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To cite this article: Laura Arenas-Calle *et al* 2024 *Environ. Res.: Food Syst.* **1** 021001

IOP Publishing Environ. Res.: Food Syst. 1 (2024) 021001 https://doi.org/10.1088/2976-601X/ad50d9

ENVIRONMENTAL RESEARCH
FOOD SYSTEMS

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RECEIVED
11 April 2024

ACCEPTED FOR PUBLICATION
28 May 2024

PUBLISHED
7 June 2024

LETTER

Agro-technology for climate-smart agriculture and resilience to climate extremes in sub-Saharan Africa

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Keywords: climate smartness, maize, mitigation, climate resilience, irrigation, extremes

Supplementary material for this article is available online

Abstract

Agro-technologies such as irrigation and new crop varieties can reduce climate risk for agricultural production in sub-Sahara Africa (SSA). SSA has the highest maize yield gaps globally, despite its importance as a staple crop in the region. Reducing maize yield gaps is key to tackling food insecurity; however, closing yield gaps might imply an increased greenhouse gas (GHG) emission cost. Climate smart agriculture (CSA) seeks to minimise this cost whilst maximising productivity and resilience. One key element of CSA is resilience to extreme events, although this is rarely examined. Accordingly, we assess the climate smartness of contrasting agro-technology and climate scenarios to assess both resilience to extremes and the overall climate smartness of the scenarios. We use simulations from an existing integrated modelling framework for Malawi, Tanzania, and Zambia, centred on 2050. Four scenarios were examined, defined by combinations of high vs. low agro-technology adoption and high vs. low climate risk (RCP2.6 and RCP8.5). We calculated a climate smartness index (CSI) to the model outputs that quantify the trade-offs between greenhouse gas emissions and agricultural productivity. CSI scores showed that the increase in GHG emissions from improved agro-technology is compensated for the yield benefits. Agro-technology in SSA can therefore benefit the pillars of climate-smart agriculture, namely increased mitigation, adaptation, and productivity. Further, we show that improved maize varieties and irrigation can substantially reduce future yield shocks and enhance resilience to climate change extremes in SSA, pointing to best-bets for agro-technology adoption. Irrigation reduces mid-century yield shocks by 64% (RCP2.6) or 42% (RCP8.5). When combined with improved maize varieties, irrigation removes the majority of yield shocks (90%) in RCP8.5. We therefore conclude that: (i) irrigation has significant potential to increase resilience in SSA; and (ii) investment in strategies to improve crop varieties is critical if the benefits or irrigation are to be fully realized under an RCP8.5 future.

1. Introduction

Climate change is a threat to the agriculture sector in sub-Sahara Africa (SSA), which represents 32% of the gross domestic product in SSA countries and the livelihoods of approximately 65% of the population (Adhikari *et al* 2015). According to the Sixth Assessment Report of IPCC, climate change has reduced agricultural productivity growth in Africa by 34% in the past five decades, being the highest impact among the regions (IPCC 2022). Whilst this large figure no doubt has variability across the continent, depending on the wide range of agro-climatic zones, there is a commonly shared agreement that climate change will have a negative impact on key crops such as maize in East Africa. Several studies have suggested that by the conclusion of the 21st century, countries in East Africa such as Malawi, Tanzania and Zambia may experience a reduction of up to 40% in its maize output (Adhikari *et al* 2015).

Such a trend represents a concern since approximately one-third of the population is already under food insecurity risk and, the prevalence of undernourishment among the SSA population is 21%, resulting in the highest morbidity and mortality rate from malnutrition in the world (Elrys *et al* 2020, Owolade *et al* 2022, Beyene *2023*).

This study is focused on maize, which is the most widely grown staple crop in SSA, consumed by 300 million people and representing approximately 15% of calories intake (Cairns *et al* 2013, Badu-Apraku and Fakorede 2017). More than 90% of maize is produced under rainfed conditions using limited agricultural inputs (Leitner *et al* 2020). Maize productivity in SSA is therefore significantly lower compared to the rest of the world, and highly dependent on rainfall (Cairns *et al* 2013). With model projections estimating an increase in drought conditions and a decrease in precipitation frequency, the high climatic dependency on maize will challenge approximately 44% of the agricultural activity in dryland and semi-dryland in SSA, (Ayanlade *et al* 2022). Increases in maize yield shocks are also likely given increases in climate change extremes (Thornton *et al* 2011).

