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Current and future cropland suitability for cereal production across the rainfed agricultural landscapes of Ethiopia

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ABSTRACT

One of the major challenges posed by climate change in agriculture is the alteration in cropland suitability. This alteration has serious consequences for food security and economic stability at global, regional, and local scales, especially in smallholder and rainfed agricultural systems like in Ethiopia. A comprehensive understanding of the current state of croplands and future changes under warming temperatures and increasing rainfall uncertainty is critical for national climate adaptation planning. Here, we evaluated cropland suitability (CLS) for four major cereal crops (teff, maize, sorghum, and wheat), under both current and future climates across the rainfed agriculture (RFA) landscapes of Ethiopia. We utilized a novel suitability modelling approach that establishes functional relationships between crop yield, and climatic factors (rainfall, temperature, and solar radiation) and soil factors (texture, pH, and organic carbon). Furthermore, we analyzed the relative influences of the growing season rainfall and temperature on the changes in CLS. The results show that 54 % of the RFA area has a suitability index of 0.6 or higher (moderately to highly suitable) for teff and that 51 %, 63 %, and 29 % of the grid cells are suitable for maize, sorghum, and wheat crops, respectively. The suitable agroecologies of the four crops will likely undergo altitudinal shifts and areal contraction, with magnitudes of the changes depending on the emission scenarios. Under the SSP2–4.5, the suitable areas are projected to decrease by 25 % for teff, 7 % for maize, 10 % for sorghum, and 16 % for wheat in the 2080s. In semi-arid and hyper-humid climates, CLS is sensitive to changes in the growing season rainfall, whereas in low and high elevation regions, it is temperature-sensitive. In light of our results, we argue that adaptation actions tailored to agroecological conditions and topographic locations are vitally necessary to mitigate the long-term impacts of climate change on Ethiopia's rainfed agriculture.

1. Introduction

One of the major impacts of climate change is the disturbance it imposes on ecosystem functioning, which ultimately leads to redistribution and even irreversible losses of species (Pecl et al., 2017; Schmidhuber & Tubiello, 2007). The influences on crop species threaten human society as they may reduce global food production and affect the livelihoods of people involved in agriculture (Godfray et al., 2010). Global assessments show that the observed and projected changes in cropland distributions follow latitudinal patterns with temperate regions gaining cropland suitability (CLS), while in the tropical regions croplands are in general becoming less suitable (Kummu et al., 2021; Ramankutty et al., 2002; Rosenzweig et al., 2014; Zabel et al., 2014). At local and regional scales, CLS changes with elevation, primarily decreasing in lowlands and increasing in highlands (Brusca et al., 2013; Castro-Llanos et al., 2019). Although climate-related changes lead to gains in suitability in some regions and losses in others, the overall cropland suitability is projected to considerably decrease globally, as a warming temperature and uncertain rainfall patterns put future food production at high risk (FAO, 2022).

Regions like sub-Saharan Africa, where the national economies and livelihoods of citizens are strongly dependent on agriculture, are likely to face severe socioeconomic crises and increase in poverty due to the climate-induced shifts and reductions in CLS (De Souza et al., 2015;

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Wheeler & Braun, 2013). Ethiopia is among the nations in which agriculture is an extremely important socio-economic sector, contributing about 34 % to the national GDP and 85 % of the export revenues, and supporting the livelihood of 85 % of the population (Eshete et al., 2020; NBE, 2021). Because nearly 95 % of the cropland is under smallholder rainfed practices (FAOSTAT, 2018), agricultural production is highly prone to weather and climate variability and changes (Shukla et al., 2021) in multiple ways. For example, the productivity of the rainfed agriculture (RFA) is extremely sensitive to fluctuations in the timing and amount of rainfall (Grossi and Dinku, 2022; Lala et al., 2021; Wakjira et al., 2021). Agricultural drought risks are high in the country and the entire horn of Africa (Carrão et al., 2016; Chere et al., 2022; Eze et al., 2022; Mera, 2018; Meza et al., 2020; Philip et al., 2018; Viste et al., 2013). Furthermore, weather-triggered pest infestations are becoming more frequent and are disastrous to crops (Alemu & Neigh, 2022; Peng et al., 2020; Zeleke et al., 2023). While these events only occur irregularly and with different severity levels depending on the driving agro-meteorological conditions, the change in CLS is a continuous effect, and a critical challenge that fundamentally determines the long-term cropland availability (Ramirez-Cabral et al., 2017; Wheeler & Braun, 2013).

In recent years, several global and continental-scale assessments and databases of CLS have been developed, highlighting the distribution of various crop species. For example, the Global Agro-Ecological Zone (GAEZ) database (Fischer et al., 2021), which was developed based on the fundamental principles of land evaluation recommended by the Food and Agriculture Organization (FAO), offers a range of agroecological information, including CLS for 50 crops. Schneider et al. (2022) compiled a global inventory of potentially suitable croplands for 26 crop species using a fuzzy logic land suitability model while Chemura et al. (2024) recently developed an Africa-wide CLS dataset for 23 major crops using the EcoCrop model (Ramirez-Villegas et al., 2013). These assessments are optimized for global and regional scales in terms of inputs and models considered, which to some extent limits their ability to represent local scale conditions. Country-specific assessments are necessary to incorporate these details by leveraging locally available inputs (e.g., crop yield data) and utilizing the best-performing gridded climatic inputs, to better inform planning and practical decisions at national and sub-national levels. In this regard, a limited number of studies have assessed the impacts of climate change on future croplands in Ethiopia. Evangelista et al. (2013) examined the future spatiotemporal changes in the major crops (teff, maize, sorghum, and barley) over the country by applying the Maxent species distribution model (Phillips et al., 2004) with several bioclimatic variables and crop yield datasets, and found an overall decrease in CLS for cereal crops. More recent country-level studies focused on the teff CLS using species distribution models (Alemayehu et al., 2020; Bezabih et al., 2020; Zewudie et al., 2021), while Gebresamuel et al. (2022) assessed the altitudinal shifts in the major crops in southern Tigray using a similar approach and found a considerable migration toward the highlands and a decline in the suitable area of crops like wheat and barley. Two major gaps are noticeable in the previous studies on CLS changes. First, the spatial predictions of CLS are solely based on climatic variables and do not account for the effects of other important environmental factors such as soil properties. Second, future changes are assessed based on a few projections of general circulation models (GCM), making the results highly uncertain.

