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Have crops already reached peak suitability: assessing global climatic suitability decreases for crop cultivation

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Abstract

Crop yield and the availability of arable land are impacted by climate change, leading to effects on global patterns of production and trading. To gain more precise insights in how future climate change might lead to redistributing productive crop areas, we developed a new method to assess climatic crop suitability, which combines temperature and precipitation suitability through water balance calculations. We applied the method to evaluate the effects of climate change under two climatic scenarios (SSP2-4.5 and SSP5-8.5), using an ensemble of five GCMs, for nine crops (Arabica coffee, cassava, common beans, common wheat, maize, plantain, rice, sorghum and sugarcane) for four periods of time: past (1995-2014), present day (2015-2034), medium term (2040-2059), long term (2080-2099. We observed that the fraction of area with optimal suitability might be on a downward trajectory for coffee, cassava, beans, wheat and plantain, and could be halved by the end of the century. The tropics and sub-tropics are negatively affected for all crops, while mid-latitudes see large decreases in suitability for beans, wheat and maize. Global patterns show that suitability decreases at local levels (in about 30% of the global area for bean and wheat) are not compensated by increases in suitability elsewhere (in about 19% of the area for bean and wheat). As relocation and expansion of production areas are constrained by available arable land, other strategies might be considered to improve suitability, such as irrigation, which would increase the area of optimal suitability from 5-25% to 40-50% of total arable land for the nine crops. Drainage could improve the optimal suitability area fivefold for maize and sorghum, while shading increases suitability for coffee (by up to 20% in both cases). The increased risk of food supply shortages led by climatic suitability loss may trigger increased deforestation if adaptation measures are not implemented.

1. Introduction

Crop yield is strongly related to climatic conditions – a third of global crop yield variability is explained by climate variations (Ray et al., 2015). Anthropogenic climate change has negative and positive impacts on yield trend in most regions of the world, with mostly negative effects of further climate change (Ray et al., 2019). Moreover, crop production could also be affected by the alteration of currently suitable areas due to climate change. It might affect food sovereignty in some countries, imbalance international trade flows of commodities, and undermine food security through price increases and spikes.

As anthropogenic changes in average and extreme climatic conditions become increasingly pronounced (IPCC, 2022) there is a growing need for making data more available for agricultural decision-making. Information about climatic trends, extreme event frequency, and their magnitude and effect on crop growth is essential for farmers to anticipate potential loss in production and adapt. Suitability assessments can be used, as a proxy, to estimate the potential impacts of climate change on crop production. Assessing suitability can support farmers in the selection of the most adapted crop mix for their farms, depending on the climate they are facing. Derived from the FAO definition of land suitability, climatic suitability refers to the possibility for local climatic conditions to meet the requirements of a given crop (FAO, 1976).

Climatic suitability is widely studied, in most cases for limited geographical areas at country level (e.g., in Angola (Rosenstock et al., 2018)) or regional level (e.g., West Africa (Egbebiyi et al., 2019), Africa and South Asia (Ramirez-Villegas et al., 2013) and for specific crops (e.g., for sorghum (Ramirez-Villegas et al., 2013), quinoa (Geerts et al., 2006)). In most cases the impacts of climate change, according to several warming scenarios resulting from SSP-RCP combinations simulated through various GCMs, are studied (Chemura et al., 2020; Egbebiyi et al., 2019; Ramirez-Villegas et al., 2013; Rosenstock et al., 2018).

A few articles compute suitability by estimating the effects of different climatic hazards on simulated yield, according to soil limitations and terrain constraints (Fischer et al., 2021). Many articles use FAO's Ecocrop database to define the temperature and precipitation conditions suitable for each crop (Egbebiyi et al., 2019; Ramirez-Villegas et al., 2013; Rosenstock et al., 2018) while a few rely on regression or machine learning approaches to identify suitable climatic conditions based on yield time series (e.g., Caubel et al., 2015; Chemura et al., 2020; Holzkämper et al., 2013). Suitability is a widely known and used indicator, however it suffers from major caveats: a low suitability score does not differentiate between above or below optimal temperature or precipitation.

Moreover, the hypothesis used to combine both temperature and precipitation in a single suitability value remains unproven (i.e., in terms of functional form and parametrization): it relies on a simplistic multiplication of temperature and precipitation suitability indexes (Peter et al., 2020; Ramirez-Villegas et al., 2013).

In this article, following FAO definition of suitability, we propose a novel approach to evaluate the extent to which crops water requirements can be met according to climatic conditions. To do so, we compute water balances as the difference between cumulated rainfall and evapotranspiration. By incorporating evapotranspiration into climate suitability assessments, our approach aims to provide a better account of the effects of combined temperature and precipitation variations in climatic conditions on crop growth. This method allows a tradeoff between realistic agronomic processes (here crop water consumption) while avoiding adding uncertainties associated with including too many mechanisms. In this sense, the model we built can be considered as a first stage of a mechanistic model and its output can be used as an estimate to assess the effects of temperature and precipitation change on crops. As this model only uses as inputs climatic variables commonly available in many climatic models, we can compute climatic suitability for many crops at a global level.

By implementing this new approach, this article aims at answering the following questions: (i) How would climatic suitability evolve with climate change? (ii) What are the implications of climate change for shifts in global production areas? (iii) Are these shifts substantially affected by (stylised) adaptation strategies?

To achieve this goal the present article studies (i) the temporal evolution of climatic suitability between four time periods: past, present day, medium term and long term, in two climate emissions scenarios SSP5-8.5 and SSP2-4.5, (ii) the geographical distribution of suitable areas and (iii) the effects of stylised adaptation measures (i.e., irrigation, drainage, shading) on climatic suitability.

2. Material and method

2.1. Suitability modelling

Climatic suitability is a crop-specific indicator referring to the climatological conditions necessary for a crop to germinate, grow and mature. The definition of precipitation or temperature suitability refers to a specified range of climate variables in which crop yields can be expected to be highest (all other factors remaining equal). The common definition of climatic suitability often relies on the multiplication of temperature and precipitation suitability; however, there is limited physical evidence supporting the benefits of this approach (Section SA1).