Closing maize yield gaps, which are higher in SSA than anywhere else globally (Hillocks 2014), is therefore a key priority for SSA, from both adaptation and livelihoods perspectives. Methods for closing yield gaps include improved access to irrigation infrastructure, agronomic inputs, and pest and weed control (Cairns *et al* 2013). Extensification through expansion of maize croplands is a second way of meeting the livelihoods and development challenges of the region.

Sustainable increasing of productivity is a priority in SS African countries, achieving these goals may have multidimensional implications, such as resource conflicts, climate exposure, or environmental impacts, including an increase in greenhouse gas emissions (Kimaro *et al* 2016). Currently, Africa is the smallest contributor to global greenhouse gas (GHG) emissions (3.7%) and faces the highest climate vulnerability (Ritchie and Roser 2019).

As most agriculture in SSA is rainfed and uses low inputs, GHG emissions and yields remain low (Nyiwul 2021). However, the intensification and expansion of agricultural land in sub-Saharan Africa can be expected; hence, studies show consistent projections of how much it might cost in terms of GHG emissions to reduce yield gaps in the region, in particular nitrous oxide (N_2O) emissions (Leitner *et al* 2020, Lemarpe *et al* 2021). According to Omotoso and Omotayo (2024), 64% of total N_2O emissions during 2020 in SSA came from agricultural soils.

Efforts to meet livelihood and development challenges in a sustainable way are often referred to by the term climate smart agriculture (CSA). African countries have been mainstreaming CSA approaches in both agricultural research and policy agendas for some years (Barasa *et al* 2021). The overarching aims of CSA are to simultaneously improve food security, reduce GHG emissions and strengthen climate resilience. CSA-framed initiatives had promoted practices including climate resilient crop varieties, the adoption of technologies to increase water and nutrients use efficiency among others (Zougmoré *et al* 2021). In practice, very few, if any, CSA practices achieve all three objectives simultaneously and to a high degree; trade-offs are inherent in the choice of CSA approaches.

In this context, a signal of climate-smartness in sub-Saharan Africa could be observed through the establishment of increasing trends in improving food production by reducing the yield gap in the region without exacerbating current greenhouse gas emissions or compromising long-term climate vulnerability and sustainability associated with such productivity improvements.

Quantifying these trade-offs is critical if informed policy choices are to be made (see e.g. Challinor *et al* 2022). What level of emissions is justified for a give yield increase? Equivalently, one can ask if the cost of closing the yield gap, in terms of increased emissions, is worth paying. A simple argument can be employed here: that the cost is justified by the age-old and ongoing food security discrepancy between SSA and much of the rest of the globe. The work presented here presents a more nuanced argument, by quantifying the trade-off between emissions and yield increases using data from a previous study (section 2.2) to calculate climate smartness indices (section 2.1) for four countries in SSA: Malawi, Tanzania, and Zambia.

In addition, given the increasing extreme precipitation conditions projected in SSA, we examine the importance of agro technologies for reducing future maize yield shocks, to better understand the role of these technologies for enhancing resilience to climate change extremes.

2. Methods

To evaluate the potential climate smartness of future climate and agro-technological scenarios, a climate smartness index (CSI) was used (section 2.1). CSI was calculated using GHG and yield model projections that were generated by the integrated future estimator for emissions and diets (iFEED) framework (section 2.2).

2.1. Study area

This study focused on three of the sub-Saharan Africa countries targeted within the iFEED framework, Malawi, Tanzania, and Zambia (Jennings *et al* 2022, 2024). *The three subtropical countries* are in Eastern and Southern Africa, *with a hot and wet season from November to April and a dry and cold season during May to October in Zambia and Malawi, and bimodal rainy seasons during March to May and October to December in Tanzania* (World Bank 2021). Agricultural land covers 64% of total land in Malawi, 44% in Tanzania and 32% in Zambia, where maize represent the main staple crop planted between 25% and 44% of croplands of these countries (FAOSTAT 2024). Maize has a high relevance as an economic and staple crop in the region but also faces the largest yield gaps (∼>70%; Gatti *et al* 2023).