In this study, we aim to define more accurate CLS maps and climate-driven changes therein by addressing the gaps mentioned above. We tackle the first gap by using a combination of climatic and soil factors. We developed a model linking observed crop yields with these combined predictors and used it to provide reliable potential CLS maps of the four major cereal crops (teff, maize, sorghum, and wheat) across the RFA areas of Ethiopia under the current climate. We tackle the second gap by examining the future changes in the CLS of the crops considering multiple GCM projections, and by separating the influences of rainfall and temperature on these changes. Moreover, we provide an in-depth analysis of the implications of these changes on future food production, the livelihoods of farmers, as well as environmental sustainability. With that information, we demonstrate the need for context-based and appropriate climate actions, which is inadequately considered in the current national adaptation plan of Ethiopia (FDRE, 2019).

2. Materials and methods

2.1. Study area

The rainfed agricultural region of Ethiopia (Fig. 1) covers ~667,000 km^2 making up 59 % of the total landmass of the country (Kassawmar et al., 2018) where over 90 % of the population is living (CSA, 2007). The elevation of the RFA region ranges from about 400 to 4500 m.a.s.l and spans arid (annual rainfall of about 270 mm y^{-1}) to hyper-humid (~2100 mm y^{-1}) climates (Wakjira et al., 2021). Crop production takes place largely between May and September, locally known as the 'Meher' production season that accounts for about 88 % of the annual crop harvest. The shorter growing season 'Belg' from February to May provides a second production window in some regions (Taffesse et al., 2012). Cereals are the main crops produced under RFA practices and comprise about 80 % of the total crop production in the country, with the top four cereals being teff, maize, sorghum, and wheat (CSA, 2010).

2.2. Data

Gridded climate (precipitation, temperature, and solar radiation) and soil properties (texture, pH, and organic carbon) data, along with national crop yield data, were used for the assessment of the CLS. The Climate Hazards Infrared Precipitation with Station (CHIRPS) rainfall (Funk et al., 2015), the bias-corrected and spatially disaggregated ERA5-Land maximum and minimum 2-m air temperature (BCE5) (Wakjira et al., 2023, 2022), and ERA5-Land surface net solar radiation (Muñoz-Sabater et al., 2021) datasets were used for the reference climate over the period 1981–2010. The future precipitation and temperature climates were retrieved from multiple GCMs (25 for precipitation and 21 for temperature) of the Coupled Model Intercomparison Project (CMIP6) for three Shared Socioeconomic Pathways, (SSPs, (Meinshausen et al., 2020; O'Neill et al., 2016), namely the SSP1–2.6 (low emission), SSP2–4.5 (intermediate emission), and SSP5–8.5 (high

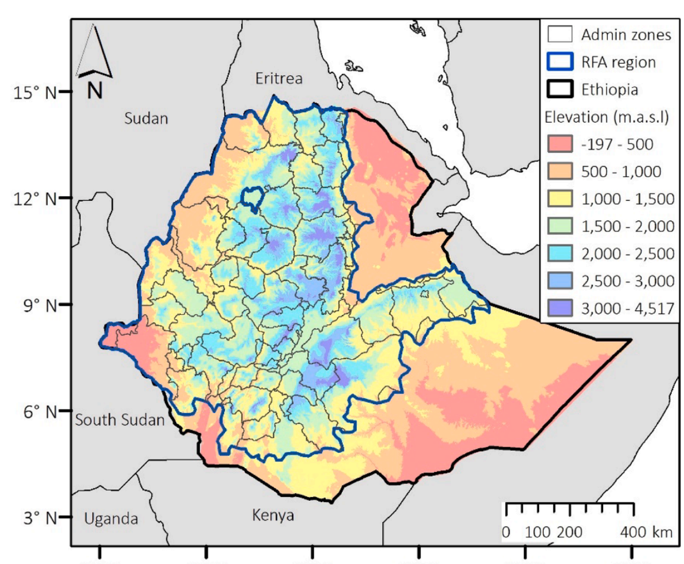

Fig. 1. Altitude and map of the rainfed agriculture (RFA) region (blue outline) in Ethiopia (Kassawmar et al., 2018). The inner polygons are the 62 administrative zones within the RFA region for which the annual crop production statistics are summarized (CSA, 2010).

emission). The list of the considered CMIP6 GCMs is given in the supplementary material (Table S1). The GCM projections were downscaled to 0.05° x 0.05° resolution in space and bias-corrected using the change factor (delta) method (Anandhi et al., 2011; Teutschbein and Seibert, 2012) for three future periods, 2020–2049, 2045–2074 and 2070–2099 (hereafter, 2030s, 2060s and 2080s respectively).

The change factor is a statistical downscaling technique. The underlying principle of this method is that the change factors that are determined from the Global Circulation Model (GCM) simulations of the current (reference) and future periods can be expressed as either relative or absolute changes, and are used to perturb the observed current climate to generate the future climate locally (Anandhi et al., 2011; Karger et al., 2020; Navarro-Racines et al., 2020; Teutschbein and Seibert, 2012). For precipitation, the change factors are typically computed as relative values, i.e., as ratios of the GCM simulations (under a given greenhouse gas emission scenario) to the GCM simulation for the current climate. The downscaled future precipitation is then derived by multiplying observed precipitation for the current (reference) period by the change factors. For temperature, absolute change factors are typically computed as the difference between the GCM simulations for the future periods and the reference period, and then added to the observed reference period temperature to determine the downscaled future temperature.