To better represent realistic agronomic processes, we further modify the common approach by recognizing the physical relationship between precipitation and temperature through the climatic water balance (CWB) (Bandoc & Prăvălie, 2015). This approach allows the incorporation of the available water for the crop into the suitability assessment. The CWB, as a difference between precipitation and evapotranspiration, which depends on temperature, allows the combination of temperature and precipitation into a single physical and agronomic quantity (Figure 1). The reference evapotranspiration is used for all crops and is measured from the Hargreaves & Samani (1985) equation (Section SA2). The calculations performed for the climatic suitability do not intend to replace an agronomic model. With this method, the objective is to estimate a range of optimal water balance, where the given crop attains the highest yield at the global level. If one were to multiply by a crop-specific coefficient (i.e., Kc, Jensen, 1968) similar in each location, this would alter the ranges of optimal water balance, without affecting the areas where more or less optimal conditions are found. Further alterations would be found if the crop coefficient were to be multiplied by a stress coefficient. This would however fall into the category of agronomic modelling, outside the range of the present study.

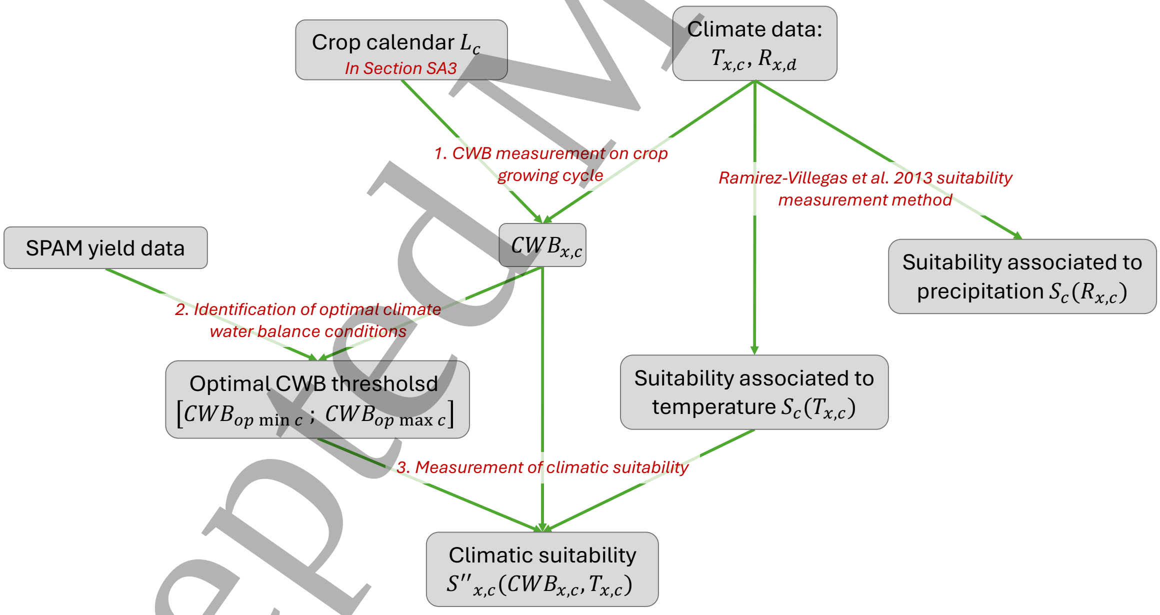

Figure 1. Schematic representation of the different steps followed to compute climatic suitability. CWB refers to climatic water balance.

2.1.1 CWB measurement on crop growing cycle

The climatic water balance $CWB_{x,d}$ in point x, for day d, is computed by subtracting the evaporated water of a reference crop from the total rainfall:

$$CWB_{x,d}(R_{x,d}, T_{x,d}) = R_{x,d} - ET_{0\,x,d}(Tmin_{x,d}, Tmax_{x,d}, R_{a\,x,d}) \qquad (1)$$

Where,

$R_{x,d}$, precipitation amount in point x, for day d. All crops are considered as rainfed (i.e., no artificial water supply through irrigation).

$ET_{0\,x,d}$, reference evapotranspiration in point x, for day d. Computed from Hargreaves & Samani (1985) (Section SA2), as a function of the maximum and minimum temperatures ($Tmin_{x,d}$ and $Tmax_{x,d}$) and radiation $R_{a\,x,d}$ which is itself a function of the latitude and the time of the year (calculated for each day) (Section SA3).

The climate dataset used for the historical period is W5E5 re-analysis data, and for the projections an ensemble of five GCMs (General Circulation Models) of the ISIMIP database (Hempel et al., 2013) in two SSP-RCP scenarios, SSP5-8.5 and SSP2-4.5, at daily scale. The ISIMIP3b protocol selected 5 "primary" models from the full CMIP6 ensemble. The five models were selected because they are structurally independent in terms of their ocean and atmosphere model components, their process representation is fair to good, and the models are good representatives of the whole CMIP6 ensemble, as they include three models with low climate sensitivity and two models with high climate sensitivity (Lange, 2021). The ISIMIP3b data is extremely useful for climate impact analysis, because of the bias correction method applied (Lange, 2021) and because many publications on agricultural climate impacts have used the same GCM input data (e.g., Jägermeyr et al., 2021). SSP2-4.5 was selected to reflect a global warming trajectory consistent with current global climate policies (about 2.7°C by end of century (Climate Action Tracker, 2023; Intergovernmental Panel on Climate Change (IPCC), 2021)), while SSP5-8.5 was selected to represent a risk perspective of much higher warming (Intergovernmental Panel on Climate Change (IPCC), 2021).

Subsequently, the water balance over the growing cycle was computed by adding the CWB values measured for each day of the cycle. The crop optimal planting time is defined mathematically, for each GCM, by finding the period for which the crop will grow in the most optimal conditions (Section SA3).

$$CWB_{x,c} = \sum_{d=1}^{L_c} CWB_{x,d}(R_{x,d}, T_{x,d}) \qquad (2)$$

Where,

L_c, the length of the crop growing cycle of crop c (in days) (Table S2 and Figure S3)

2.1.2. Identification of optimal climate water balance conditions

To obtain the optimal range of CWB, $[CWB_{op\,\min c}\,; CWB_{op\,\max c}]$ specific for each crop, the following approach is implemented. For the same level of external inputs, such as fertilizers, at the global level, it is possible to assume that the divergences in rainfed crop yields result from water balance conditions and overall climatic suitability. Thus, for every crop analysed, the approach consists in identifying locations across the globe where yield exceeds the 90th percentile of yield distribution according to the available SPAM data for 2000, 2005, and 2010[1], for rainfed and high-input crop (You et al., 2014).

