/10.1016/j.agee.2017.11.004

Svoboda MD, Fuchs BA (2017) Handbook of Drought Indicators and Indices. In: Wilhite D, Pulwarty RS (eds) Drought and Water Crises. Integrating Science, Management, and Policy, 2nd edn. CRC Press, Boca Raton, pp 155–207

Tayel MY, Mansour HA, Pibars SK (2015) Performance of maize under bubbler irrigation system. In: Goyal MR, Mansour HAA (eds) Closed Circuit Trickle Irrigation Design, 1st edn. Apple Academic Press, New York, pp 135–147

Thierfelder C, Paterson E, Mwafulirwa L, Daniell TJ, Cairns JE, Mhlanga B, Baggs EM (2022) Toward greater sustainability: how investing in soil health may enhance maize productivity in Southern Africa. Renew Agr Food Syst 37:166–177. https://doi.org/10.1017/S1742170521000442

Tully K, Sullivan C, Weil R, Sanchez P (2015) The state of soil degradation in sub-Saharan Africa: baselines, trajectories, and solutions. Sustainability-Basel 7:6523–6552. https://doi.org/10.3390/su7066523

Ussiri DAN, Lal R (2019) Soil Degradation in Sub-Saharan Africa: Challenges and Opportunities for Restoration. In: Lal R, Stewart AB (eds) Soil Degradation and Restoration in Africa. CRC Press, Boca Raton, pp 1–24

van Ittersum MK, Rabbinge R (1997) Concepts in production ecology for analysis and quantification of agricultural input-output combinations. Field Crops Res 52:197–208. https://doi.org/10.1016/S0378-4290(97)00037-3

Vanlauwe B, Bationo A, Chianu J, Giller KE, Merckx R, Mokwunye U, Ohiokpehai O, Pypers P, Tabo R, Shepherd KD, Smaling EMA, Woomer PL, Sanginga N (2010) Integrated soil fertility management: operational definition and consequences for implementation and dissemination. Outlook Agric 39:17–24. https://doi.org/10.5367/000000010791169998

Vanlauwe B, Descheemaeker K, Giller KE, Huising J, Merckx R, Nziguheba G, Wendt J, Zingore S (2015) Integrated soil fertility management in sub-Saharan Africa: unravelling local adaptation. Soil 1:491–508. https://doi.org/10.5194/soil-1-491-2015

von Fromm SF, Hoyt AM, Lange M, Acquah GE, Aynekulu E, Berhe AA, Haefele SM, McGrath SP, Shepherd KD, Sila AM, Six J, Towett EK, Trumbore SE, Vågen T-G, Weullow E, Winowiecki LA, Doetterl S (2021) Continental-scale controls on soil organic carbon across sub-Saharan Africa. Soil 7:305–332. https://doi.org/10.5194/soil-7-305-2021

Weil RR, Brady NC (2016) The nature and properties of soils, 15th edn. Pearson London, London, UK

Woomer PL, Swift MJ (1994) The biological management of tropical soil fertility. John Wiley, Chichester, UK

Xiao Q, Huang Y, Wu L, Tian Y, Wang Q, Wang B, Xu M, Zhang W (2021) Long-term manuring increases microbial carbon use efficiency and mitigates priming effect via alleviated soil acidification and resource limitation. Biol Fert Soils 57:925–934. https://doi.org/10.1007/s00374-021-01583-z

Zhang J, Fu G, Jin Z, Chi L, Xu G, Yue D (2022) Optimization of organic mulches thickness improves soil moisture retention under controlled conditions. Phyton 91:841–857. https://doi.org/10.32604/phyton.2022.017938

Zhang S, Zhu Q, de Vries W, Ros GH, Chen X, Muneer MA, Zhang F, Wu L (2023) Effects of soil amendments on soil acidity and crop yields in acidic soils: a world-wide meta-analysis. J Environ Manage 345:118531. https://doi.org/10.1016/j.jenvman.2023.118531

Zuur A, Ieno EN, Walker N, Saveliev AA, Smith GM (2009) Mixed Effects Models and Extensions in Ecology with R. Springer-Verlag, New York