Soil properties were obtained from the SoilGrids dataset (Hengl et al., 2017; Poggio et al., 2021). SoilGrids contains various soil properties at a global 250 m x 250 m spatial resolution, interpolated from about 240,000 soil samples using machine-learning. The soil data were spatially averaged to re-grid them to a coarser spatial resolution of ~5 km x 5 km grid size (0.05° x 0.05°) to match the spatial resolution of the climate data. The Meher (May-Sep) growing season crop yield data for the four major crops (teff, maize, sorghum, and wheat) were obtained from the published Agricultural Sample Survey (AgSS) of seven years (2000, 2003, 2004, 2005, 2006, 2007 and 2010) for 62 administrative units (Fig. S1), locally known as 'zones' (CSA, 2010). These yield data years were considered because they provide a representative average of agrometeorological conditions for the reference period, as illustrated in Fig. S2 of the supplementary material. AgSS is an annual countrywide survey conducted by the Central Statistical Agency (CSA) of Ethiopia and is aimed at collecting and compiling agricultural (crop and livestock) production data from over 45,000 agricultural households across the country for both Meher and Belg seasons. For this analysis, only the Meher crop yield data was used, considering that Meher is the dominant growing season in the country.

2.3. Modelling of cropland suitability

Climate and soil are major factors that determine cropland suitability (Akpoti et al., 2019; Suhairi et al., 2018; Zabel et al., 2014). We termed "cropland suitability" as the potential of an agroecological setting to provide optimal climatic and biophysical conditions for the growth and productivity of a specific crop. We estimate CLS by establishing functional (nonlinear) relationships between crop yields and climatic and soil factors. Cropland suitability is also influenced by topographic factors, such as terrain slope and aspect (Gebrelibanos & Assen, 2014). Nevertheless, we did not consider these factors in our analysis as their effects are obscured at the coarse resolution, i.e., grid-scale of 5 km. Three climatic factors: the total rainfall (RF), mean temperature (Tm), and solar radiation (Rs) during the growing season, and three soil factors: sand-to-clay ratio (S2C), pH, and soil organic carbon (SOC), were considered in the CLS modelling. The choice of these suitability factors is motivated by the need to better represent the crop growth defining factors (Tm and Rs), the limiting factor (RF), and the soil-related factors that determine suitability (S2C, pH, and SOC) (Ittersum et al., 2013; Lobell et al., 2009). Because the cessation dates of the Meher rainy season vary across the RFA region, ranging from September to November (Wakjira et al., 2021), and because the corresponding harvest season ranges from September to February depending on locations and crop types (CSA, 2010), RF, Tm, and Rs were computed over the period from May to November to match the crop yield data. The seven years of crop yield data (see Section 2.2) and the growing season RF, Tm, and Rs of the corresponding yield years were averaged for each of the 62 zones. Similarly, average S2C, pH, and SOC were computed for each zone.

2.3.1. Partial suitability models

The CLS models were derived from the partial yield responses (PYR) of crops to each of the six individual factors (Fig. 2). We assume that high partial yield responses (hPYR), which represent the upper limit of the PYR for each factor (assuming all other factors remain optimal; Fig. 2), indicate the factor's potential impact on suitability. We sampled the hPYR data points from PYR across the range of observed values of each factor using the convex hull algorithm, which determines the smallest polygon that encloses the PYR scatters through geometric computations (Berg et al., 2008; Jarvis, 1973). We considered the data points on the upper envelope of the polygon as hPYR. The number of hPYR data points sampled by the algorithm is determined by the geometry of the polygon resulting from the PYR scatter. The fewer vertices the polygon has, the fewer hPYR data points will be picked. In cases where the algorithm picks a limited number of data points, like in S2C for wheat and SOC for maize for example, we manually picked supplementary hPYR data points (the green circles in Fig. 2) that are relatively closer to the algorithm-picked points. Detailed steps for sampling the hPYR data points are provided in Appendix A.2 of the supplementary material.

The sampled hPYR data points were then used to build the partial suitability models by fitting polynomial functions:

$$Y(x_i) = p_1 x_i^n + p_2 x_i^{n-1} + \ldots + p_{n-1} x_i + p_n \quad (1)$$

where Y is the potential yield that is associated with factor x_i (x is the value of the hPYR data points for factor i, that is, RF, Tm, Rs, S2C, pH, or SOC), and $p_1, p_2, \ldots, p_n$ are the coefficients of the polynomial function of order n. The yield responses to the climatic and soil factors can be adequately explained by quadratic functions, except for the responses of teff, maize, and sorghum to soil texture (Fig. 2). These crops exhibited strong sensitivity to S2C values below approximately 0.5, while they were much less sensitive to higher values. These non-symmetrical relationships are better represented by fourth-degree polynomials. The influences of the factors on the partial suitability are related to the plant growth mechanisms and agroecological processes that are described in Table 1. High partial suitability is associated with optimum values depending on the crop types. It represents the highest (normalized) yield that can be achieved for each controlling factor.

2.3.2. CLS under the current climate

The partial suitability models $Y(x_i)$ were applied to the current growing season climate (the average over the reference period 1981–2010) and soil factors. The maps of these factors are provided in Fig. S3 of the supplementary material. Subsequently, the gridded PYR results were normalized to derive the partial suitability indices at each grid cell with values ranging from 0 (not suitable) to 1 (highly suitable). The max-min scaling approach given as:

$$y' = \frac{y - y_{min}}{y_{max} - y_{min}} \quad (2)$$

was used for the normalization, where y' is the normalized value of PYR, and y_{min} and y_{max} are the minimum and maximum PYR values across the entire RFA region. Then, the partial suitability indices from the six factors individually were combined to determine the overall CLS suitability index (SI) for each crop. In computing the SI, factors related to the climate and soil were not taken into consideration equally. The rainfall, temperature, and solar radiation as yield defining and limiting factors, were assumed as fundamental factors (Holzkämper et al., 2013),