The CWB distribution was calculated for each GCM separately, spanning the period from 1995 to 2014. Then, the optimal range of CWB of each crop c is established through historical agricultural performance: $CWB_{op\min c}$ and $CWB_{op\max c}$ corresponding to the first quartile (for $CWB_{op\min c}$) and to the third quartile (for $CWB_{op\max c}$) of the distribution of CWB measured in areas where yields were considered as close to potential yield (i.e., exceeding the 90th percentile of yield distribution) (Figures S4-S5).

2.1.3. Measurement of climatic suitability

The critical thresholds $CWB_{op\min c}$ and $CWB_{op\max c}$ indicate the range of optimal water balance conditions (Table S3 and Figures S6-S7) and thus allow measuring the associated suitability (Equation 3). As CWB can either be positive or negative, we first center the suitability function around zero by adding or removing half of the water balance optimal range (ϕ_c), so that the two sides of the suitability function are symmetrical.

$$S'_c(CWB_{x,c}) = \begin{cases} \frac{\overline{CWB}_{op\min c}}{\overline{CWB}_{x,c}} \; if \; CWB_{x,c} < CWB_{op\min c} \\ 1 \; if \; CWB_{x,c} \in \left[CWB_{op\min c}\,;\, CWB_{op\max c}\right] \\ \frac{\overline{CWB}_{op\max c}}{\overline{CWB}_{x,c}} \; if \; CWB_{x,c} > CWB_{op\max c} \end{cases}$$

Where, (3)

$$\overline{CWB}_{op\min c} = CWB_{op\min c} + \phi_c$$

$$\overline{CWB}_{op\max c} = CWB_{op\max c} + \phi_c$$

$$\overline{CWB}_{x,c} = CWB_{x,c} + \phi_c$$

$$\phi_c = -\frac{CWB_{op\min c} + CWB_{op\max c}}{2}$$

To ensure that the climatic suitability variable coupling precipitation and temperature is also respecting the thresholds of temperature suitability for the crop, which also influence the growth cycle (Zhu et al., 2021), it is defined as follow:

$$S''_{x,c}(CWB_{x,c}, T_{x,c}) = S'_c(CWB_{x,c}) * S_c(T_{x,c}) \qquad (4)$$

Where,

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[1] This paper and methodology were prepared before the release of SPAM for year 2020.

$S_c(T_{x,c})$, the suitability of crop c associated with the average temperature on the crop growing cycle and computed from Ramirez-Villegas et al. 2013.

For both cold and warm locations, this approach avoids indicating an area as climatically suitable while CWB is adequate but the temperature is outside the suitability range (Figure S8).

2.2. Adaptation technologies simulations

We tested the effects of the implementation of several adaptation measures on climatic suitability: irrigation, drainage, and shading. To do so we used stylized representations of each adaptation measure. For simplicity, we measured suitability with these adaptation practices everywhere on available arable land. It should be noted that, in practice, certain external constraints limit their implementation (e.g., limited amount of water available for irrigation, and drainage regulations) and these technologies might already be widely used in some areas (e.g., irrigation in India).

For irrigation, we considered that optimal suitability is achieved even when the water balance is below $CWB_{op\min c}$ thanks to irrigated water supply allowing the achieving of $CWB_{op\min c}$. The suitability function becomes:

$$S'_c(CWB_{x,c}) = \begin{cases} 1 \; if \; CWB_{x,c} < CWB_{op\max c} \\ \frac{\overline{CWB}_{op\max c}}{\overline{CWB}_{x,c}} \; if \; CWB_{x,c} > CWB_{op\max c} \end{cases} \tag{5}$$

We represented drainage by considering that optimal suitability includes when the water balance is above $CWB_{op\max c}$ as water excess is removed by drains. Thus, the suitability function is modified as follows:

$$S'_c(CWB_{x,c}) = \begin{cases} \frac{\overline{CWB}_{op\min c}}{\overline{CWB}_{x,c}} \; if \; CWB_{x,c} < CWB_{op\min c} \\ 1 \; if \; CWB_{x,c} > CWB_{op\min c} \end{cases} \tag{6}$$

We represented shading practices (through net shading or agroforestry practices) through a decrease in air temperature due to lower radiation. We measured from a literature review, a mean temperature reduction due to shading of 4.5% (Section SA4), leading to a slower increase in suitability when temperature was in theory too high. The climatic suitability function becomes:

$$S''_{x,c}(CWB_{x,c}, T_{x,c}) = S'_c(CWB_{x,c}) * \; S_c(0.955 * T_{x,c}) \tag{7}$$

2.3. Suitability data postprocessing

We computed climatic suitability for 36 crops (data available at: https://abc-map.fao.org). We display the results for nine crops under three categories: staple crops (maize, rice, common wheat); cash crops (common beans – progressively moving from subsistence to market-oriented cash crops – sugarcane, coffee); and subsistence crops (cassava, sorghum, plantain). These crops represent more than 50% of the calories annually consumed in the world (FAO, 2022).

To assess the evolution of the suitability index across four time periods, past (1995-2014), present day (2015-2034), medium term (2040-2059), and long term (2080-2099), we aggregate the suitability index by taking the median of the 20-year periods for each GCM, the median of the five GCMs is then used for the temporal aggregation.

We exclude non-arable land (water and ice bodies, and urban areas) by using a mask derived from the land cover data ESA CCI, at a 300-meter resolution (ESA, 2017). We further define available arable land as the remaining arable land after removal of forested and/or protected areas (i.e., unavailable arable land), using the same land cover dataset for forests and the World Database on Protected Areas dataset (UNEP-WCMC, 2024) for protected areas. We aggregate the remaining available arable land to 0.13x0.13 degrees pixels, to fit the suitability index data by averaging all pixels of each land cover type. We removed all pixels where the sum of non-arable, protected or forested area was more than 20% of the surface. These areas were considered as constant in time.