2.2. Climate-smartness index (CSI)

CSI (Arenas-Calle *et al* 2019) is a quantitative measure of Climate smartness based on the trade-off between greenhouse gas intensity (GHGI) and water productivity (WP). The CSI works on the premise that cropping systems that produce more grain with lower GHG emissions associated, and lower water requirements are simultaneously contributing to mitigation and adaption goals by reducing their carbon footprint and increasing the resilience of crops under drought-prone and water scarcity scenarios. The extent to which both outcomes occur is considered a signal of climate-smartness, while the opposite outcomes (higher GHG intensity and water use) might reflect a cropping system with low carbon and water efficiency and, in turn, lack climate-smartness.

It was first applied to assess the climate smartness of water-oriented practices in rice systems, comparing Alternate Wetting and Drying to conventional water management across various locations.

The CSI calculation consists of three steps. First, we calculated WP (kg grain m^{-3}) and GHGI (/kg CO_2-eq /kg grain) using yield, direct N_2O emissions and cumulative evapotranspiration. Second, we normalized both WP and GHGI using minimum and maximum references values from previous sub-Saharan Africa studies. Third, we aggregated the normalized WP and GHGI to calculate the index. Details of each step are given below.

Step 1. Calculation WP and GHGI. The WP was calculated by the dividing yield by cumulative evapotranspiration expressed in m^3 (equation (1)); GHGI was calculated by dividing the N_2O emissions per area expressed as CO_2-eq by the yield (equation (2)),

$$\mathrm{WP} = \frac{\mathrm{yield}\ \left(\mathrm{kg\ ha^{-1}}\right)}{\left(\mathrm{CumET}\ (\mathrm{cm}) * 100\,000\ \mathrm{litre\ ha^{-1}}\right) * 0.001\mathrm{m^3}} \quad (1)$$

$$\mathrm{GHGI} = \frac{\mathrm{N_2O}\ \left(\mathrm{kg\ ha^{-1}\,yr^{-1}}\right) * 265}{\mathrm{yield}\ \left(\mathrm{kg\ ha^{-1}}\right)}. \quad (2)$$

Step 2. Calculation of normalized WP and GHGI. We reviewed 12 published in Africa, China, North America, and Europe dated from 2007 to 2020 studies that reported seasonal N_2O emissions and maize grain yield to estimate reference GHGI values, resulting in 54 data records; and 31 WP studies, resulting in 464 data points. The studies of WP were selected just for Sub-Sahara African countries covering from 2005 to 2020 (see supplementary material_1), to ensure relevance. Based on the reference values found in the literature review, the minimum and maximum values found for WP were 0.04 and 2.0 kg m^{-3} respectively. The GHGI values were normalized using minimum and maximum values 0 and 1.1 kg CO_2-eq/kg grain, which were derived from data across the globe,

$$\mathrm{GHGI}_{(N)} = \frac{\mathrm{GHGI} - 0}{1.1 - 0} \quad (3)$$

$$\mathrm{WP}_{(N)} = \frac{\mathrm{WP} - 0.04}{2.0 - 0.04}. \quad (4)$$

Step 3. Calculation of CSI. CSI is simply the difference between the normalized values of GHGI and WP (equation (5)). CSI has a scale between −1 and 1. Negative values indicate relatively high GHGI and relatively low WP, i.e. a lack of climate smartness. Positive values indicate the converse. Thus, the more negative the index, the less climate smart the system, while more positive represents increasing climate smartness,

$$\mathrm{CSI} = \mathrm{WP}_{(N)} - \mathrm{GHGI}_{(N)}. \quad (5)$$

2.3. Scenarios

We used the iFEED simulations of Jennings *et al* (2022) for Malawi, Tanzania, and Zambia for the calculation of CSI. The baseline period of these iFEED simulations was 1990–2010, and the projection period was 2040–2060. A total of 18 climate models were used to drive the yield and emissions models. All yield and

