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RESEARCH ARTICLE

Beyond Climate Change: The Role of Integrated Soil Fertility Management for Sustaining Future Maize Yield in Sub-Saharan Africa

Antoine Couëdel[1,2] | Gatien N. Falconnier[1,3,4,5] | Myriam Adam[6,7] | Rémi Cardinael[1,3,5] | Johan Six[8] | Moritz Laub[8] | Alex C. Ruane[9] | Kenneth Boote[10] | Eric Justes[11] | Ward N. Smith[12] | Anthony M. Whitbread[13] | François Affholder[1,14,15] | Folorunso M. Akinseye[16,17] | Juraj Balkovic[18] | Bruno Basso[19] | Arti Bhatia[20] | Bidisha Chakrabarti[20] | Regis Chikowo[5,21] | Mathias Christina[1,2,22] | Babacar Faye[23] | Fabien Ferchaud[24,25] | Christian Folberth[18] | Thomas Gaiser[26] | Marcelo Galdos[27] | Sebastian Gayler[28] | Aram Gorooei[29] | Brian Grant[12] | Hervé Guibert[1,2] | Gerrit Hoogenboom[10] | Bahareh Kamali[29] | Fidel Maureira[19] | Fasil Mequanint[28,30] | Claas Nendel[31,32,33] | Cheryl H. Porter[10] | Dominique Ripoche[34] | Leonard Rusinamhodzi[35] | Shikha Sharma[20] | Upendra Singh[36] | Amit Srivastava[26] | Bernard Vanlauwe[37] | Antoine Versini[38] | Murilo Vianna[29] | Heidi Webber[31,39] | Tobias Weber[28,40] | Congmu Zhang[10] | Marc Corbeels[1,37,41]

Correspondence: Antoine Couëdel (antoine.couedel@cirad.fr)

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ABSTRACT

Climate change is projected to exacerbate food insecurity in sub-Saharan Africa (SSA) by reducing crop yields and soil fertility. Many climate change impact studies in SSA have overlooked long-term effects of soil fertility on crop yield. We evaluated maize yields under different scenarios of soil fertility (using soil organic carbon as a proxy) and climate change (considering changes in temperature, rainfall, and CO_2) at four sites in SSA. Using an ensemble of 15 calibrated soil-crop models, we found a strong consensus that, without fertilization, soil fertility declines over time, impacting maize yields more strongly than changes in temperature, rainfall, or CO_2. The model ensemble indicated that when accounting for soil fertility changes, the yield benefits of combined application of organic and mineral inputs increase over time, even under climate change. These findings highlight the importance of considering long-term change in soil fertility when assessing impacts of climate change and integrated nutrient management on crop production in SSA.

1 | Introduction

Sub-Saharan Africa (SSA) faces significant food security issues despite its considerable agricultural potential (Van Ittersum et al. 2016; Giller 2020). Food insecurity in the region has been exacerbated by recent geopolitical conflicts (Behnassi and El Haiba 2022), but is largely due to low soil fertility (Sanchez 2002; Vanlauwe et al. 2015), inadequate nutrient inputs (Jayne and Sanchez 2021), insufficient or erratic rainfall (Kamali et al. 2022; Bouhenache et al. 2025), and pathogen and pest pressures (Savary et al. 2019), all leading to low crop yields. Maize productivity plays a crucial role in ensuring food security in SSA, as it is the most widely grown cereal and the main source of dietary energy, providing at least 30% of the total caloric intake of the region's population (OECD 2016; Ekpa et al. 2019). Since the beginning of the 21st century, the area dedicated to maize cultivation in SSA has nearly doubled (FAOSTAT 2023), currently occupying about 40% of the total area cropped with cereals. Yet, average maize yields across the continent have largely stagnated at about 1.9 $t\,ha^{-1}$ (FAOSTAT 2023), although some countries exhibit modest increases, such as Ethiopia, Angola, Mozambique, Ivory Coast, and parts of Nigeria, while others experience yield declines (Ray et al. 2013). The projected 2.3-fold increase in maize demand by 2050 (Robinson et al. 2015) is expected to put further pressure on food security and land resources.

The urgent need for increased food production contrasts sharply with current trajectories of environmental factors affecting crop productivity in SSA. On one hand, rising temperatures across SSA and decreasing rainfall in West and Southern Africa (Trancoso et al. 2024), together with the increasing frequency of extreme weather events (Westra et al. 2014; Lesk et al. 2020; Ranasinghe et al. 2021; Reed et al. 2022), are expected to negatively impact maize yields (Sultan and Gaetani 2016; Jägermeyr et al. 2021), thereby worsening food insecurity (Tadross et al. 2009; Falconnier et al. 2020; Carr et al. 2022; Ren et al. 2024). On the other hand, soil fertility continues to decline in many regions of SSA due to the low use of mineral fertilizers and organic inputs, along with the shortened fallow periods and widespread soil erosion (Vanlauwe and Giller 2006; Vanlauwe et al. 2015; Kihara et al. 2020; Falconnier et al. 2023). Evidence from long-term field experiments shows that low fertilizer inputs lead to a progressive decline in both soil fertility and crop yields over time (Adams et al. 2020; Cardinael et al. 2022; Laub, Corbeels, Mathu Ndungu, et al. 2023; Laub, Corbeels, Couëdel, et al. 2023). Therefore, if soil fertility continues to decline, maize productivity in SSA is likely to decrease even further.

Integrated soil fertility management (ISFM), which includes the combined use of mineral and organic inputs, offers the prospect of increasing crop yield and soil fertility (Vanlauwe et al. 2010), thereby improving resilience to climate change (Gram et al. 2020). However, due to the difficulty of conducting climate manipulation experiments, the effectiveness of the combined use of mineral and organic inputs in the context of climate change remains insufficiently evaluated, leaving uncertainty about whether its benefits are maintained in changing climatic conditions. In this context, an ensemble of process-based soil-crop models can help assess the impacts of climate change (Falconnier et al. 2020), as they can account for the complex, nonlinear interactions between soil organic carbon (SOC) dynamics and crop growth (Couëdel et al. 2024; Couëdel, Laub, et al. 2026).

By reinitializing soil conditions at the start of each simulated year, most crop modeling studies assessing the impact of future climate change on crop productivity have focused on evaluating the direct effects of changing temperatures, rainfall, and atmospheric CO_2 concentrations on crop growth and yield (Challinor et al. 2014; Falconnier et al. 2020; Jägermeyr et al. 2021; Rezaei et al. 2023). These studies ignored possible soil fertility decline over time, thus overlooking the combined effects of climate change and soil degradation on crop yields. Simulation studies that incorporate soil fertility dynamics are particularly important in tropical low-input cropping systems, where soil organic matter mineralization is the primary source of nutrients for crop growth (Giller et al. 2011).

The aim of our study was to assess how long-term changes in soil fertility and climate drivers affect maize yield in SSA, how these factors interact, and to what extent ISFM can alleviate the negative effects. SOC was used as a proxy for soil fertility, given its central role in determining soil chemical, physical, and biological properties (Lehmann et al. 2020). We simulated key components of climate change affecting crop growth, namely atmospheric CO_2, temperature and precipitation, using an ensemble of 15 process-based soil-crop models. The models were calibrated using data from four long-term field experiments, covering diverse representative climates and soils in SSA (see Figure 1). Such long-term experiments remain scarce in the region, making them particularly valuable for model calibration and scenario analysis. The study evaluated scenarios of soil fertility change, climate change impacts, and their combined effects under two contrasting crop management options: (i) no use of mineral or organic inputs, representing current smallholder farmers' practices, and (ii) combined use of mineral (80 kg N ha^{-1} $season^{-1}$) and organic (2 t C $ha^{-1} yr^{-1}$) inputs, a core principle of ISFM, representing a plausible sustainable intensification scenario with nutrient levels required to achieve food security across SSA (Falconnier et al. 2023). We hypothesized that (i) soil fertility decline has a stronger impact on maize yields than climate change alone, though with varying magnitudes across sites, and (ii) ISFM mitigates the negative effects of soil fertility decline, although its effectiveness is reduced under climate change.