We discretized the climatic suitability index into five classes for an easier understanding of the figures: (i) 0, not suitable, (ii) >0 – 0.39, limited suitability, (iii) 0.40 – 0.79, marginal suitability, (iv) 0.80 - <1, moderate suitability and (v) 1, optimal suitability (Section SA5). The results were computed and processed using the packages “terra” and “ggplot2” from R version 4.3.1.

3. Results

1. Suitable areas for half of the selected crops are already decreasing or will decrease soon because of climate change

For five out of the nine crops studied, at global level, a peak in fraction of available arable land where suitability is optimal has already been observed (Figure 2). In both climate scenarios, suitable area is on a downward trajectory for coffee, beans, cassava, plantain and wheat. For maize and possibly rice, the peak of optimal suitability area is projected to occur later in the 21st century, especially in the SSP5-8.5 scenario, meaning that there could be a near-term increase in suitable areas followed by a decline. We do not project a peak and decline in suitable areas for sorghum and sugarcane in either scenario. This could be due to the high tolerance to high temperature for these two crops compared to the others: the optimal temperature range for sorghum is from 27 °C to 35 °C and for sugarcane from 24°C to 37°C, while the optimal ranges for the others are from below 20°C to 33°C (Table S1).

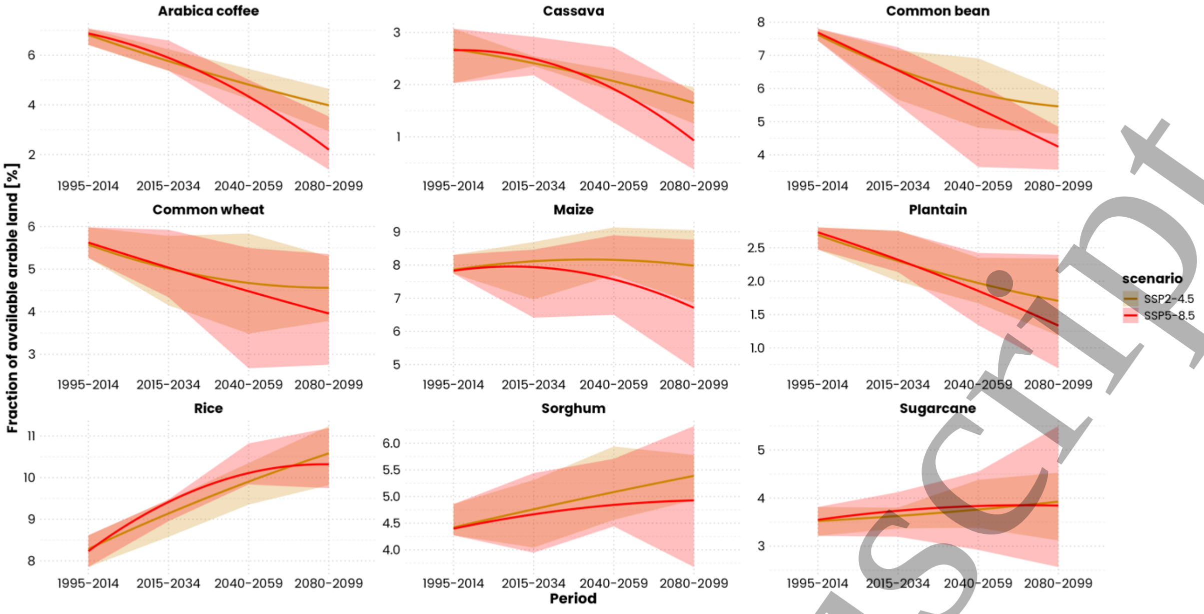

Figure 2. Evolution of optimal suitability areas proportion from 1994 to 2100 for arabica coffee, cassava, common bean, common wheat, maize, plantain, rice, sorghum and sugarcane for five GCMs in the SSP2-4.5 and SSP5-8.5 scenarios, at global level, on available arable land. Plain lines describe the trends followed in each scenario.

The decline for crops that have already reached peak area is relatively consistent across climate scenarios. As expected, the scenario SSP5-8.5 of rapid and extreme global warming shows a faster decrease in the fraction of available arable land projected as having optimal suitability than the SSP2-4.5 scenario. This might be due to the higher average temperature and to the lower cumulated precipitation projected in most of the tropical and temperate areas (Figures S9-14). In addition, the high warming scenario leads to a substantially smaller increase in optimal suitable areas for sorghum than the SSP2-4.5 scenario, most likely due to a higher loss of optimal suitable areas in the Guinean zone and in the Southern Amazonian zone because of higher temperatures under scenario SSP5-8.5 than under scenario SSP2-4.5 (Figures S13-S14). The high warming scenario also leads to a possible peak in the long term for both sorghum and rice.