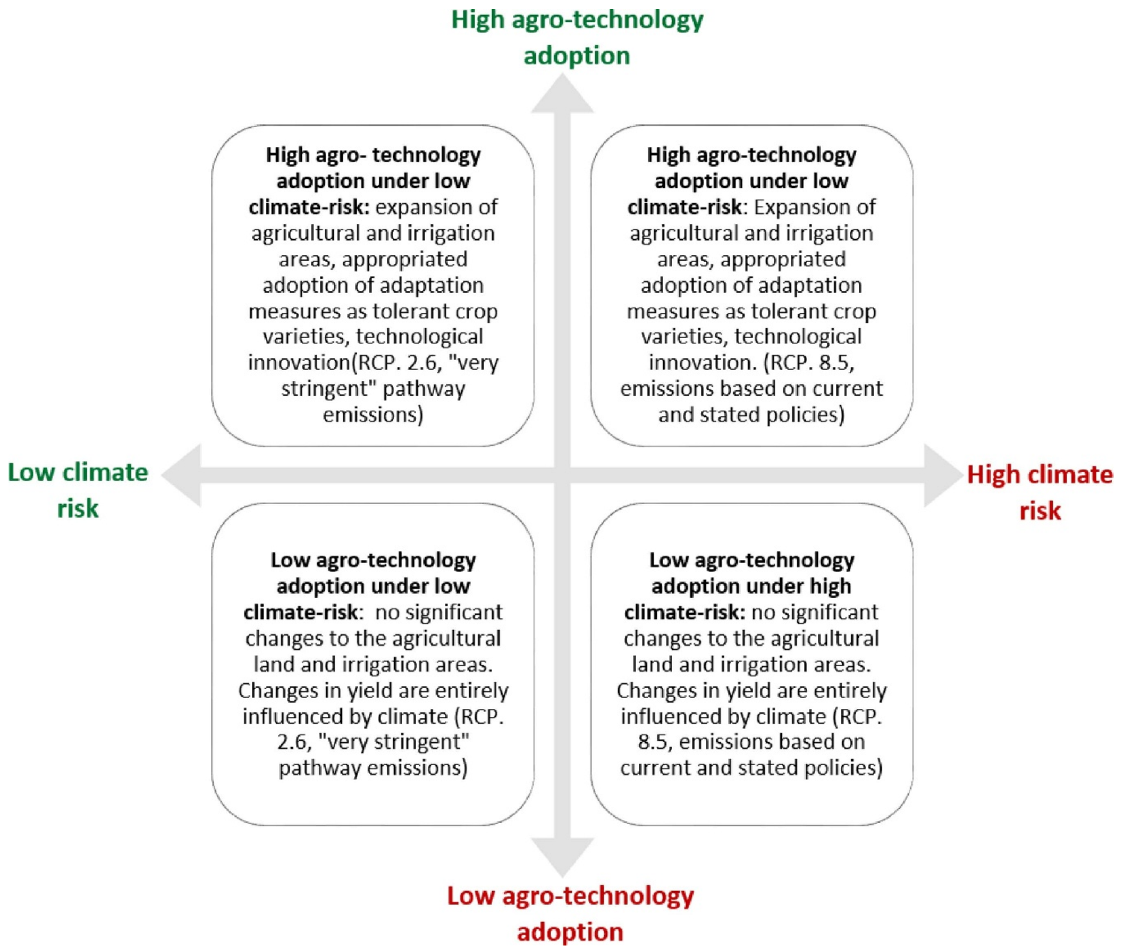

Figure 1. Description of the four scenarios of technological and climate scenarios (representative concentration pathways, RCP) from the integrated future estimator for emissions and diets (iFEED) integrated assessment framework. Reproduced from Jennings *et al* (2022). CC BY 4.0.

emissions simulations were conducted at 0.5° resolution. The iFEED data used for CSI calculation were maize yields, cumulative evapotranspiration, and N_2O emissions per hectare.

The maize yield model used for the iFEED simulations was the General Large Area Model for annual crops (GLAM; Challinor *et al* 2004). Simulations of N_2O emissions came from the estimating carbon in organic soils—sequestration and emissions model (Smith *et al* 2010).

The iFEED framework produced maize yields and GHG emissions simulations for four scenarios, defined by a combination of two climate scenarios (RCP 2.6 and 8.5) and two scenarios of agro-technology adoption and land crop expansion (figure 1). RCP 2.6 describes an optimistic and ambitious climate pathway characterized by a continuous removal of atmospheric CO_2 driving net negative emissions after 2100, representing relatively low climate risk. RCP 8.5 describes a concentration pathway with very high atmospheric CO_2 concentrations without any mitigation efforts to reduce GHG emissions, which represents a relatively high climate risk scenario (IPCC 2014).