2 | Materials and Methods

2.1 | Multi-Model Ensemble and Model Calibration Methods

An ensemble of 15 calibrated process-based soil-crop models was used in this study (see Table 1 and Couëdel et al. (2024) for detailed model descriptions). In brief, the models differ in how they simulate soil processes, crop development, crop growth, and grain yield formation. SOC dynamics are generally simulated using first-order decay kinetics, but models vary in the number and type of SOM pools, with some models differentiating active, slow, and passive pools (e.g., DSSAT), while others use a single-pool approach (e.g., CELSIUS). Ten of the 15 models include an explicit soil microbial biomass pool with first-order decay. The representation of fresh organic matter inputs (crop residues, organic amendments) ranges from a single pool to multiple specialized pools, as for example implemented in SIMPLACE. All models simulate soil nitrogen (N) cycling coupled with the SOM pools. Models also differ in their treatment of other soil processes such as soil water dynamics and nitrate leaching, while crop growth processes vary in their simulation of leaf area development, light interception, biomass accumulation, and grain formation. A single experienced modeling team conducted the simulations with each model. Different versions of a given model (i.e., DSSAT, Expert-N, and SIMPLACE) were conducted by the team working with that specific version of the model.

Model calibration and evaluation under current conditions were deemed essential for ensuring plausible maize yield simulations under the future climate change scenarios, while accounting for long-term SOC dynamics and their interactions with maize growth. The median of the model ensemble (15 soil-crop models) was used to evaluate how well the ensemble reproduced maize yields and SOC dynamics over time across the four long-term experiments. The modeling teams

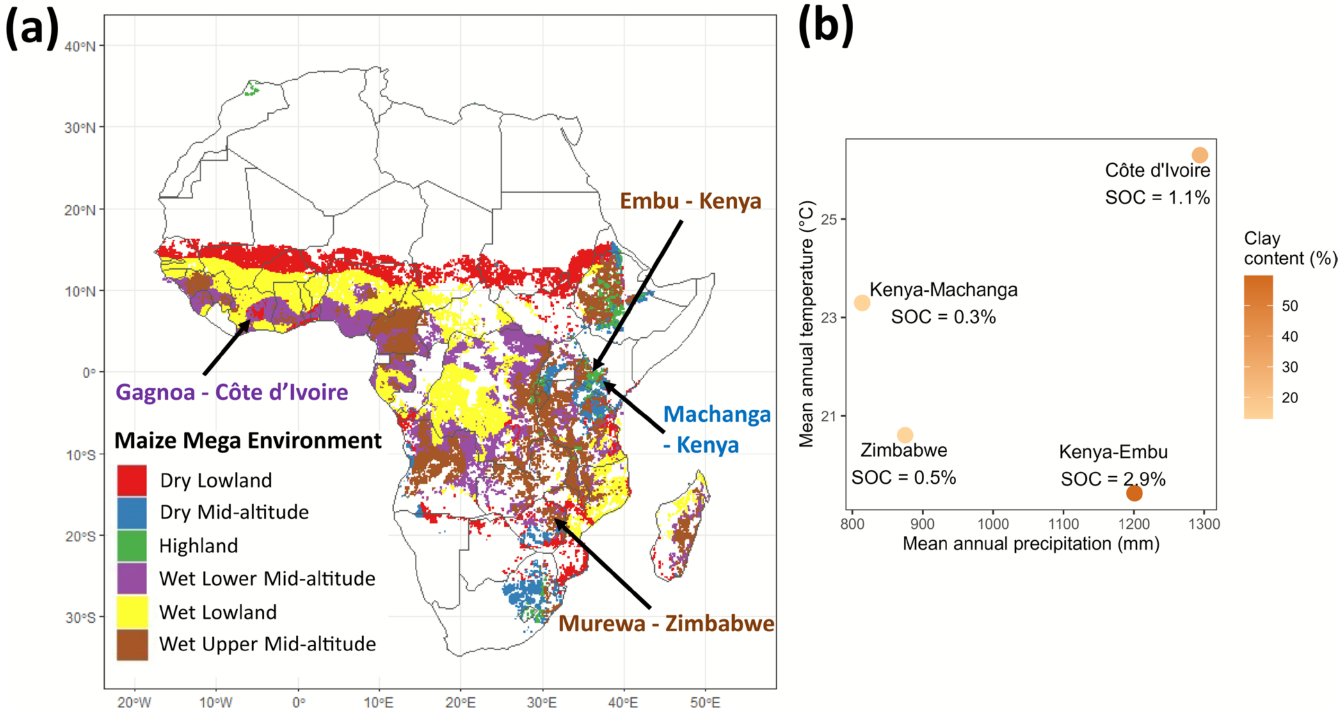

FIGURE 1 | Harvested areas of maize in sub-Saharan Africa showing the four study sites representativeness of the six CIMMYT maize mega environments (a) and their baseline (1980–2010) mean annual temperature, mean annual precipitation, and clay content (b). Soil organic carbon (SOC) is the initial SOC concentration (%) (0–20 cm). Map lines delineate study areas and do not necessarily depict accepted national boundaries.

TABLE 1 | The 15 soil-crop process-based models used in the model intercomparison study.

Model	Model references
APSIM v7.9	Holzworth et al. (2014)
CELSIUS	Ricome et al. (2017)
DayCent	Del Grosso et al. (2001)
DNDC v.CAN	Smith et al. (2020a, 2020b)
DSSAT v4.8.0.19-CERES-Maize + Century	Ritchie et al. (1998), Gijsman et al. (2002), Hoogenboom et al. (2021)
DSSAT v4.8.0.19-CERES-Maize + Ceres-SOM	Godwin and Jones (1991), Hoogenboom et al. (2021)
EPIC	Izaurralde et al. (2006)
Expert-N v5.1-Gecros	Biernath et al. (2011)
Expert-N v5.1-Spass	Biernath et al. (2011)
Expert-N v5.1-Ceres	Biernath et al. (2011)
MONICA v3.3.1	Aiteew et al. (2024), Nendel et al. (2011)
SALUS	Basso et al. (2010)
SIMPLACE-Lintul + Option 1	Enders et al. (2023), Gaiser et al. (2013)
SIMPLACE-Lintul + Option 2	Faye et al. (2018)
STICS v10	Brisson et al. (2003), Beaudoin et al. (2023)

were free to use their own methods for calibration of the crop and soil modules of their respective model versions. Values for model input parameters and variables (observed or estimated), including soil characteristics, initial soil conditions, weather, soil and crop management, were provided to the modeling teams for conducting simulations of maize growth during the years of the experiments at the four sites. Observed data on maize phenology, grain yield, aboveground biomass, and SOC were used for model calibration. Couëdel et al. (2024) provide more detailed information about model structural differences and calibration procedures. In summary, model calibration consisted of adjusting maize phenology and key crop and soil parameters to reproduce observed yield, aboveground biomass, and SOC. The initialization and turnover of soil organic matter pools were calibrated using observed SOC levels, spin-up model runs, or empirical relationships with soil texture, depending on the model, with each team applying its standard procedure to improve the agreement between simulated and observed SOC dynamics.

Model calibration inputs and outputs are available in the CIRAD repository (Couëdel, Falconnier, et al. 2026).