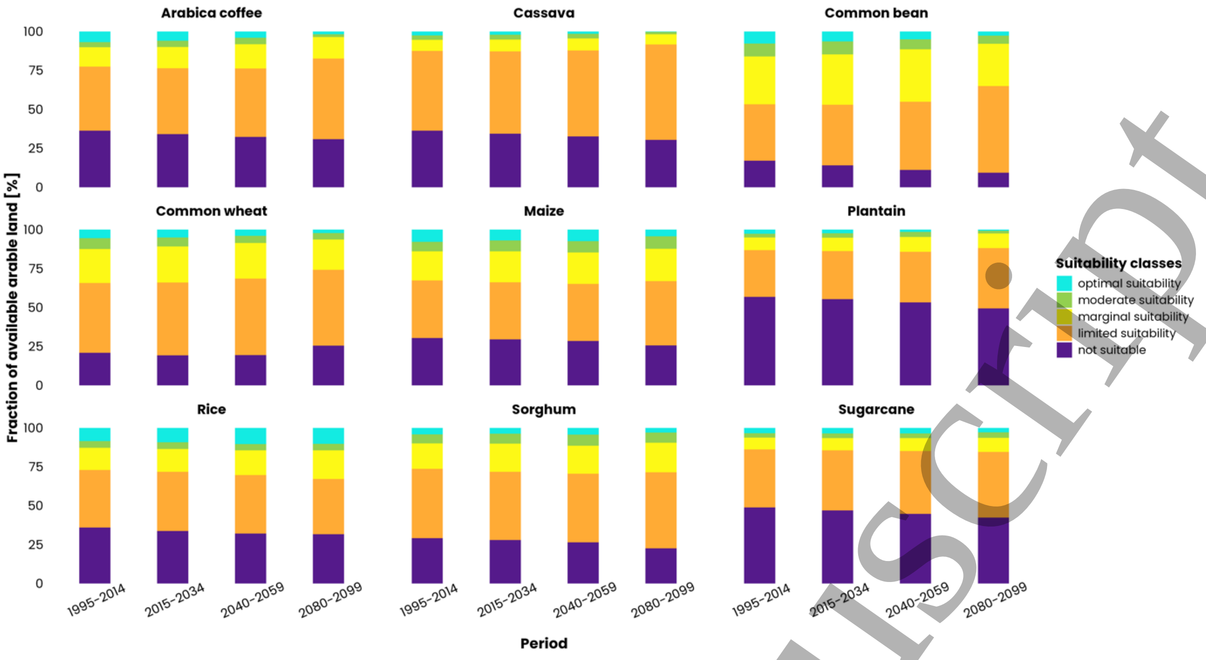

Figure 3. Suitability classes in percentage of available arable land for the 1994-2014, 2015-2034, 2040-2059 and 2080-2099 periods, for Arabica coffee, cassava, common beans, common wheat, maize, plantain, rice, sorghum and sugarcane in the SSP5-8.5 scenario (see Figure S15 for scenario SSP2-4.5).

Figure 3 shows that, for some crops (i.e., coffee, sugarcane, cassava, rice, sorghum and plantain), the marginal to optimal suitable areas proportion is narrow (between 10% and 30% of global area). These crops can grow in restricted areas with narrow temperature and rainfall optimal conditions: they are specialist. On the contrary, wheat, maize, and beans show a large dispersion of the areas where their suitability is marginal to optimal (between 30 and 50% of global area). These crops can grow in a large array of environments, including a large range of temperature and rainfall conditions, meaning that these crops are more generalists. For beans, sorghum, plantain and maize, the optimal and not suitable areas proportions are decreasing, while the proportion of areas with intermediate suitability is increasing. For these crops, at global level, the expected suitability decreases could be because a lower proportion of areas with optimal suitability is compensated by the increased proportion of lower suitability areas. For the other crops, not suitable areas could increase while areas with optimal suitability could decrease. Under scenario SSP2-4.5, the fraction of available arable land is decreasing slower than under the high warming scenario (Figure S15).

However, as the reduction of suitable areas in one place could be compensated by an increase in another point of the world, a study of the suitability class repartition evolution is provided at grid cell level (Table 1).

Beans and wheat may experience shifts in climatic suitability classes across a significant number of grid cells, with beans showing changes of 21.4% in the medium term and 50.4% in the long term and wheat of 23.4% and 52.1% respectively. Coffee, beans, cassava and wheat are expected to have a larger fraction of grid cells experiencing a decrease in climatic suitability than grid cells benefiting from an increase in suitability: in the long term, 14.6% for coffee compared to 6.3%, 31.5% for bean compared to 19.0%, 8.5% for cassava compared to 5.1%, 32.8% for wheat compared to 19.3%. In contrast, more areas with increasing suitability than those with decreasing suitability could be observed in both the medium and long term, for rice, sorghum and sugarcane.

Table 1. Fraction of arable land grid cells where suitability is expected to decrease ("Decreases of 2+ classes" and "Decreases of 1 class") or increase ("Increases in 2+ classes" and "Increases in 1 class") in the medium term (difference of suitability between the periods 2015-2034 and 2040-2059) and in the long term (difference of suitability between the periods 2015-2034 and 2080-2099) for nine crops, for the median of the ensemble in the SSP5-8.5 scenario. ACOF refers to arabica coffee, BEAN to common beans, CASS to cassava, CWHE to common wheat, MAIZ to maize, PLNT to plantain, RICE to rice, SORG to sorghum and SUGC to sugarcane. Crops in bold letters indicate that the proportion of grid cells where suitability decreases is higher than that where suitability increases in the long term.

	Medium term					**Long term**				
	Decreases of 2+ classes	Decreases of 1 class	Stable in class	Increases of 1 class	Increases of 2+ classes	Decreases of 2+ classes	Decreases of 1 class	Stable in class	Increases of 1 class	Increases of 2+ classes
ACOF	0,2%	6,1%	89,1%	4,5%	0,0%	4,8%	9,8%	79,1%	5,8%	0,5%
BEAN	0,2%	12,2%	78,7%	8,9%	0,0%	6,3%	25,2%	49,6%	17,7%	1,3%
CASS	0,2%	3,2%	93,4%	3,2%	0,0%	2,1%	6,4%	86,4%	5,0%	0,1%
CWHE	0,4%	14,0%	73,6%	8,9%	0,0%	8,4%	24,4%	47,9%	18,1%	1,3%
MAIZ	0,1%	4,8%	86,9%	7,9%	0,3%	2,1%	11,2%	73,8%	11,7%	1,2%
PLNT	0,0%	2,7%	93,3%	4,0%	0,0%	1,8%	6,3%	82,6%	8,7%	0,6%
RICE	0,0%	1,5%	91,2%	7,2%	0,0%	0,5%	4,3%	82,1%	12,4%	0,7%
SORG	0,1%	3,2%	89,0%	7,6%	0,2%	1,4%	7,6%	76,8%	13,6%	0,6%
SUGC	0,1%	1,8%	93,4%	4,7%	0,0%	0,6%	3,6%	86,3%	9,0%	0,4%

While the optimal suitability is projected to decrease at global level (Figure 2), at long term, between 5.1% (for cassava) to 19.4% (for wheat) of available arable land areas are projected to experience an increase in climatic suitability leading to more areas experiencing an improvement in their suitability conditions.

Facing this optimal suitability decrease due to climate change, three strategies can be intended to mitigate the associated risk of production decrease: (i) relocation of the production areas, (ii) expansion of production areas and (iii) adaptation through implementation of new measures.

2. Expansion or relocation of cropping areas might be constrained by available land

Modifications of cropping areas, through relocation towards areas that could show higher suitability or through expansion to compensate for the loss of suitability and thus of productivity, might be constrained by available arable land and national borders. Other land uses can impede relocation or expansion. Some areas, such as urban areas are not planned to decrease and cultivation into these areas, at least in open fields, is not a feasible solution. Whereas protected and/or forested areas could possibly be cultivated this is not a desirable solution, for example given the expected associated loss of biodiversity and ecosystem services including carbon sequestration.