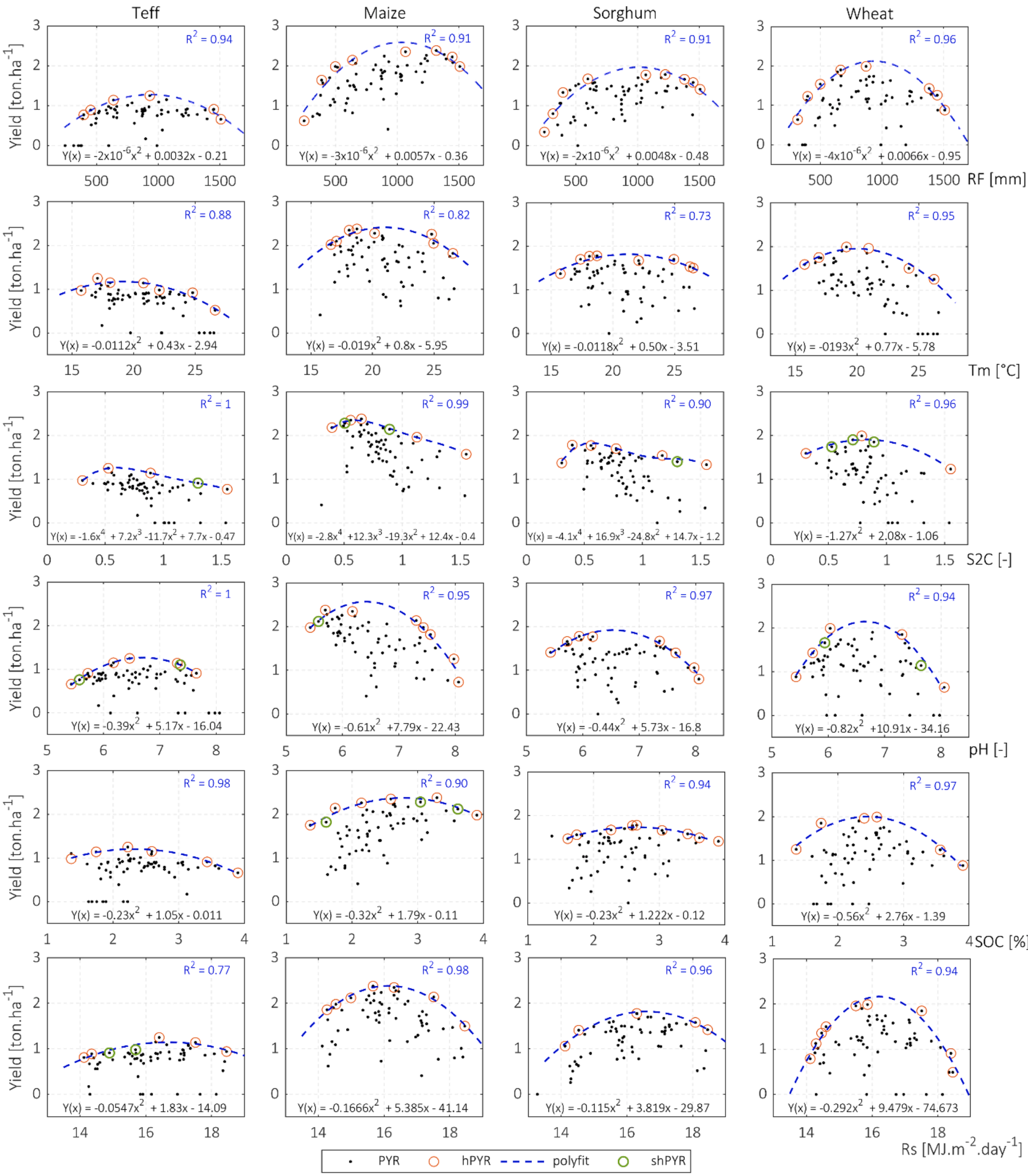

Fig. 2. Partial yield responses (PYR) of the four crops to individual climatic and soil factors. Each dot represents a zone. The orange circles are the hPYR picked automatically and the green circles (shPYR) are the supplementary hPYR picked manually that were used for the construction of the partial suitability models. The dashed lines are the fitted polynomial function (partial suitability model). RF is the May to November total rainfall, Tm and Rs are May to November mean temperature and solar mean radiation for each zone respectively.

and thus they were considered independently as rainfall suitability (S_{RF}), temperature suitability (S_{Tm}), and radiation suitability (S_{Rs}).

The soil factors (reducing factors) were combined on a weighted basis to define the soil suitability (S_{soil}). To determine the weights of the soil factors, quadratic functions of the form

$$y(x_i) = p_{1,i}x_i^2 + p_{2,i}x_i + p_{3,i} \tag{3}$$

were fitted to the normalized hPYR and factor x_i (i in this case is either S2C, pH, or SOC). The weight w for each soil factor i was then computed as

Table 1
Summary of the agroecological processes and plant growth mechanisms affected by the climatic and soil limiting conditions (very low and high values). RF, Tm, and Rs represent the rainfall total, mean temperature, and mean shortwave solar radiation, respectively, during the growing season (May to November). S2C represents sand to clay ratio, and SOC is soil organic carbon.