2.2 | Experiments and Data

Data from long-term maize field experiments at four sites in SSA were used to calibrate 15 process-based soil-crop models (see Couëdel et al. (2024) for experimental details and model descriptions; in the present study InfoCrop was used only for the calibration exercise and not for the sensitivity analysis to climate change factors). These sites cover contrasting climates, soil textures, and soil fertility levels, and are representative of three of the six maize mega-environments in SSA that are broad agroecological zones that share similar climatic, soil, and biotic conditions, which together determine how maize performs and adapts in a given region (Hartkamp et al. 2000; Figure 1). The four experiments (Côte d'Ivoire-Gagnoa, Kenya-Embu, Kenya-Machanga, and Zimbabwe-Murewa) spanned between 9 and 18 years and were managed by researchers either on-station or on-farm. Such long-duration field experiments are scarce in SSA, making them particularly valuable for model calibration and scenario analysis. All sites, except Zimbabwe-Murewa, had two maize growing seasons per year. The experiments were rainfed and included the following two treatments: (i) a control without exogenous C and N inputs, and (ii) a combined application of mineral N (between 100 and 160 kg N ha^{-1} per growing season depending on the site) and organic inputs (between 3 and 4 t C ha^{-1} per year depending on the site). This latter treatment represents the input practice in ISFM. Organic input was compost made from crop residues at Côte d'Ivoire-Gagnoa and farmyard manure at the other sites. The input of crop residues to the soil was limited to roots, as aboveground biomass residues were removed from the experimental plots. Biotic stresses (weeds, pests, and diseases) were controlled to minimize their impact on maize yield.

General soil characteristics and initial soil conditions were determined at the beginning of the experiments. Data on crop management (tillage, maize cultivar, planting date and density, and fertilizer application) was available for all sites and years. Flowering and maturity dates of the maize cultivars were recorded for Côte d'Ivoire-Gagnoa and Kenya-Embu, while only cultivar maturity periods were available for Zimbabwe-Murewa and Kenya-Machanga. Grain yield data was available for all years and sites, and total aboveground biomass data was available for all sites except Zimbabwe-Murewa. SOC data were collected from measurements at multiple time intervals throughout the experiments on topsoil samples (0–15 cm at Kenya-Machanga and Kenya-Embu, and 0–20 cm at Zimbabwe-Murewa and Côte d'Ivoire-Gagnoa; see Figure 2).

Weather data during experimental years were obtained primarily from onsite records (rainfall at all sites, minimum and maximum temperatures at all sites except Zimbabwe-Murewa). For daily incident solar radiation and relative humidity, and for temperature data at Zimbabwe-Murewa, records from NASA's Prediction Of Worldwide Energy Resources (POWER) database (Duarte and Sentelhas 2019) were used.

More information about the experiments is provided in earlier publications, for Côte d'Ivoire-Gagnoa (Pichot et al. 1977; Guibert 1999; Cardinael et al. 2022), for the two sites in Kenya (Chivenge et al. 2009, 2011; Gentile et al. 2009; Laub, Corbeels, Mathu Ndungu, et al. 2023; Laub, Corbeels, Couëdel, et al. 2023), and for the site in Zimbabwe (Zingore et al. 2007; Rusinamhodzi et al. 2013).

2.3 | Model Simulation Scenarios

The response of the model ensemble to the climate change factors of changing temperature, rainfall and atmospheric CO_2 was assessed for two crop management scenarios: (i) without external C and N inputs and (ii) with combined mineral and organic inputs, representing ISFM. The model simulations for the 30-year baseline climate (1980–2010) were done with uniform maize management practices across all years (Table S1). The 30-year baseline climate data (1980–2010) for rainfall and temperature were derived from onsite records, supplemented with bias-corrected NASA POWER data when necessary. NASA POWER also provided the data for daily incident solar radiation and relative humidity for the 30-year baseline climate. The ISFM system combined application of mineral N fertilizer (80 kg N ha^{-1} per growing season) and organic input (2 t C ha^{-1} $year^{-1}$), as manure at all sites except Côte d'Ivoire-Gagnoa where the addition of compost made from crop residues was simulated. This scenario represents a plausible sustainable intensification pathway with nutrient inputs sufficient to meet food security needs across sub-Saharan Africa (Falconnier et al. 2023).

Following the AgMIP and C3MP protocols (Ruane et al. 2014; Rosenzweig et al. 2013), we applied individual changes of temperature, rainfall and atmospheric CO_2 to assess model responses. This approach isolates crop model sensitivities to each climate driver, allowing for direct comparisons across models and sites while avoiding confounding effects from co-varying changes in climate scenarios. The response to increasing atmospheric CO_2 was analyzed using concentrations of 360, 450, 540 and 720 ppm. The response to warmer temperatures was analyzed by uniformly increasing daily minimum and maximum temperatures by respectively 2°C, 4°C and 6°C, relative to the baseline climate. Finally, the response to change in rainfall was analyzed by decreasing daily rainfall by 25% and 50%, or by increasing it by 25% and 50%. The changes in CO_2, temperature and rainfall were assessed independently, and factorial combinations were not considered to isolate the individual effects of change in climate variables. This approach avoids additional uncertainty, as current models are not yet fully equipped to reliably simulate complex interactions among multiple concurrent climate stresses (Webber et al. 2022).

In the scenario without C and N inputs, both reset and continuous model simulations were performed to isolate the effects