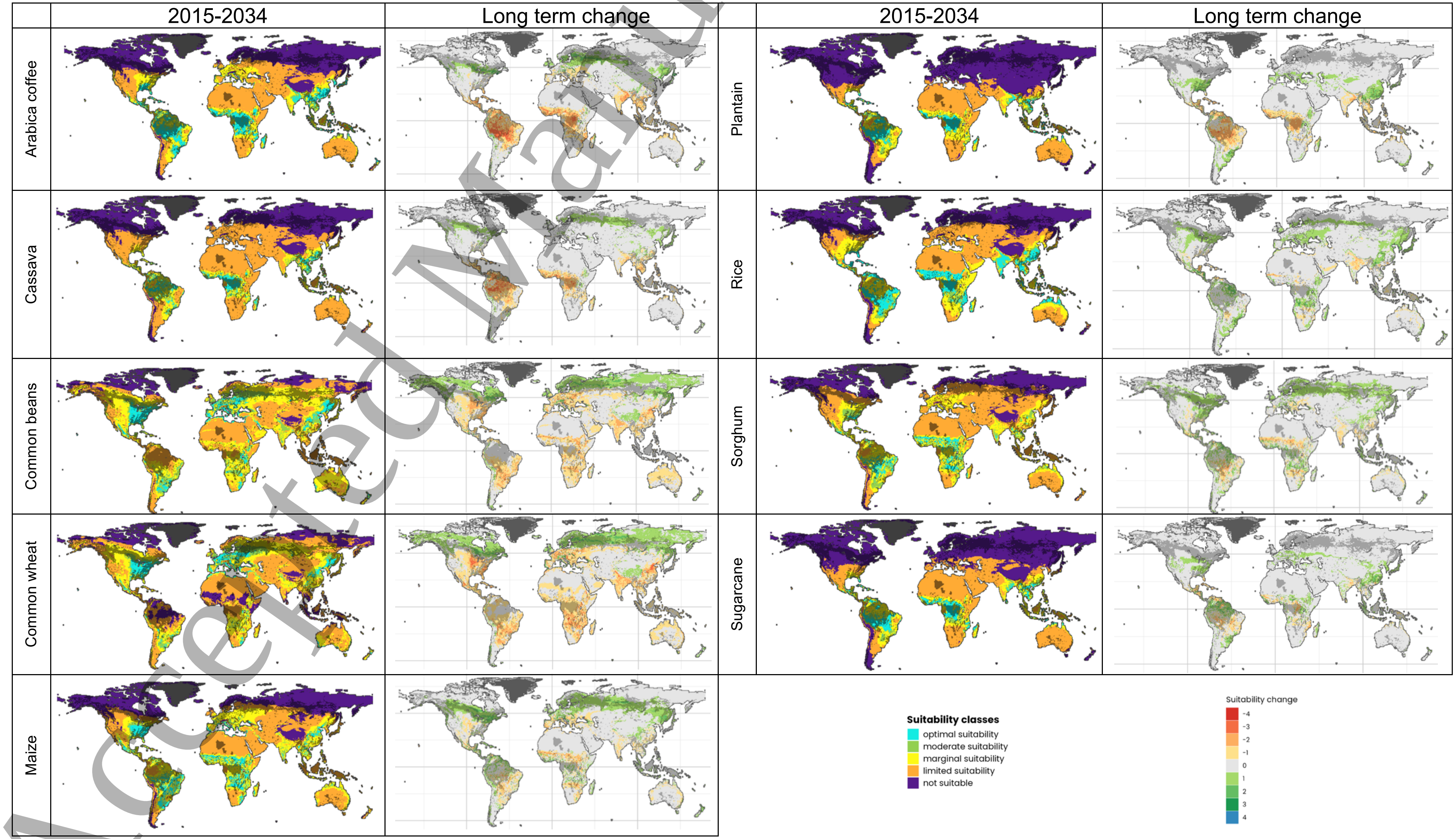

Figure 4. Suitability maps of Arabica coffee, cassava, common beans, common wheat, maize, plantain, rice, sorghum and sugarcane for present day (2015-2034), and long-term changes (i.e. classes differences between 2015-2034 and 2080-2099) in the SSP5-8.5 scenario. All results are for the median of the ensemble. Dark grey areas refer to not arable land and light grey areas refers to not available arable land.

Figure 4 shows that the specialist crops are suitable in a narrow area: the tropical and equatorial zones while the generalist crops can have a marginal to optimal suitability almost at all latitudes, except in arid or polar zones. For coffee, it can be observed that the areas with the highest suitability might turn into marginal to limited suitability areas especially around the Congo Basin, Amazonia and Southeast Asia by the end of the century, leading to the decrease of the fraction of available arable land with optimal suitability that we observe in Figures 2 and 3. Hence, the main green coffee producers (i.e., Brazil, Vietnam, Indonesia (FAO, 2017)) could experience a significant decrease in areas most suitable for coffee production, potentially leading to a decrease in production (assuming constant productivity). The expansion of coffee production towards new areas could be constrained by the availability of arable land for example in the Amazonian Forest and the Congo Basin due to forested and / or protected areas.

The same phenomenon is observed for cassava and plantain. However, these two crops are subsistence crops and a potentially lower willingness to compensate for reduced productivity might be observed.

For bean, wheat and maize, while there are projected suitability decreases in Sub-Saharan Africa and in South America, there are projected increases towards higher latitudes, especially in the Scandinavian, North American and Taiga boreal forests. However, even with an increase in suitability across these areas, they remain far below optimal suitability and do not compensate for the greater loss of suitability elsewhere, as is clear from Figures 2 and 3. In addition, even if boreal forests might also migrate northward with climate change it could take a lot of time, and deforestation is not desirable.

Rice suitability is predicted to increase in South America, especially in Brazil, and in the African tropical area while it could decrease in Northern India in the long term. With India currently the world’s largest rice exporter by far, the lower productivity impeded by the suitability decrease could lead to significant changes of trade flows at the global level. For the largest rice importing countries from India, particularly countries in Sub-Saharan Africa and the Middle East, this could necessitate a structural shift in trade partners.