The agro-technological scenarios in iFEED were co-designed with stakeholders (Jennings *et al* 2022). The high agro-technology scenarios represent a high degree of transformation to agricultural systems, typically assuming cropland expansion, and various agricultural technological innovations. Crop yield increases are simulated to match historical increases in the region—specifically, taking the highest yield trend from 1960 to 2010 from the three countries for every crop. Future cropland allocation is designed to maximize food production by optimizing the highest producing combination of crops on available land (i.e. placing the highest yielding crops available on available land). New crop varieties are simulated that counteract the effect of warming on growing season reduction. Lastly, irrigation is expanded to all arable crop areas to alleviate water stress. The low agro-technology scenarios represent more pessimistic futures where none of these significant changes to crop management and varieties occur.

The four scenarios for each of the three countries are labelled as follows: high technology (HT) adoption under low climate risk (HT_RCP_2.6); HT adoption under high climate risk (HT_RCP_8.5); low technology

(LT) adoption under Low climate risk (LT_RCP_2.6), and LT adoption under high climate risk (LT_RCP_8.5). To know more about the design of iFEED framework and highlight results of the project visit https://ifeed.leeds.ac.uk.

2.4. Crop yield shock calculations

The iFEED simulations described in section 2.2 were used to analyse the importance of specific agro-technological innovations included in the iFEED scenarios for reducing future maize yield shocks. Crop yield shocks (or crop failures) can, in general, be said to occur when yields are below the value needed for a farmer to break even on costs. The threshold for crop yield shock is therefore econometric, and it is impossible to calculate without detailed economic analysis. Yield thresholds chosen using yield statistics serve as a proxy for econometric thresholds. In this analysis, we defined the threshold as equal to baseline mean yield minus 1.5 standard deviations. This translates into 1139–1538 kg ha^{-1}, which is 48%–56% of mean yields (ranges across countries). We calculated yield shock rates in the baseline (1990–2010) and future (2040–2060) periods, defined as the number of years in each 21 year period that are below the threshold for yield shock.

We explored the importance of agro technology for reducing future yield shock rates using three methods that between them address both water and temperature stress: (i) use of irrigation for reducing future yield shocks by comparing future rainfed yield shock rates to futures where irrigation is sufficient to alleviate any water stress. (ii) Changes in both planting dates and crop varieties. Varieties are restricted to those available in the baseline simulation. (iii) Accounting for warming impacts on the time between planting and maturity (Challinor *et al* 2014) by simulating hypothetical cultivars that compensate for any reductions in the duration of the growing season. All three of these methods follow (Jennings *et al* 2022).

3. Results and discussion

3.1. Climate-smartness index (CSI)

Figure 2 presents the baseline and future projection values of CSI for the three countries. All baseline assessments show low climate smartness, with mean CSI values of −0.32 (Malawi), −0.27 (Tanzania) and −0.19 (Zambia). All LT simulations are like the baseline, albeit with a small increase, mediated through a small reduction of GHGI (supplementary material: figure SI.1). The lack of climate smartness in baseline and LT scenarios is due to the very low productivity of maize, which resulted in highly inefficient water use and high GHG emission intensity. Whilst farmers in SSA contribute the lowest emissions per unit area, extremely low productivity makes GHG intensities relatively high (Anuga *et al* 2020).

HT scenarios, by contrast, showed largely positive CSI, with climate (i.e. RCP8.5 vs RCP2.6) showing little difference in CSI values. These results therefore show that high agro technology, rather than climate change, is the major driver of CSI in these scenarios. This agrees with several studies that identified agro-technological development as the most important strategy to reduce yield gaps in SSA. According to van Dijk *et al* (2017), 44% of the maize yield gap in Tanzania can be reduced by the implementation of advanced technologies. Similar analysis developed for Zambia revealed that technical efficiency contributed 33% of the yield gap at national level (Gatti *et al* 2023).