Factors	Low values	High values
RF	Low soil moisture, high plant water stress, low biomass production, and thus low crop yield (Kang et al., 2009; Rockström et al., 2010)	Soil saturation (waterlogging in clay soils), inhibition of aerobic plant metabolism, denitrification, soil nutrient leaching and erosion, plant growth inhibition, crop failure (Jørgensen et al., 2020; Kaur et al., 2020; Palmer et al., 2023; Pan et al., 2021)
Tm	Cold stress, frost damage, reduced root water uptake, water stress, limited photosynthesis, low/no biomass productivity, and thus low crop yield (Hassan et al., 2021; Hussain et al., 2018)	Heat stress, inhibited/limited plant metabolic activities, limited evapotranspiration and photosynthesis, leading to lower crop yield (Hatfield and Prueger, 2015)
S2C	High clay content, poor soil internal drainage, waterlogging and nutrient deficiency, less crop yield (Manik et al., 2019)	Low clay content, poor water retention capacity and low fertility, less plant-available water, water and nutrient stress, less biomass productivity and low crop yield (Huang & Hartemink, 2020)
pH	Toxicity, limited root development, less ability to extract nutrients, and crop failure (Msimbira & Smith, 2020)	Poor nutrient recycling, nitrogen, phosphorous, potassium and zinc deficiencies, less infiltration and soil hydraulic conductivity, poor root development, toxicity, and crop failure (Marlet et al., 1998; Msimbira and Smith, 2020)
SOC	Less fertile soil (less dissolved organic carbon for soil microbes which are responsible for nutrient recycling), poor soil structure and moisture fluxes, and reduced crop growth and yield (Lehmann & Kleber, 2015)	Too many nutrients available to soil microbes, increased respiration, enhanced nutrient recycling (e.g., nitrogen fixation), accelerated crop growth, but weak root anchorage due to extremely high organic matter content, resulting in crop lodging (stem buckling and root anchorage failure) (Blanchet et al., 2016; Wu et al., 2022)
Rs	Low rate of photosynthesis, less biomass productivity and thus less crop yield (Hatfield & Dold, 2019; Muchow et al., 1990)	Increased evapotranspiration, high water stress and hence low yield under moisture limited conditions (Hatfield & Dold, 2019; Muchow et al., 1990)

$$w_i = \frac{|p_{1,i}|}{\sum |p_{1,i}|} \quad (4)$$

where p_1 is the coefficient of the second-degree term of $y(x_i)$, which is the measure of the concavity of the fitted curve and can be considered as an estimate of the average rate of change in soil suitability per unit absolute change in the soil factor under sub-optimal conditions. The computed weights are given in

Table 2. The soil suitability for each crop was computed as:

$$S_{soil} = w_{S2C}S_{S2C} + w_{pH}S_{pH} + w_{SOC}S_{SOC} \quad (5)$$

Finally, the overall potential cropland suitability index (SI) was computed for every grid cell and the four crops as a multiplicative combination of the climatic and soil factors (Eq. (6)).

Table 2
Computed weights of the soil factors for teff, maize, sorghum, and wheat.

	Teff	Maize	Sorghum	Wheat
S2C	0.26	0.16	0.24	0.26
pH	0.42	0.37	0.37	0.42
SOC	0.32	0.47	0.39	0.32

$$SI = S_{RF}S_{Tm}S_{Rs}S_{soil} \quad (6)$$

We defined SI as a multiplicative combination of the partial suitabilities because the limitations of each factor, in most cases, cannot be compensated for by the optimality of the others. Instead, they have a scaling effect on each other. In other words, the suitability factors considered in the model are assumed independent.

2.3.3. Model performance evaluation

The CLS model we developed is conceptually similar to the fuzzy classification approach (Burrough et al., 1992; Zabel et al., 2014), except that the classification membership functions (suitability curves) in our case are built based on 'high' crop yield responses (a proxy for best suitability, which represents maximum observed yield) across the range of the suitability factor instead of assuming hypothetical functions that define the yield responses. We evaluated the performance of our approach with independent data, i.e., all of the black data points (PYR) in Fig. 2, using the Receiver Operating Characteristics (ROC) analysis (Fawcett, 2006). The aim here is to evaluate the model predictions against observations (normalized crop yield). We transformed the normalized crop yield into binary data using SI threshold of 0.4 (FAO, 1976). If SI is greater than or equal to 0.4, then a crop is considered to be present (1), otherwise absent (0) in a given zone.We evaluated the presence/absence of each crop in each zone using the binary data (observed suitability) and the corresponding modelled suitability, and summarized the results in a ROC plot.

The ROC analysis compares the tradeoffs between maximizing the correct detection of crop presence (true positives) and minimizing false detection of presence (false positives) at different SI thresholds. This done by computing True Positive Rate (TPR) and False Positive Rate (FPR) using Eqs. (7) and (8).

$$TPR = \frac{TP}{TP + FN} \quad (7)$$

$$FPR = \frac{FP}{FP + TN} \quad (8)$$

where in the classification process, TP is true positive, FN is false negative (missed detection), FP is false positive and TN is true negative (correct rejection) as shown in Fig. 3a. The ROC curve is the plot of TPR on the y-axis and FPR on the x-axis (Fig. 3b). The area under the ROC curve (AUC) is used as a performance metric, where AUC = 0.5 shows the performance of a random prediction and AUC = 1 shows a perfect prediction.

2.4. Climate change impact and sensitivity analysis

Future CLS values for the four major crops in Ethiopia were computed by forcing the suitability models with projected climate scenarios. We took the multi-model median values of rainfall and temperature, computed from the downscaled CMIP6 ensemble described in Section 2.2. Three SSPs and three future periods (the 2030s, 2060s, and 2080s) were examined for which the May-November RF and Tm were computed. Only changes in rainfall and temperature were considered in the assessment of future changes in CLS. Solar radiation was not considered in the assessment of future changes in CLS because the projected future changes in this variable are small in magnitude, largely <3 %, even under the extreme emission scenario by the end of the century. Similarly, soil factors were assumed to remain fixed in the computation of future CLS as their timescales of natural change are much longer.