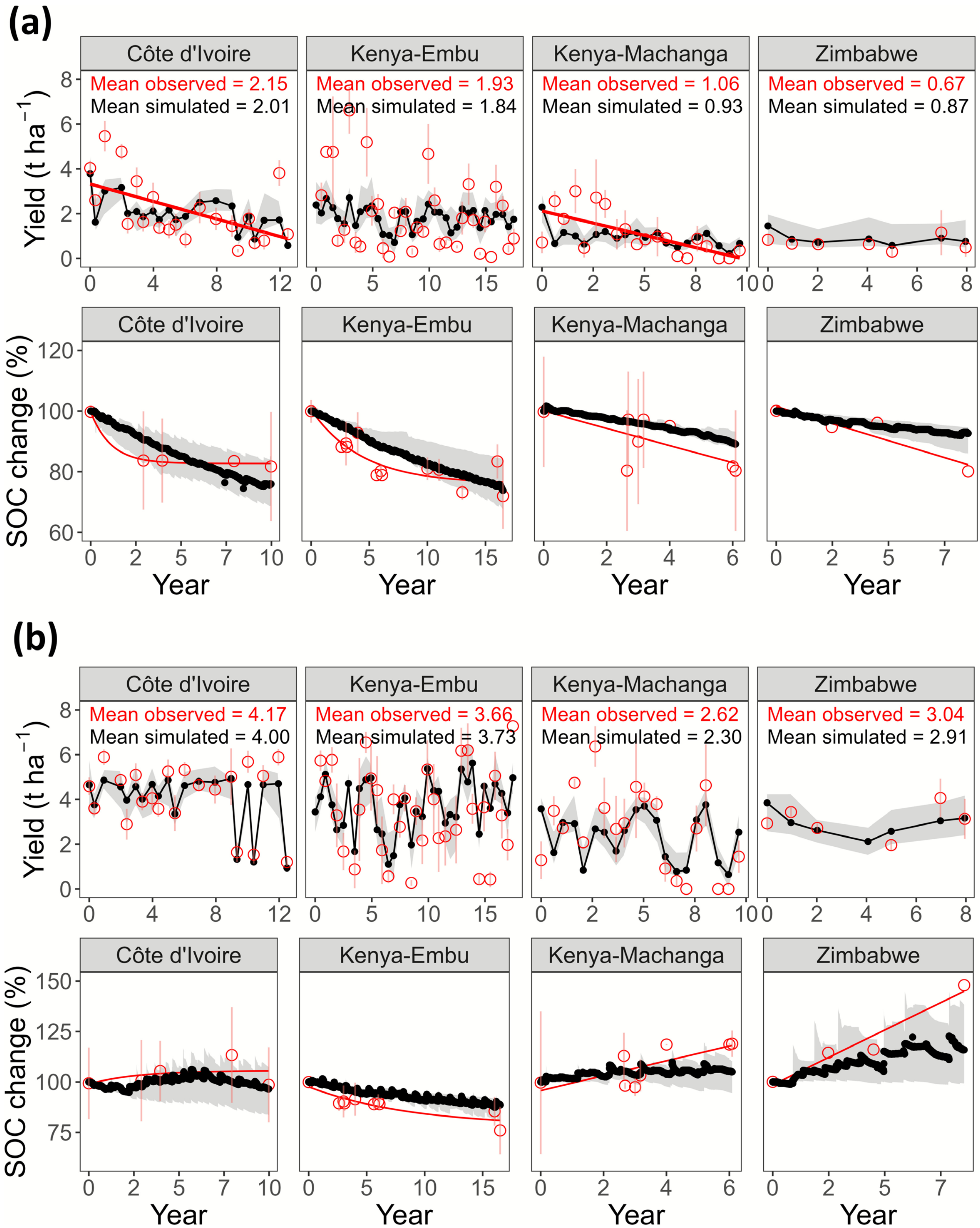

FIGURE 2 | Observed (in red) and simulated (in black) maize yield and soil organic carbon (SOC) change for no input (a) and mineral and organic fertilizers (b) treatments across four long-term experiments in sub-Saharan Africa. 'Year' represents years from the start of the experiments. Black data points are medians of 15 soil-crop models. Dark gray areas indicate the 25th to 75th percentile range of the values simulated. Red lines are linear (for observed yield) and/or exponential regression functions (for observed SOC). Only significant regressions at $p < 0.05$ are displayed.

of climate change factors and those of soil fertility dynamics. In the reset model simulations, SOC, soil total N, soil mineral N, and soil water were reinitialized each year with the same starting values, thereby eliminating the cumulative effects of changes in soil fertility over time. In contrast, in continuous simulations, the initial values of these variables for each year were set according to the simulated values at the end of the previous year. This allowed each model of the ensemble to simulate the full 30-year period continuously, accounting for soil-crop feedback effects on crop yield. In the ISFM scenario with mineral and organic inputs, only continuous simulations were conducted.

In the main text and figures, we present results only for the scenarios of +2°C, −25% rainfall, +25% rainfall, and 540 ppm CO_2, denoted as 'warmer temperature', 'decreasing rainfall', 'increasing rainfall', and 'higher CO_2', respectively. The +2°C and 540 ppm CO_2 scenarios correspond to conditions projected under a high-emission pathway (SSP3-7.0) by 2050 (Meinshausen et al. 2020; Thrasher et al. 2022). The ±25% rainfall scenarios were chosen to represent the widespread uncertainty in rainfall projections across global climate models, capturing plausible dry and wet future conditions (see Table S2). The simulation results from the other, more extreme scenarios (±50% rainfall, up to +6°C, up to 720 ppm CO_2) are summarized briefly in the "Results" section and provided in detail in the "Supporting Information". Model simulation inputs and outputs are available in the CIRAD repository (Couëdel, Falconnier, et al. 2026).

2.4 | Data Analysis

Comparing the reset and continuous model simulations in the scenario without external C and N inputs enabled to quantify the average relative change in maize yield (%) due to climate change alone (CC, Figure S1A), soil fertility change alone (SF, Figure S1B) and their combined (CCSF, Figure S1C) and interactive effects (CC × SF), as follows:

$$CC\,(\%) = \frac{CC_{reset} - BL_{reset}}{BL_{reset}} \times 100 \quad (1)$$

$$SF\,(\%) = \frac{BL_{cont} - BL_{reset}}{BL_{reset}} \times 100 \quad (2)$$

$$CCSF\,(\%) = \frac{CC_{cont} - BL_{reset}}{BL_{reset}} \times 100 \quad (3)$$

$$CC \times SF(\%) = CCSF - (CC + SF) \quad (4)$$

where BL_{reset} and CC_{reset} represent the average simulated maize yields from a given model within the 15-model ensemble across the 30-year simulation period under the reset simulation mode. BL_{reset} corresponds to the baseline climate scenario, while CC_{reset} refers to scenarios with changes in climate factors. BL_{cont} and CC_{cont} represent the average simulated maize yields from a given model within the 15-model ensemble across the 30-year simulation period under the continuous simulation mode. BL_{cont} corresponds to the baseline climate scenario, while CC_{cont} refers to scenarios with changes in climate factors. The interactive effect (CC×SF) represents the non-additive component of the combined effect of climate change and soil fertility change on maize yield, that is, the portion of the yield response that cannot be explained by the sum of their individual effects. A positive CC×SF value indicates a synergistic interaction, while a negative value indicates that one factor partially offsets the effect of the other.

The differences between maize yield simulations in the scenario without C and N inputs and that with mineral plus organic inputs under continuous simulation mode allowed to compute the yield response (%) to organic and mineral input, considering soil-crop feedbacks, as follows:

$$\Delta Y_{MOF}\,(\%) = \frac{Y_{MOF} - Y_0}{Y_0} \times 100 \quad (5)$$

where Y_0 and Y_{MOF} are the simulated maize yields from a given model within the 15-model ensemble across the 30-year simulation period without and with the mineral and organic inputs, respectively. Results are then shown using the median of the 15 models (Figure 4).

We assessed the agreement between models by counting the number of models performing in the same direction for a given analysis. Following this approach, agreement between models was categorized into low (< 50% models agreed), medium (50% < models agreed < 75%), and high (> 75% models agreed) confidence levels.

The relationships between (i) observed or simulated maize yield versus time since the start of the experiment (Figure 2, Figure S7) and (ii) simulated yield change with organic plus mineral inputs versus time (Figure 4) were fitted using the lm function in R (R core team 2023). For all statistical tests, the significance level, α, was set at 0.05.

For the scenario without C and N inputs, observed SOC changes over time (Figure 2a) were fitted with an exponential decay function using the EXD.3 function of the 'drc' package in R (R core team 2023). For the scenario with C and N inputs, an asymptotic function using the AR.3() function was used (Figure 2b).

3 | Results

3.1 | The Calibrated Soil-Crop Model Ensemble Reproduced Trends in Maize Yield and SOC

For the treatment without C and N inputs, the ensemble median accurately reproduced the observed decrease in SOC over time at the Côte d'Ivoire-Gagnoa and Kenya-Embu sites, but underestimated SOC loss at the Kenya-Machanga and Zimbabwe-Murewa sites (Figure 2a). Although the models did not fully capture interannual maize yield variability and tended to overestimate yields in the first years at all sites except Zimbabwe, they reproduced the observed temporal trends reasonably well, showing declining yields at Côte d'Ivoire-Gagnoa and Kenya-Machanga, and stable yields at Kenya-Embu and Zimbabwe-Murewa (Figure 2a). For the treatment with combined use of