The high CSI values associated with HT futures are evident in the significant reduction in GHGI (supplementary material: figure SI.1) and an approximate tripling of WP (supplementary material: figure SI.2). Other model-generated evidence indicates that high-input agricultural management, combined with expanded irrigation infrastructure, could reduce water use intensity of staple crops such as maize by up to 64% (Giordano *et al* 2023).

The higher yields associated with increased agro-technology drive both components of CSI—i.e. both water use, and greenhouse gases reduction are used more efficiently under HT futures. In all countries the iFEED simulations showed that HT scenarios would increase maize yields up to 3 times (between 207% and 224%) compared to baseline productivity levels. These maize yield improvements represent an increase of 2.9–3.0 tonnes ha^{-1} in Malawi; 3.2–3.3 tonnes ha^{-1} in Tanzania and 3.5–3.7 tonnes ha^{-1} in Zambia for both RCPs scenarios.

The HT scenario in this study included the adoption of improved varieties which has been shown to reduce yield gaps in the study region. Katengeza and Holden (2021) reported that drought tolerant maize seeds increased yields by 44% in six districts in Malawi. Similar findings are reported in Zambia where the adoption of drought tolerant varieties increase maize yield by 15%, as well as the stability of yields (Amondo *et al* 2019).

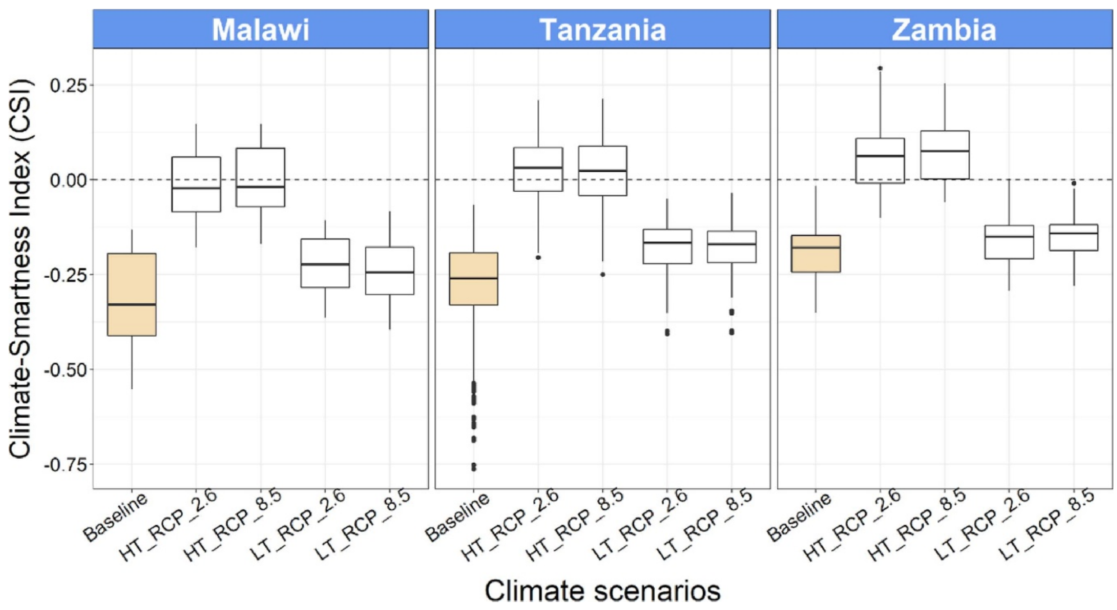

Figure 2. Boxplots of CSI at country-level for the baseline and future agro-technological (high technology: HT and low technology: LT) and climate (high climate risk: RCP_8.5 and low climate risk: RCP_2.6).

Unsurprisingly, GHG emissions increase in HT scenarios, with N_2O emissions increasing by between 21% and 47% under both RCPs, with emissions either reducing or unchanged in LT scenarios. Similar results are shown by van Loon *et al* (2019), who developed an analysis of the impact of intensification and cropland expansion on GHG emissions for 10 countries in SSA (Tanzania and Zambia included), reporting that meeting cereal demand can cause an increase by up to 50% of GHG emissions by 2050. Moreover, Leitner *et al* (2020), reported that closing the maize yield gap by 75% in SSA would increase N_2O more than six times, doubling the overall contribution of N_2O emissions from the region.