The sensitivity of CLS to changes in RF and Tm was analyzed using the One-At-a-Time (OAT) sensitivity analysis (Hamby, 1994; Lobell & Burke, 2008). OAT is a local sensitivity analysis method in which changes in the modelled quantities are examined by modifying one variable at a time. When the model is forced by continuous input

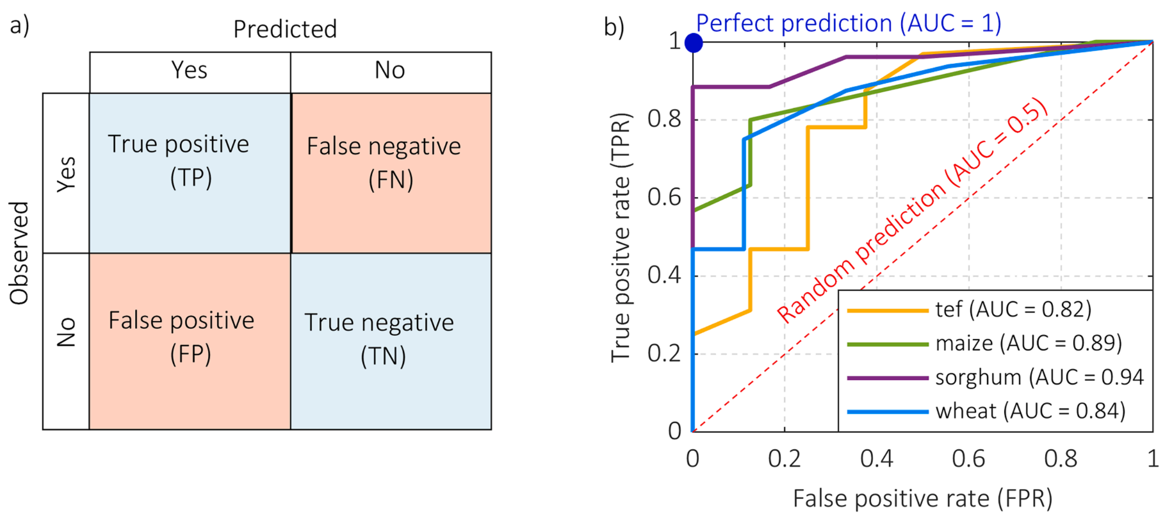

Fig. 3. (a) Confusion matrix illustrating the possible prediction outcomes of CLS with SI > SI*, where SI* is a chosen threshold indicating crop presence/absence and, (b) the resulting ROC curves for the four crops.

variables, the sensitivity can be determined by taking the partial derivatives of the output with respect to the inputs (Bhatt & Abbassi, 2023). The suitability models were forced by discretized inputs, i.e., the future RF and Tm. We simplified the sensitivity analysis by assuming that the overall change in suitability associated with the combined effects of the changes in RF and Tm is equal to the weighted sum of the changes in partial suitability associated with the change in the corresponding factor when the other factor remains unaltered. This can be formulated as (Lobell & Burke, 2008):

$$\Delta \mathrm{SI} = \beta_{\mathrm{RF}} \Delta \mathrm{S}_{\mathrm{RF}} + \beta_{\mathrm{Tm}} \Delta \mathrm{S}_{\mathrm{Tm}} \quad (9)$$

where β_{RF} is rainfall-sensitivity and β_{Tm} is temperature-sensitivity and were determined using the OAT approach. Note also that this assumption holds only when the factors (RF and Tm) are independent (Goodman, 1960). We tested this by correlating RF and Tm over the RFA region and found a statistically insignificant correlation (Pearson's r = −0.13) at a significance level of $\alpha = 0.05$. Similarly, we verified that the temporal changes in RF and Tm are uncorrelated. We then computed a sensitivity ratio (β_{ratio}) to identify the relative controls of RF and Tm on the changes in CLS.

$$\beta_{\mathrm{ratio}} = \frac{\beta_{\mathrm{RF}}}{\beta_{\mathrm{Tm}}} \quad (10)$$

The condition $\beta_{ratio} > 1$ indicates that changes in CLS are rainfall-sensitive whereas $\beta_{ratio} < 1$ shows temperature-sensitivity.

3. Results

3.1. Performance of the CLS models

From the ROC analysis, it is evident that the suitability models predict well the CLS for all crops, with AUC values of 0.82, 0.89, 0.94, and 0.84 for teff, maize, sorghum, and wheat respectively (see also Fig. 3b). In comparison with the other crops, the teff suitability model showed the least predictive power. This is most likely due to the socioeconomic dimension of teff production, which may have been reflected in the observed suitability, but is not represented in our model. Teff is a typical staple food crop and the most commercialized cereal in Ethiopia because it is a basic and traditional element of the food system for the entirety of the urban population and a significant part of the rural population (Tadele & Hibistu, 2022). As a result, depending on the climatic and biophysical suitability, teff is intensively cropped near cities and towns, and along major road networks that ease access to market (Amede et al., 2017; Tadele & Hibistu, 2022). Teff is also the most labor-intensive crop (Hailu et al., 2017; Lee, 2018). In remote areas where access to market and transport infrastructure is limited, for example, in humid lowland agro-pastoral regions, farmers prefer growing less labor-intensive crops, like sorghum and maize over teff (Amede et al., 2017), although the croplands are classified as suitable for teff. We note that our suitability models have higher predictive power for teff, maize and sorghum when compared to the Maxent-based suitability model performance presented by Evangelista et al. (2013), who reported AUC values of 0.79 for teff, 0.81 for maize, and 0.79 for sorghum. The improvements in predictive performance can be attributed to the robustness of the modelling framework we implemented, combined with the use of state-of-the-art climatic data (including solar radiation) and key soil properties, thus accounting for suitability-defining, limiting and reducing factors.

3.2. Current potential suitability

The derived CLS maps in Fig 4 show the continuous suitability indices SI of the four cereal crops over the RFA area of Ethiopia. The Food and Agriculture Organization of the United Nations (FAO) provides guidelines for land suitability classification (FAO, 1976) as given in Table 3.