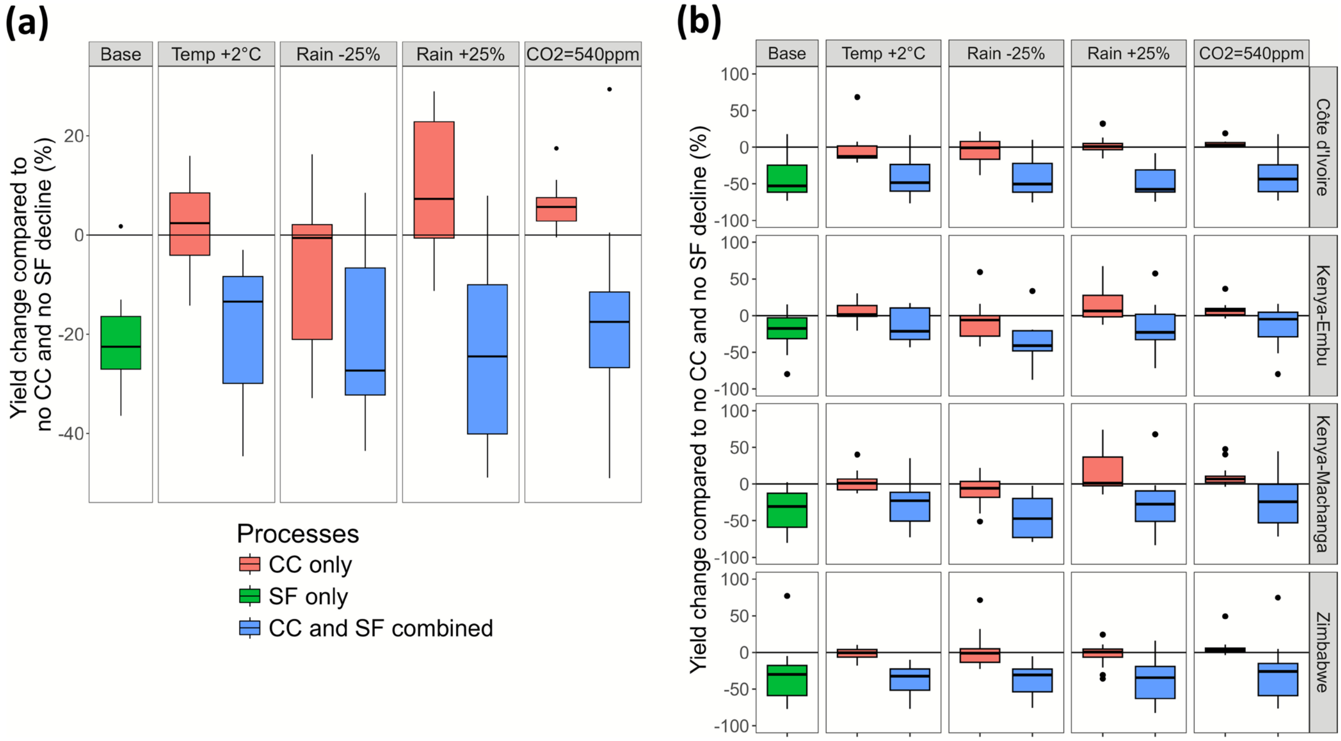

FIGURE 3 | Boxplots of simulated maize yield change (%) by climate change only (CC only, see Equation (1) in Section 2.4), soil fertility declines only (SF only; i.e., difference between yearly reinitialization of soil conditions vs. continuous model simulation, see Equation (2) in Section 2.4) and the combination between climate change and soil fertility decline (CC and SF combined, see Equation (3) in Section 2.4) compared to no climate change and no soil fertility decline scenario (no CC and no SF decline). Simulations represent no fertilizer systems, averaged across 30 years for each of the 15 individual models. Results are averaged across sites (a) and per site (b).

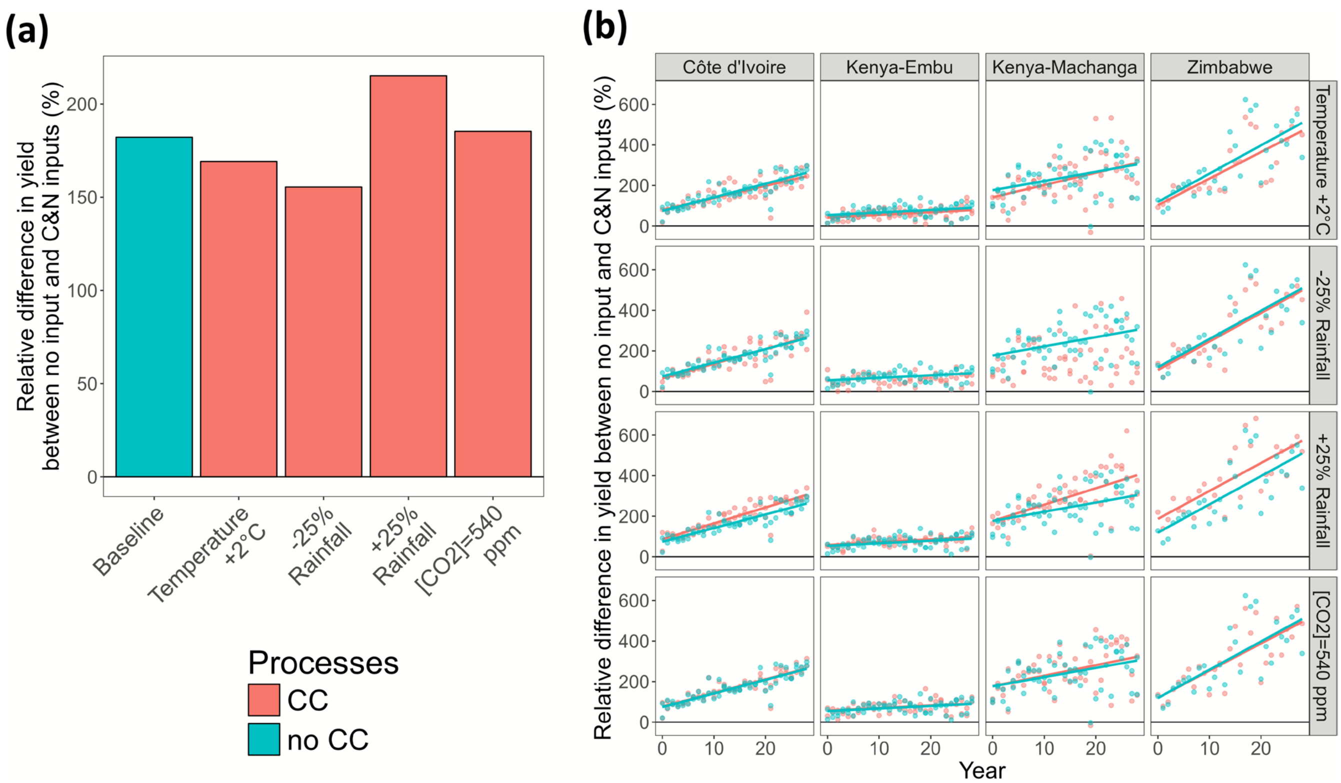

FIGURE 4 | Simulated maize yield change (%) with mineral and organic inputs (80 kg N ha^{-1} season^{-1} and 2 t C ha^{-1}yr^{-1} organic amendment) compared to no fertilizer systems under climate change (CC) or not (no CC). Simulations are averaged across sites (a) and trends over years for the four sites (b). Data are from the median of 15 soil-crop models' simulations. Only significant linear regressions at $p < 0.05$ are displayed. All simulations included long-term soil-crop feedback (continuous model simulation without yearly reinitialization of soil conditions).

mineral and organic inputs, the ensemble median reproduced reasonably well the observed stability of SOC levels over time at Côte d'Ivoire-Gagnoa, but underestimated the SOC decrease at Kenya-Embu and the SOC increases observed at Zimbabwe-Murewa and Kenya-Machanga. Despite not fully capturing the interannual maize yield variability, the ensemble median reproduced well the observed stability of yields over time at all four sites (Figure 2b).

3.2 | Soil Fertility Decline Has a Larger Impact on Maize Yield Than Climate Change Factors

In the maize systems without C and N inputs, the scenario simulations with the model ensemble over the 30-year period suggest that the decline in soil fertility had a larger impact on yield than climate change factors (Figure 3a, high confidence). The average simulated decrease in maize yield due to soil fertility decline was 24% across the four sites, far outweighing the effects of individual climate factors: +2% for warmer temperature (+2°C), −4% for reduced rainfall (−25%), +8% for increased rainfall (+25%), and +6% for higher CO_2 levels (540 ppm; Figure 3a). This greater impact of declining soil fertility over climate change factors was consistently simulated across a wider range of changes in temperature (from +2°C to +6°C), rainfall (from −50% to +50%), and CO_2 levels (from 450 to 720 ppm; Figure S2). The differences in maize yield impacts between the soil fertility decline scenario and the climate change factors scenarios were most pronounced at Côte d'Ivoire-Gagnoa (for all climate change factors, medium confidence; Figure 3b), the site with the highest SOC loss (Figure S3). In contrast, the differences were smallest at Kenya-Embu (medium confidence), the site with the highest initial SOC and soil clay content.