The yield increase in HT scenarios surpassed the GHG increases, resulting in less GHG emissions per unit of grain. An increase of agricultural efficiency in SSA has been suggested as a sustainable pathway to meet future food security without obstructing mitigation efforts, that nevertheless represent a less pressing priority in low-income regions such as rural areas in SSA (Steenwerth *et al* 2014).

3.2. Crop yield shocks and resilience through irrigation

Figure 3 shows the impacts of climate change on maize yield shocks for RCP2.6 and RCP8.5 for Zambia for both rainfed and irrigated futures. Baseline yield shock rates are on average 9% (1.9 out of 21 years). Future rainfed yield shock rates rise to 16% for RCP2.6, and 19% for RCP8.5 (3.3 and 3.9 out of 21 years, respectively).

The benefits of irrigation in Zambia are present for both RCP2.6 (64% reduction in yield shock rates) and RCP8.5 (42% reduction). The reduction is greater in RCP2.6 since rising temperatures are responsible for a greater proportion of yield shocks with RCP8.5. Irrigation shows similar, although smaller, benefits in Malawi and Tanzania (supplementary material: figures SI.3 to SI.6).

Considering that current total area under irrigation is around 10% of the potential irrigated land (estimated in 2.75 million of hectares) in Zambia, increasing the coverage of irrigation would substantially contribute to improving climate resilient food security (Mango *et al* 2018).

Figure 4 shows the impacts of climate change on maize yield shocks when assuming new crop varieties are developed in future that compensate for some of the impacts of these increased temperatures by mid-century. With improved maize varieties, irrigation removes most yield shocks: 87% and 90% for RCP2.6 and RCP8.5, respectively.

Upgrading current agro-technology is a necessity for climate-smart agro-systems in Malawi, Tanzania, and Zambia; however, countries might need to overcome major implementation challenges on the way. Several studies comment on the importance of extension services for providing timely and relevant information that encourages the adoption of advance agricultural technologies such as improved varieties (Beyene and Kassie 2015, Manda *et al* 2018). From an economic perspective, the access to infrastructure and affordable agricultural inputs (e.g. improved seeds, fertilizers, and irrigation) needs to be addressed. The

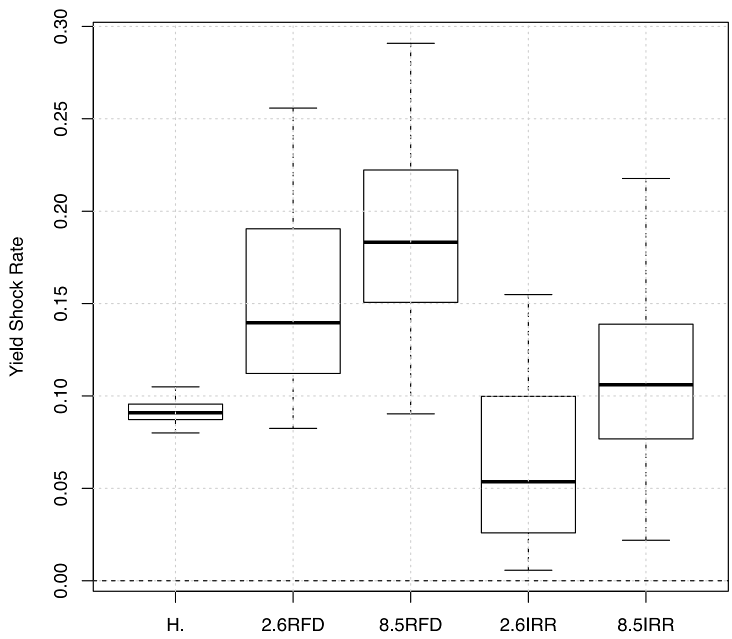

Figure 3. Maize yield shock rates in Zambia assuming the same crop varieties by mid-century. Boxplots show the range across climate models. H. = historical period yield shock rates (the proportion of years from 1990 to 2010 that are below the yield shock threshold). 2.6RFD = the proportion of years from 2050 to 2060 for rainfed RCP2.6 simulations that are below the yield shock threshold. 8.5RFD = the proportion of years from 2050 to 2060 for rainfed RCP8.5 simulations that are below the yield shock threshold. 2.6IRR = the proportion of years from 2050 to 2060 for irrigated RCP2.6 simulations that are below the yield shock threshold. 8.5IRR = the proportion of years from 2050 to 2060 for irrigated RCP8.5 simulations that are below the yield shock threshold.