Accordingly, we found that sorghum is the most suitable crop to be grown in the RFA area of Ethiopia (with moderate and high suitability of 63 % of the grid cells), followed by teff (54 %), maize (51 %), and last but not least wheat (29 %). Teff and wheat croplands mostly overlap, covering mainly the eastern half of the RFA region. Wheat is more limited to higher altitude regions (Fig. 4) while maize and sorghum are crops that are more versatile and grown also at lower elevations. The western humid areas (indicated by the dashed rectangles in Fig. 4) are characterized by high rainfall and clayey soils where waterlogging can be a major constraint. This low rainfall suitability (Fig. S4) together with high soil acidity (refer Fig. S3e) and too high soil organic carbon (Figs. S3f and S8) are the main limitations, particularly for wheat and teff in this region (Fig. S5). The low suitability for wheat, teff, and maize in the western and northwestern lowland areas is predominantly due to temperature limitations (Fig. S6). Additionally, low soil organic carbon in the northwest (Fig. S3f) further reduces suitability, particularly for wheat and maize. In the eastern and southeastern peripheries of the RFA region, suitability for all crops, especially wheat and maize, is low (Fig. 4); this is mainly due to low rainfall (Fig. S3a) and high soil alkalinity (Fig. S3e). Cropland suitability in the forest and Afro-alpine regions across the southern part of the RFA (the dotted areas in Fig. 4) is strongly limited by low solar radiation (Figs. S3c and S7) that results in

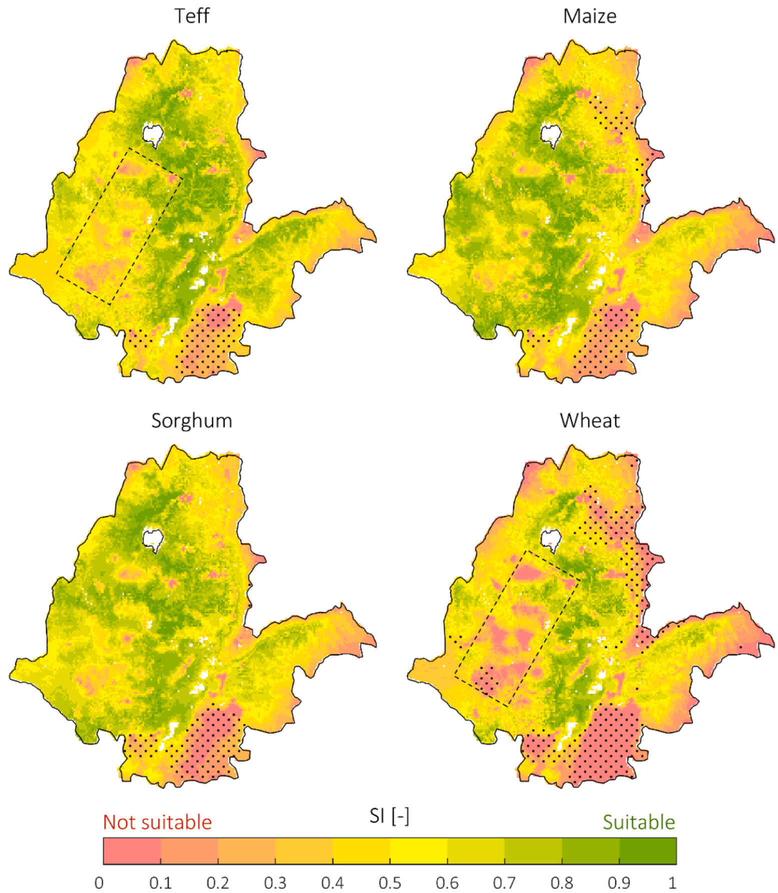

Fig. 4. Cropland suitability (CLS) maps for teff, maize, sorghum and wheat under the present climate (1981–2010). The dashed rectangles show the areas where waterlogging limits cropland suitability. The dots indicate regions where radiation-unlimited CLS is reduced by 50 % or more under radiation-limited conditions.

Table 3
Percent of grid cells in the RFA region corresponding to the FAO suitability classes (FAO, 1976). SI is the overall suitability index.

	Highly suitable (SI≥0.8) in %	Moderately suitable (0.6≤SI<0.8) in %	Marginally suitable (0.4≤SI<0.6) in %	Not suitable (SI<0.4) in %
Teff	19	35	30	16
Maize	19	32	26	23
Sorghum	21	42	21	17
Wheat	8	21	28	43

low rates of photosynthesis for all crops, particularly wheat. Additionally, low suitability for wheat and maize is observed in the northeastern part of the RFA region. However, in this case, the limitation is due to high solar radiation (Fig. S3c), resulting in increased evapotranspiration and leading to crop water stress.

While the influence of climatic factors is clearly evident in the overall CLS for each crop, the effects of soil factors are also significant. The influence of soil texture (S2C) appears to be greater in the lowland areas (see Fig. S9), where S2C is high, indicating a higher sand fraction compared to clay (Fig. S3d). When comparing the effects of soil factors, it is evident from the partial suitability maps (Figs. S5, S8, and S9) and Table 2 that teff and wheat are more influenced by pH, while maize and sorghum are more sensitive to SOC. All of the crops are relatively less influenced by S2C.

3.3. CLS under the future climate

3.3.1. Projected changes in the may-november season

The downscaled multi-model median projections show that the May-November season of the RFA regions of Ethiopia is likely to become warmer (Fig. 5b) and mostly wetter (Fig. 5a) under all emission scenarios. Under SSP1–2.6, the May-November *RF* is expected to increase by up to 100 mm, especially over the highlands in the 2030s without further changes into the mid- and end- of-the-century. However, incremental *RF* intensifications are expected in the future under SSP2–4.5 and SSP5–8.5, the latter is likely to increase by up to 300 mm by the end of the century. Unlike the changes in RF, which vary significantly among regions, the projected changes in *Tm* have little spatial variability. *Tm* is expected to increase by up to 1.8 °C, 2.8 °C, and 4.6 °C under the low, intermediate, and high emission scenarios (respectively) by the end of the century (Fig. 5b).