In the scenarios of climate change alone (i.e., without incorporating soil fertility decline in the model simulations, see Methods), simulated maize yields without C and N inputs decreased significantly (−10%) under a +2°C temperature increase at Côte d'Ivoire-Gagnoa, which is the warmest site (Figure 3b, high confidence). In contrast, simulated yields increased under warmer temperatures at Kenya-Embu (Figure 3b, medium confidence), the site with the coolest baseline climate. This was likely due to temperatures approaching the optimum thresholds for maize photosynthesis (Rezaei et al. 2023), as also reported for other high-altitude sites in Kenya (Waha et al. 2013). At Kenya-Machanga and Zimbabwe-Murewa, a +2°C temperature increase had no effect on simulated maize yields, although with low confidence among the models. This uncertainty may arise from differences in how models simulate the processes driving yield reductions (shorter growth period and frequency of heat stresses on for example, photosynthesis, grain number development, and grain filling) or yield increases (when temperatures are nearing optimal thresholds for photosynthesis) (Webber et al. 2022). Changes in simulated maize yield due to increased or reduced rainfall were strongest at the two Kenyan sites (Figure 3b). At Zimbabwe-Murewa, simulated yields remained unchanged under higher rainfall but with low confidence among the models. This uncertainty could come from differences in how models simulate nitrate leaching and waterlogging, which can reduce yields under excessive rainfall (Webber et al. 2022; Kim et al. 2024).

When comparing the combined effect of soil fertility decline and climate change factors on maize yield with the sum of their individual effects (Figure 3), it becomes clear that the models simulated only minor interactive effects, on average and per site. Indirect effects of climate change factors resulted in yield changes of +2% for warmer temperatures, +3% for lower rainfall, −3% for higher rainfall, and −1% for higher CO_2 levels (Figure S4a). These small interactive effects are largely explained by the minimal impacts of climate change factors on SOC dynamics in the model simulations (Figure S3, high confidence).

3.3 | Maize Yield Responses to ISFM Increase Over Time

Under the baseline climate scenario, the combined application of mineral and organic inputs increased average maize yield across the four sites by about 182% over the 30-year simulation period compared to no input use (Figure 4a, high confidence). The simulated yield response decreased slightly in the scenarios of warmer temperatures (170% yield increase) and lower rainfall (156%), but increased under higher rainfall (215%) and higher CO_2 levels (186%; Figure 4a). The yield responses were even more pronounced in scenarios with more severe climate change (e.g., +6°C warming and −50% rainfall resulted in 160% and 95% yield increases, respectively; Figure S5). The relatively small differences in simulated yield responses between the baseline and climate change scenarios can be partly attributed to the simulation of small direct effects of the climate change factors on SOC dynamics, as influenced by input use (−5.5% SOC in the baseline versus −4.5% to −6% in the climate change scenarios), leading to only modest differences in maize growth over time (Figure S6, high confidence).

At all sites, simulated maize yield responses to inputs increased over time both in the baseline climate (medium confidence) and climate change scenarios (except for the reduced rainfall scenario at Kenya-Embu and Kenya-Machanga; Figure 4b). Simulated yield responses to C and N inputs were larger at Côte d'Ivoire-Gagnoa, Zimbabwe-Murewa, and Kenya-Machanga, which are characterized by low initial soil fertility and high SOC loss without fertilization, than at Kenya-Embu, characterized by a high initial SOC content (medium confidence). With mineral and organic inputs, simulated SOC was maintained over time at Kenya-Machanga and Zimbabwe-Murewa, but slightly decreased at Côte d'Ivoire-Gagnoa and Kenya-Embu. Despite the SOC decline, absolute maize yield at Côte d'Ivoire-Gagnoa remained constant, in contrast to the scenario without C and N inputs, where both SOC and yield declined (Figure S7). At Kenya-Embu, the combined use of mineral and organic inputs was simulated to have the lowest yield benefit. It was the only site where simulated maize yields decreased significantly over time with C and N inputs (Figure S7).

4 | Discussion

4.1 | Soil Fertility Decline Outweighs Climate Change Effects on Maize Yield

Our study has important implications for understanding the relative impact of soil fertility and climate change on maize yields in smallholder cropping systems in SSA, which are typically characterized by maize monoculture with low input use. To our knowledge, this is the first study to use calibrated models that reproduce long-term trends in both soil and crop yield dynamics to investigate soil–crop feedbacks, apart from a few comparable modeling studies conducted in temperate conditions (e.g., Smith et al. 2020a, 2020b).

Our model simulations show that if fertilizer inputs remain low, maize yields in SSA are expected to further decline by 20%–50% over the next three decades, as a result of soil nutrient depletion (notably N, as represented in our study). Soil nutrient depletion driven by SOC decline is a major form of soil degradation in SSA (Kihara et al. 2020), reducing crop productivity, biomass, and soil cover (Woomer and Muchena 1996). This, in turn, accelerates other degradation processes like erosion, acidification, and compaction, further reducing soil health (Lal et al. 1997); these processes are not accounted for in the simulations of the study and would require further model improvement. Poor soil health is linked to low crop productivity, food insecurity, and persistent rural poverty across the continent (Sanchez 2002).

Confirming our first hypothesis, climate change is expected to have a relatively smaller impact on maize yields than soil fertility decline, with the contrast in maize yield responses being strongest at sites with greater SOC loss and weakest at those with higher initial SOC and clay content. However, climate change may exacerbate these impacts, with the magnitude and direction of yield changes varying substantially across regions and maize mega-environments in SSA. Our model simulations indicate that rising temperatures and decreasing rainfall are likely to reduce maize yields in areas located in West Africa (Côte d'Ivoire-Gagnoa in our study), whereas increasing temperatures combined with higher rainfall are expected to enhance yields in the highland regions of Eastern Africa (Kenya-Embu in our study). Lowland and dry mid-altitude areas may experience greater relative yield reductions compared to highland and mid-altitude environments (Waha et al. 2013; Dale et al. 2017). Besides, impacts will likely vary within regions, depending on differences in crop management and resource use (e.g., Falconnier et al. 2020; Siatwiinda et al. 2021).

The interaction between climate change and soil fertility decline, defined as the non-additive component of their combined effects on maize yield, was relatively small. This finding is notable because soil organic matter is expected to decrease under warmer climate due to higher mineralization rates (e.g., Nissan et al. 2023), potentially leading to negative soil–crop feedback loops. A stronger influence of climate change on soil fertility might have been expected through its effects on mineralization dynamics, yet this was not evident in our simulations.

4.2 | ISFM as a No-Regret Climate Change Adaptation Option

African governments have endorsed the 2024 Nairobi Declaration on Fertilizer and Soil Health, emphasizing the need to promote agricultural practices that improve soil health, to increase fertilizer use, and to enhance food security across SSA (African Union 2024). In line with findings from long-term field experiments conducted in several countries in SSA (e.g., Adams et al. 2020; Cardinael et al. 2022; Sommer et al. 2018), our model simulations show the potential to maintain SOC or slow its loss and enhance maize productivity through the combined application of mineral fertilizer and organic inputs. The simulations further suggest an increasing yield benefit of mineral and organic inputs over time due to their accumulating positive effects on SOC. Combined application of mineral fertilizer and organic inputs is one of the core principles of ISFM, recognizing that substantial improvements in crop productivity in SSA require addressing both the immediate nutrient needs of crops and the long-term maintenance of soil fertility (Vanlauwe et al. 2010).