No major changes in sorghum and sugarcane suitability areas repartition are projected even though the sorghum suitability may slightly decrease in Brazil, most likely due to the projected decrease in cumulated precipitation in this area (Figure S13).

The most suitable crop in an area could change with climate change, leading to changes in production patterns at local level with, for example, rice facing a slower decrease in suitability than maize in the Sudanian and Guinean zones.

3. Adaptation would vastly improve suitability

Adaptation measures such as irrigation, drainage and shading could reduce the suitability decrease, due to climatic conditions moving outside optimal suitability ranges. In areas where rainfall amount is insufficient to meet crop water needs, irrigation can be a solution – assuming it is technically and environmentally feasible. In flood prone areas exposed to excess precipitation, drainage may increase suitability. In areas where the temperature exceeds the optimal threshold, shading measures such as agroforestry or net shading can improve suitability.

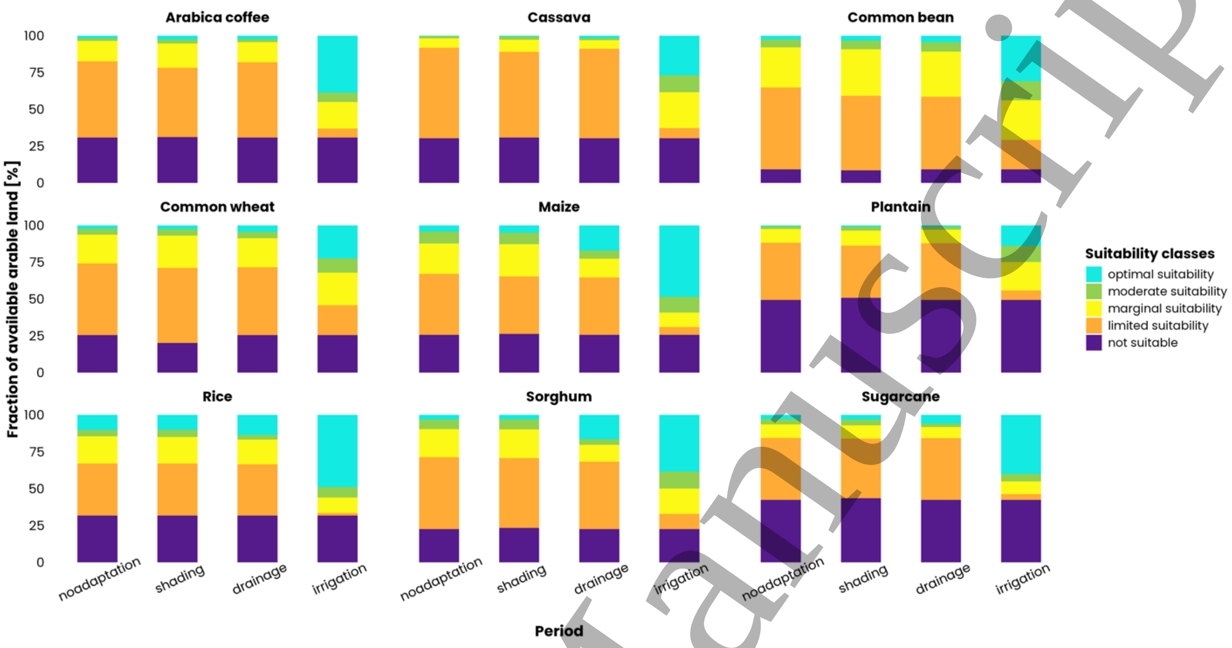

Figure 5. Suitability classes with shading, drainage and irrigation, and without adaptation technologies implemented for the nine crops in the long term (i.e., 2080-2099) in the SSP5-8.5 scenario. All results are for the median of the ensemble.

Irrigation could lead to a major improvement in suitability for all crops. As a response to the implementation of irrigation, the fraction of arable land with optimal suitability reaches almost 50% for coffee, common bean, maize and rice and about 40% of arable land for the other crops (Figure 5). Shading and drainage also lead to an increase in optimal suitability, although to a lesser extent than with irrigation. Shading has more impact on coffee than drainage whereas for the other crops, the opposite is observed, showing the greater tolerance of coffee to excess precipitation. Drainage might substantially improve 9suitability for maize and sorghum, from around 5% to around 20% of the arable area having an optimal suitability. This is linked to the CWB optimal ranges that are lower for these two crops than for the others (Table S3). The effects of adaptations are similar at medium-term (Figure S25).

4. Discussion

In this paper, we evaluated the evolution of climatic suitability for nine crops at a global level, considering two climate change scenarios. The use of the water balance allows us to consider physical and agronomic mechanisms such as evapotranspiration, combining both temperature and precipitation into climatic suitability.

The data used, and the choices made to compute climatic suitability can have effects on the robustness of the results obtained. While the GCMs used in this paper for climate-data input were selected based on how well they represent the full CMIP6 GCM ensemble (Jägermeyr et al., 2021) it has been noted for the previous generation of GCMs selected for ISIMIP were not fully representative of the full CMIP5 ensemble for all geographical regions (McSweeney & Jones, 2016). This has not been tested for the current selection of CMIP6 GCMs, but the situation may be similar and therefore would limit how representative our results are compared to applying the full ensemble. We only focus on precipitation and temperature, while suitability also depends on other factors such as soil quality and moisture, CO_2 levels, windspeed, and photosynthetically active radiation for long crop growing cycle. Hargreaves equation was selected for two reasons (1) as it requires less variables than the Penman-Monteith equation with a reasonable agreement between these two methods (Droogers & Allen, 2002) and (2) to keep the consistency of variables between the current suitability approach, that relies on temperature and precipitation, and this new method. In further research, it would be possible to combine climatic suitability with other suitability indicators to assess a suitability index encompassing more dimensions.

To determine the location of the most suitable areas and thus optimal climatic conditions, we relied on the hypothesis that these areas correspond to the areas where achieved yields are the highest. Considering very high percentiles (90th and above) ensures that the selected areas are effectively the locations with the highest yield – independently from the uncertainties associated with the data. Moreover, it has been verified that, in these areas, achieved yields are close to potential yield, and thus, reflect climatic suitability (Figures S4-S5).