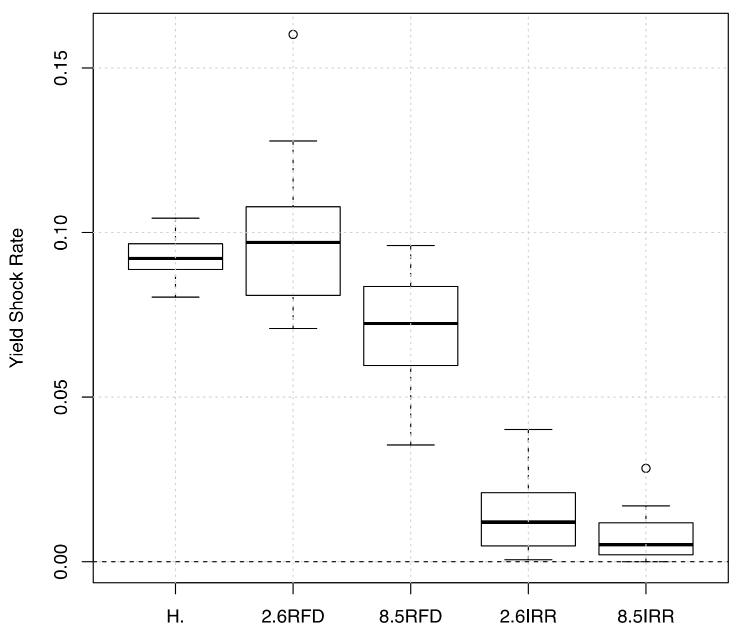

Figure 4. Maize yield shock rates in Zambia assuming new crop varieties that compensate for accelerated crop development by mid-century. Boxplots show the range across climate models. H. = historical period yield shock rates (the proportion of years from 1990 to 2010 that are below the yield shock threshold). 2.6RFD = the proportion of years from 2050 to 2060 for rainfed RCP2.6 simulations that are below the yield shock threshold. 8.5RFD = the proportion of years from 2050 to 2060 for rainfed RCP8.5 simulations that are below the yield shock threshold. 2.6IRR = the proportion of years from 2050 to 2060 for irrigated RCP2.6 simulations that are below the yield shock threshold. 8.5IRR = the proportion of years from 2050 to 2060 for irrigated RCP8.5 simulations that are below the yield shock threshold.

implementation financial mechanisms that support long-term investment or the implementation of agricultural subsidies can also be better targeted to low-income farmers (Kim *et al* 2021).

The enormous gap between outcomes in LT and HT reflects the harm of decades of stagnation in farming development in SSA but also highlights the untapped potential of agriculture in the region. The intensification and expansion of the agricultural area, coupled with the massive adoption of modern agricultural innovations, would give SSA countries the potential to increase productivity and achieve food self-sufficiency (Wudil *et al* 2022).

4. Conclusions

The yield increases outlined above, together with largely positive CSI values, suggest that HT futures can be largely climate-smart, despite their inherent increase in emissions. Thus, changes in agriculture should be consistent enough to deliver benefits in all or some of mitigation, adaptation, and productivity objectives, while avoiding any potential Drawback that affects the sustainability of such transformation. By using an objective measure (i.e., CSI) to show that productivity gains outweigh GHG emissions increases, our results support the suggestion made elsewhere (see e.g. Steenwerth *et al* 2014, Jennings *et al* 2024) that GHG emission reduction is not the highest priority in low-income regions such as rural areas in SSA.

The results also show that agro-technologies can improve resilience to maize yield shocks, since irrigation reduced the likelihood of future yield shocks in both climate scenarios. However, for the benefits of irrigation to be fully realised in the higher emissions scenario, as well as in the longer-term, maize varieties will need to keep pace with warming (Challinor *et al* 2016).

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

Acknowledgments

This work was carried out with support from the CGIAR Initiative on Climate Resilience, ClimBeR. We would like to thank all funders who supported this research through their contributions to the CGIAR Trust Fund: www.cgiar.org/funders/.

Conflict of interest

The authors declare no competing interests.

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