The combined application of mineral and organic inputs is often promoted as an effective climate change adaptation strategy in SSA (Nezomba et al. 2018; Gram et al. 2020; Carr et al. 2022; Markos et al. 2023). Our findings support this to a certain extent, showing that their combined use acts as a 'true-adaptation' measure (Lobell 2014) to increased rainfall, with yield benefits becoming more pronounced under climate change in our model simulations. However, the model ensemble also indicates that the combined use of mineral and organic inputs, whilst increasing maize yields, does not mitigate the negative impacts of warmer temperatures and reduced rainfall. Therefore, application of mineral and organic inputs can be seen as a 'no-regret adaptation', beneficial under current conditions, yet insufficient on its own to counteract future climatic stresses (Hallegatte 2009), thereby confirming the second hypothesis of this study. Finally, it is also important to note that the no-regret adaptation benefits of input use under warmer and drier climates could be further enhanced by reducing crop sensitivity to climate extremes, for example through the use of heat- and drought-tolerant cultivars, longer-cycle cultivars, or adjusted sowing dates (Hunt et al. 2019; Hasegawa et al. 2022). These strategies form an integral part of the ISFM approach but were not simulated in our study.

4.3 | Limitations of the Study and Future Research Directions

In most climate change impact studies conducted to date, soil-crop models were reinitialized each year with the same initial soil water, soil N, and SOC levels (e.g., Dale et al. 2017; Falconnier et al. 2020; Waha et al. 2013). As a result, these studies fail to account for the shifts in baseline crop productivity caused by progressive soil fertility loss over time, which our study shows to be of high importance for low-input cropping systems in SSA. Only a few studies, all conducted in temperate regions, have included long-term soil-crop feedback and reported their significant impact on simulated crop yields (Basso et al. 2015, 2018; Smith et al. 2020a). Here we argue that to accurately assess the long-term impacts of climate change and the effectiveness of adaptation strategies, models must be run continuously, incorporating soil-crop feedback mechanisms. This is essential to prevent underestimation of both yield losses due to soil fertility decline and yield gains from fertilizer application.

Our study calls for future research to reduce uncertainties in assessing the impacts of climate change on crop growth and soil fertility, as displayed by the variability of outputs from our modeling ensemble. Although our findings suggest that soil degradation currently exerts a stronger influence on maize yield than climate change in our study locations, they highlight the dual challenges of declining soil fertility and increasing climate threats over the coming decades. Over longer time horizons, climate change effects are expected to become more pronounced and will likely emerge as the predominant driver of crop productivity (Waha et al. 2013; Dale et al. 2017). There are, however, a number of important limitations to consider in our study and in most crop simulation modelling of climate change impacts in general (Corbeels et al. 2018; Kephe et al. 2021; Wang, Jägermeyr, et al. 2024). First, our simulations do not account for the projected increase in weather variability with more frequent extreme events. Extreme temperatures causing heat stress in crops and extreme rainfall leading to drought or flooding are likely to become more common with climate change (Taylor et al. 2017; IPCC 2023). Some regions in SSA already experience crop failure rates of 15% or more, and these are projected to increase significantly in the future (Parkes et al. 2018). Many current crop models do not adequately simulate the effects of extreme weather events and this requires further methodological development (Webber et al. 2022; Kim et al. 2024), coupled with innovative field experiments (for example manipulating rainfall in SSA) to better calibrate these processes (Bouhenache et al. 2025). Second, experiments show that the combined effects of heat and drought stress have a more adverse impact on maize grain yield than the individual stresses alone (Cohen et al. 2021; Bheemanahalli et al. 2022), leading to larger yield penalties and increased yield variability. Models need further development and evaluation to account for these interactions (Webber et al. 2022). Using individual change in temperature, precipitation, and CO_2, our study omits factorial combinations between climate factors (e.g., CO_2×temperature or CO_2×rainfall), which may lead to under- or overestimation of combined effects under real-world conditions. However, this was a deliberate methodological choice, as most current crop–soil models are not yet well equipped to simulate multiple simultaneous stresses reliably, and including them would have introduced additional model uncertainty (Webber et al. 2022). Recent work has further demonstrated the diagnostic value of this approach, showing that modeled yield sensitivities to individual climate factors differ widely across models (Müller et al. 2024).

Third, climate change directly impacts soil fertility. Intensive rainfall events, expected to become more frequent with climate change (Donat et al. 2016; Reed et al. 2022), accelerate soil degradation and erosion (Van Oost et al. 2007; Borrelli et al. 2020). Most soil-crop models either oversimplify or omit soil erosion processes (Raza et al. 2021). Accurately assessing the impact of climate change on soil fertility processes requires incorporating the relationships between intense rainfall and soil erosion into models. Moreover, climate extremes, such as heatwaves, are also expected to have an exacerbated negative impact on SOC (Anjileli et al. 2021), further declining soil fertility (Lugato 2024; Wang, Zhang, et al. 2024). Our model-ensemble simulated relatively small impacts of climate change factors on SOC which likely led to an underestimation of the negative impacts of climate change on maize yield. Finally, climate change may also alter the dynamics of pathogens and pests, important yield-reducing factors not yet captured by current soil-crop models. While addressing these biotic interactions is beyond the scope of this study, it represents a valuable direction for future research and model development (Savary et al. 2018). A strong engagement of the modeling community is now critically required to address the above modeling issues on extreme climate events and conduct climate change impact studies that account for soil fertility changes, thereby enabling more realistic projections of climate change impacts on agriculture in SSA.

5 | Conclusion

Over the long term, soil fertility decline can reduce maize yields more strongly than climate change in SSA, making soil degradation a priority to address alongside climate adaptation efforts. By explicitly accounting for soil fertility changes, our findings support the value of ISFM, through the combined application of organic and mineral inputs, as an effective long-term no-regret adaptation strategy to sustain and increase yields under both current and future climates. We recommend that assessments of long-term climate impacts and adaptation strategies require continuous model simulations that capture soil–crop feedbacks to realistically represent long-term system dynamics. Finally, improving model representation of climate extremes and interacting stressors on crops and soils will be key to avoid underestimating climate change impacts in smallholder farming systems in sub-Saharan Africa.

Author Contributions

Antoine Couëdel: conceptualization, data curation, formal analysis, investigation, methodology, project administration, software, supervision, validation, visualization, writing – original draft, writing – review and editing. **Gatien N. Falconnier:** conceptualization, formal analysis, funding acquisition, investigation, methodology, project administration, resources, supervision, validation, visualization, writing – original draft, writing – review and editing. **Myriam Adam:** conceptualization, investigation, methodology, supervision, validation, visualization, writing – review and editing. **Rémi Cardinael:** conceptualization, funding acquisition, investigation, methodology, resources, supervision, validation, visualization, writing – review and editing. **Johan Six:** conceptualization, data curation, funding acquisition, investigation, methodology, resources, supervision, validation, writing – review and editing. **Moritz Laub:** conceptualization, data curation, formal analysis, investigation, methodology, software, validation, visualization, writing – review and editing. **Alex C. Ruane:** conceptualization, funding acquisition, methodology, project administration, resources, supervision, validation, writing – review and editing. **Kenneth Boote:** conceptualization, investigation, methodology, software, validation, visualization, writing – review and editing. **Eric Justes:** conceptualization, investigation, methodology, software, validation, writing – review and editing. **Ward N. Smith:** conceptualization, investigation, methodology, software, validation, writing – review and editing. **Anthony M. Whitbread:** conceptualization, investigation, methodology, software, validation, writing – review and editing. **François Affholder:** investigation, software, validation, writing – review and editing. **Folorunso M. Akinseye:** investigation, software, validation, writing – review and editing. **Juraj Balkovic:** investigation, software, validation, writing – review and editing. **Bruno Basso:** investigation, software, validation, writing – review and editing. **Arti Bhatia:** investigation, software, validation, writing – review and editing. **Bidisha Chakrabarti:** investigation, software, validation, writing – review and editing. **Regis Chikowo:** data curation, investigation, resources, validation, writing – review and editing. **Mathias Christina:** investigation,