Because of a lack of available data on water limited yield for all those crops, at global level, it was not possible to calibrate the functional form of the suitability associated to CWB outside the optimal range. For this reason, the intermediate suitability classes may give qualitative information rather than quantitative and this should be considered when reading the results.

To represent the competition with other land uses, we removed urban, forested, protected areas and areas covered by water or ice. This mask is considered as constant in time while some of these areas are deemed to evolve such as the expansion of urban areas, reduction of water bodies, migration of forests toward more suitable climate, or new protected areas. However, considering it as constant in time allows simplification and reduces the risk of adding uncertainties to our results. As this mask includes all forested areas it can lead to the removal of tree-shaded cultivated areas (e.g., coffee in Brazil or Indonesia). However, no land cover dataset was available at global level to allow excluding only not cultivated forests.

When aggregating 20 years to represent the present day, medium-term and long-term periods, we computed the median of the suitability. The suitability median is computed as the median GCM, over the 20 years of each time horizon, for each grid cell. In the present article, the focus was on the overall suitability evolution at global level. The temporal aggregation also limits the ability to test for the synchronicity of shocks in suitability at the global level. The variability could be the topic of future research.

When adding stylized adaptation measures in our model, we do not consider areas where these have already been implemented (e.g., shading for coffee in Brazil, irrigation for wheat in USA). Thus, the avoided suitability loss due to the adaptation implementation we obtain might be overestimated. However, no data is available to identify, at the same resolution as in our model, the areas where drainage, irrigation or shading is used and specify for which crop. Furthermore, other adaptation practices such as using crop cultivars that are drought resistant, or that have shorter growing cycles, could be tested in future research.

Our results agree with those found in Ray et al., (2019) showing increased wheat yield and suitability in eastern Russia. While our results show a decrease in wheat climatic suitability in several of the main production areas, especially China, Europe and USA, Jägermeyr et al. (2021) showed a weak increase in yield by the end of the century in the SSP5-8.5 scenario. Two reasons could explain this difference: (1) climatic suitability does not consider increases in atmospheric CO_2 concentrations, which could compensate the negative effects of sub-optimal precipitation and/or temperature conditions, and (2) climate suitability accounts for negative effects of excess precipitation, while most crop models do not. Moreover, Jägermeyr et al. (2021) predict a decrease in global rice productivity in the long term which could be partially correlated to the reaching of a threshold in optimal suitability fraction of available arable land that we observe under the climatic scenario SSP5-8.5.

Chemura et al. (2024) computed climatic suitability of major food crops across Africa also using EcoCrop and calibrating it using MAPSPAM for some crops (i.e., rice, wheat, cassava, yam, plantain and banana). By 2050, under climatic scenario SSP5-8.5, they found similar results for maize, rice and wheat. For cassava, while very similar results were found for the current period, the suitability for the 2050s is higher than those presented in this study which could be explained by the selection of GCMs. They found different results for sorghum with a very low suitability in the Sudanian zone and very different results for beans with high suitability in the Congo Basin and the Guinean zone, which might be explained by the integration of soil pH in the suitability computation. The FAO GAEZ v4 model (Fischer et al., 2021), which measures suitability according to climatic and soil conditions, shows similar areas with high to very high suitability as obtained with our method, for maize (FAO & IIASA, 2021a) and for wheat (FAO & IIASA, 2021b).

Mumo et al. (2021) found that sorghum suitable areas were expected to increase by 2050, leading to yield gain because of its lower vulnerability to climate change than other crops (Hossain et al., 2022), which aligns with our results.

Our findings align with previous studies indicating a decline in climatic suitability for coffee and beans. Bunn et al. (2015) projected a decrease in suitability for coffee in major production areas by 2050, a trend echoed in Mozambique by 2040 unless agroforestry practices are adopted (Cassamo et al., 2023). Similarly, for beans, Manners et al. (2020) predicted a decrease in suitability in France, by 2050.

5. Conclusion

For most crops studied in this paper, it is shown that the optimal suitable areas at global level has either already peaked or is projected to decrease during the 21st century. For these crops, the suitability decreases observed in some areas are not compensated by increases in other areas. This decrease in suitable areas could induce a decrease in global production due to a reduction in areas offering optimal growing conditions. To maintain and increase production to meet global demand for food, strategies must be implemented either by focusing on areas or on productivity. The relocation or expansion of production areas could be constrained by available land and national borders. Adaptation practices such as irrigation, drainage and shading, could impede the decline in productivity by stabilizing or by improving climatic suitability. The effects of suitability changes could generate imbalances in international trade which could lead to food supply shortages in low-income countries highly reliant on imports, due to higher global prices (as happened with the 2008 food prices crisis).

These changes in suitability could lead to local loss of productivity, pushing countries to adapt and inducing changes to global food trade balances. Maintaining current and meeting expected increased demand of these key crops, could be at risk unless adaptation measures are introduced. Decreasing suitability in countries already facing low productivity could also further exacerbate the encroachment of agricultural land in forested and / or protected areas, leading in turn to higher emissions and decreased environmental services provided at the local level. To compensate for the expected loss of productivity due to decreasing climatic suitability the overall productivity must improve faster than in the past and faster than the decrease in suitability. International collaboration is, thus, needed to anticipate the effects of climate suitability changes on food trade balances and to prevent rapid deforestation. Governments in countries whose income is partly derived from cash crops (e.g., coffee) should anticipate the effects of climate change on their production through incentives to implement adaptation measures (e.g., subsidies) as large agribusinesses could progressively turn to other suppliers to avoid shortages. The main findings of this paper should also enlighten country-level decision-makers considering food security and sovereignty and inform budgetary discussions on the needs for adaptation. As much as adaptation could contribute to the reduction of suitability losses over the planet, it is essential to accelerate the reduction of emissions in line with the Paris Agreement. Without faster and steeper emission reductions, even adaptation could fall short in reducing suitability losses risking global food security and sovereignty issues for countries.

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[Conflict of interest]

The authors declare no conflict of interest.

[Authors contributions]

FB and VM developed the methodology, VM prepared the data and computed results, MD analyzed the results and prepared the manuscript, MS supervised and reviewed the methodology and results. All reviewed the manuscript.

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