software, validation, writing – review and editing. **Babacar Faye:** investigation, software, validation, writing – review and editing. **Fabien Ferchaud:** investigation, software, validation, writing – review and editing. **Christian Folberth:** investigation, software, validation, writing – review and editing. **Thomas Gaiser:** investigation, software, validation, writing – review and editing. **Marcelo Galdos:** investigation, software, validation, writing – review and editing. **Sebastian Gayler:** investigation, software, validation, writing – review and editing. **Aram Gorooei:** investigation, software, visualization, writing – review and editing. **Brian Grant:** investigation, software, validation, writing – review and editing. **Hervé Guibert:** data curation, investigation, validation, writing – review and editing. **Gerrit Hoogenboom:** investigation, methodology, software, validation, visualization, writing – review and editing. **Bahareh Kamali:** investigation, software, validation, writing – review and editing. **Fidel Maureira:** investigation, software, validation, writing – review and editing. **Fasil Mequanint:** investigation, software, visualization, writing – review and editing. **Claas Nendel:** investigation, software, visualization, writing – review and editing. **Cheryl H. Porter:** investigation, software, validation, writing – review and editing. **Dominique Ripoche:** investigation, software, validation, writing – review and editing. **Leonard Rusinamhodzi:** data curation, investigation, validation, writing – review and editing. **Shikha Sharma:** investigation, software, validation, writing – review and editing. **Upendra Singh:** investigation, software, validation, writing – review and editing. **Amit Srivastava:** investigation, software, validation, writing – review and editing. **Bernard Vanlauwe:** funding acquisition, investigation, methodology, resources, validation, writing – review and editing. **Antoine Versini:** investigation, software, validation, writing – review and editing. **Murilo Vianna:** investigation, software, validation, writing – review and editing. **Heidi Webber:** investigation, software, validation, writing – review and editing. **Tobias Weber:** investigation, software, validation, writing – review and editing. **Congmu Zhang:** investigation, software, validation, writing – review and editing. **Marc Corbeels:** conceptualization, funding acquisition, investigation, methodology, project administration, resources, supervision, validation, visualization, writing – original draft, writing – review and editing.

Affiliations

[1]AIDA, Univ Montpellier, CIRAD, Montpellier, France | [2]CIRAD, UPR Aida, Montpellier, France | [3]CIRAD, UPR Aida, Harare, Zimbabwe | [4]International Maize and Wheat Improvement Centre (CIMMYT)-Zimbabwe, Harare, Zimbabwe | [5]Department of Plant Production Sciences and Technologies, University of Zimbabwe, Harare, Zimbabwe | [6]AGAP Institut, Univ. Montpellier, INRAE, CIRAD, Inst. Agro., Montpellier, France | [7]Faculty of Agriculture and Food Processing, National University of Battambang, Krong Battambang, Battambang Province, Cambodia | [8]Department of Environmental Systems Science, ETH Zurich, Zurich, Switzerland | [9]NASA Goddard Institute for Space Studies, New York, New York, USA | [10]Department of Agricultural and Biological Engineering, University of Florida, Gainesville, Florida, USA | [11]PERSYST Department, Univ Montpellier, CIRAD, Montpellier, France | [12]Ottawa Research and Development Centre, Agriculture and Agri-Food Canada, Ottawa, Ontario, Canada | [13]International Livestock Research Institute, Dar es Salaam, Tanzania | [14]CIRAD, UPR Aida, Maputo, Mozambique | [15]Faculdade de Agronomia e Engenharia Florestal, Universidade Eduardo Mondlane, Maputo, Mozambique | [16]International Crop Research Institute for the Semi-Arid Tropics (ICRISAT), Thiès, Senegal | [17]Centre d'Etude Régional pour l'Amélioration de l'Adaptation à la Sécheresse (CERAAS), Thiès Escale, Senegal | [18]Biodiversity and Natural Resources Program, International Institute for Applied Systems Analysis, Laxenburg, Austria | [19]Department of Earth and Environmental Sciences, Michigan State University, East Lansing, Michigan, USA | [20]ICAR, Indian Agricultural Research Institute, New Delhi, India | [21]Plant, Soil and Microbial Sciences Department, Michigan State University, East Lansing, Michigan, USA | [22]CIRAD, UPR Aida, Saint-Denis, La Réunion, France | [23]Université du Sine Saloum El Hadj Ibrahima Niass (USSEIN), Kaolack, Senegal | [24]BioEcoAgro Joint Research Unit, INRAE, Université de Liège, Université de Lille, Université de Picardie Jules Verne, Barenton-Bugny, France | [25]UMR Eco&Sols, Univ Montpellier, CIRAD, INRAE, IRD, Institut Agro Montpellier, Montpellier, France | [26]Institute of Crop Science and Resource Conservation, University of Bonn, Bonn, Germany | [27]Sustainable Soils & Crops, Rothamsted Research, Harpenden, UK | [28]Biogeophysics, Institute of Soil Science and Land Evaluation, Hohenheim University, Stuttgart, Germany | [29]Institute of Bio- and Geosciences, Agrosphere (IBG-3), Forschungszentrum Jülich GmbH, Jülich, Germany | [30]CIMMYT, Addis Ababa, Ethiopia | [31]Leibniz Centre for Agricultural Landscape Research (ZALF), Müncheberg, Germany | [32]Institute of Biochemistry and Biology, University of Potsdam, Potsdam, Germany | [33]Global Change Research Institute CAS, Brno, Czech Republic | [34]AgroClim, INRAE, Avignon, France | [35]International Institute of Tropical Agriculture, Accra, Ghana | [36]International Fertilizer Development Center (IFDC), Muscle Shoals, Alabama, USA | [37]International Institute of Tropical Agriculture (IITA), Nairobi, Kenya | [38]CIRAD, UPR Recyclage & Risque, Saint-Denis, La Réunion, France | [39]Faculty of Environment and Natural Sciences, Brandenburg University of Technology, Cottbus, Germany | [40]Section of Soil Science and Agrohydrology, University of Kassel, Kassel, Germany | [41]CIRAD, UPR AIDA, Nairobi, Kenya

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available at CIRAD repository: https://doi.org/10.18167/DVN1/EGJXVL.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Figure S1:** Summary of the methods used to calculate the impact of climate change only (A), soil fertility only (B) and the combined impact of climate change and soil fertility on maize yield (C). **Figure S2:** Boxplots of simulated maize yield change (%) by climate change only (CC only) and soil fertility declines only (SF only; i.e., difference between yearly reinitialization of soil conditions vs. continuous model simulation) compared to no climate change and no soil fertility decline scenario. **Figure S3:** Simulated soil organic carbon (SOC) change (%) compared to initial SOC under climate change (CC) or not (no CC). **Figure S4:** Boxplots of simulated maize yield change (%) due to the interaction between climate change (CC) and soil fertility (SF) compared to no climate change and no soil fertility decline scenario (no CC and no SF decline). **Figure S5:** Boxplots of simulated maize yield change (%) across years due to climate change for four sites with organic plus mineral fertilizers (160 kg N ha^{-1} $season^{-1}$ and 4 t C ha^{-1} yr^{-1} organic amendment). **Figure S6:** Simulated soil organic carbon (SOC) change (%) with mineral and organic fertilizers (80 kg N ha^{-1} $season^{-1}$ and 2 t C ha^{-1} yr^{-1} organic amendment) compared to initial SOC under climate change (CC) or not (no CC). **Figure S7:** Simulated maize yield trends (t ha^{-1}) and SOC change (%) for the four sites with organic plus mineral fertilizers (80 kg N ha^{-1} $season^{-1}$ and 2 t C organic amendment ha^{-1} yr^{-1}, in red) or without fertilizer (in blue) under baseline climate. Data are from the median of 15 soil-crop models simulations. All simulations included long-term soil-crop feedback (continuous model simulation without yearly reinitialization of soil conditions). For yields, significant linear regressions at $p < 0.05$ are displayed. **Table S1:** Management practices used in the simulation design for the four sites in Sub-Saharan Africa. DOY = day of the year. **Table S2:** Future climate scenarios from the Phase 6 of the Climate Model Intercomparison Project (CMIP6) for each site using the low (SSP1-2.6) and high (SSP3-7) emission scenarios from the 2040 to 2069 period compared to the 1980–2010 period. Results correspond to the median of 21 climate models.