3.3.2. Changes in cropland suitability

The future changes in CLS under projected changes in total rainfall and mean temperature during the growing season are presented in Fig. 6. Ethiopia's RFA areas are likely to become less suitable for teff and wheat production on average. This is evident even under the low emission scenario (SSP1–2.6) already in the near future (the 2030s) when the climate is <1 °C warmer than the reference period. Under the medium and high emission scenarios, substantial areas where teff and wheat are growing are likely to be at risk of abandonment. While teff and wheat croplands will mostly experience decreases in suitability, that of maize and sorghum will generally remain unchanged, as some areas will lose suitability while nearly comparable areas will gain suitability in the future. The exception is under the medium and high emission scenarios

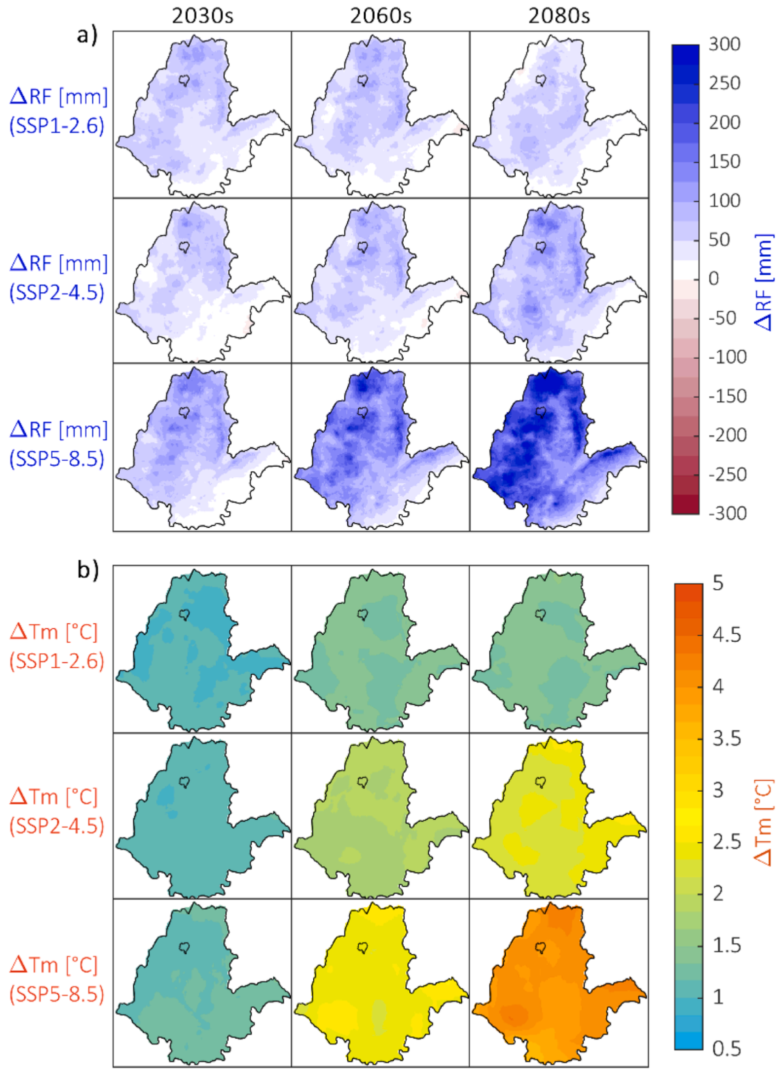

Fig. 5. The expected future changes in the May-Nov season climate: a) total rainfall (RF) and b) mean temperature (Tm) under three shared socioeconomic pathways. The indicated changes correspond to the median of 25 CMIP6 models for RF and 21 models for Tm.

where the majority of the maize and sorghum areas are expected to lose suitability by the end of the century.

The spatial patterns of the changes in CLS under SSP2–4.5 are shown in Fig. 7, and the CLS changes for the other climate scenarios are presented in the supplementary material (Fig. S10-S13). Decreases in CLS are evident largely in the northwestern, western, and southwestern lowland parts of the RFA region for all crops under all climate scenarios and future periods. When comparing the crops, teff and wheat croplands are more affected with projected decreases in the suitability of up to 0.40 (on a scale of 0 – 1) compared to maize and sorghum (projected decreases of up to 0.25). Suitable cropland areas in the lowland agro-ecologies (altitude <1300 masl), particularly that of teff and wheat, are expected to shrink considerably (Fig. S14a) under all scenarios. The expected decreases in the suitable cropland (SI > 0.6) area ranges from 21 % and 34 % (low emission, in the 2030s) to 87 % and 96 % (high emission, in the 2080s) for teff and wheat respectively. The CLS in the midlands with an altitude range of about 1300–2500 masl (shown by dots in Fig. 7) are largely expected to remain unaffected or change only slightly. Only teff and wheat areas are expected to decrease significantly by 18 % and 27 % by the end of the century under SSP5–8.5 (Fig. S14b). In the highland regions (altitude above 2500 masl), on the other hand, the croplands will become more suitable under all emission scenarios (Figs. 7, S14c).

3.3.3. Altitudinal shifts and areal changes in CLS

The predicted changes in CLS suggest a shift in suitable croplands from lowland to highland regions. For example, the altitudes of the moderately and highly suitable croplands of the four cereal crops are predicted to shift by 85–135 m (depending on the crops) under SSP1–2.6 by 2080s (Fig. 8, left panels). The altitudinal shifts are relatively stable under SSP1–2.6 throughout the future periods for the four crops compared to SSP2–4.5 and SSP5–8.5, which are predicted to result in shifts by over 210 m and 390 m respectively by the end of the century. The average shifts under the intermediate and high emissions are projected to be similar in the 2030s but will diverge after that. Overall, the altitudinal shifts tend to be higher for maize and sorghum compared to teff and wheat, probably because teff and wheat are midland and upland crops, and further upward shifts are limited or slowed by environmental constraints.

The future changes in CLS are also accompanied by decreases in the area of the suitable croplands as indicated in the right panels of Fig. 8. In particular, the average area of suitable teff cropland is projected to decrease by 9 % in the 2030s and by 12.5 % in the 2080s under the low emission scenario. The intermediate and high emissions will exacerbate the impacts pushing about 17 % and 22 % of the teff area out of the suitable climate space in the 2060s, and 25 % and 39.5 % of the area by the end of the century. Wheat cropland is the second most affected

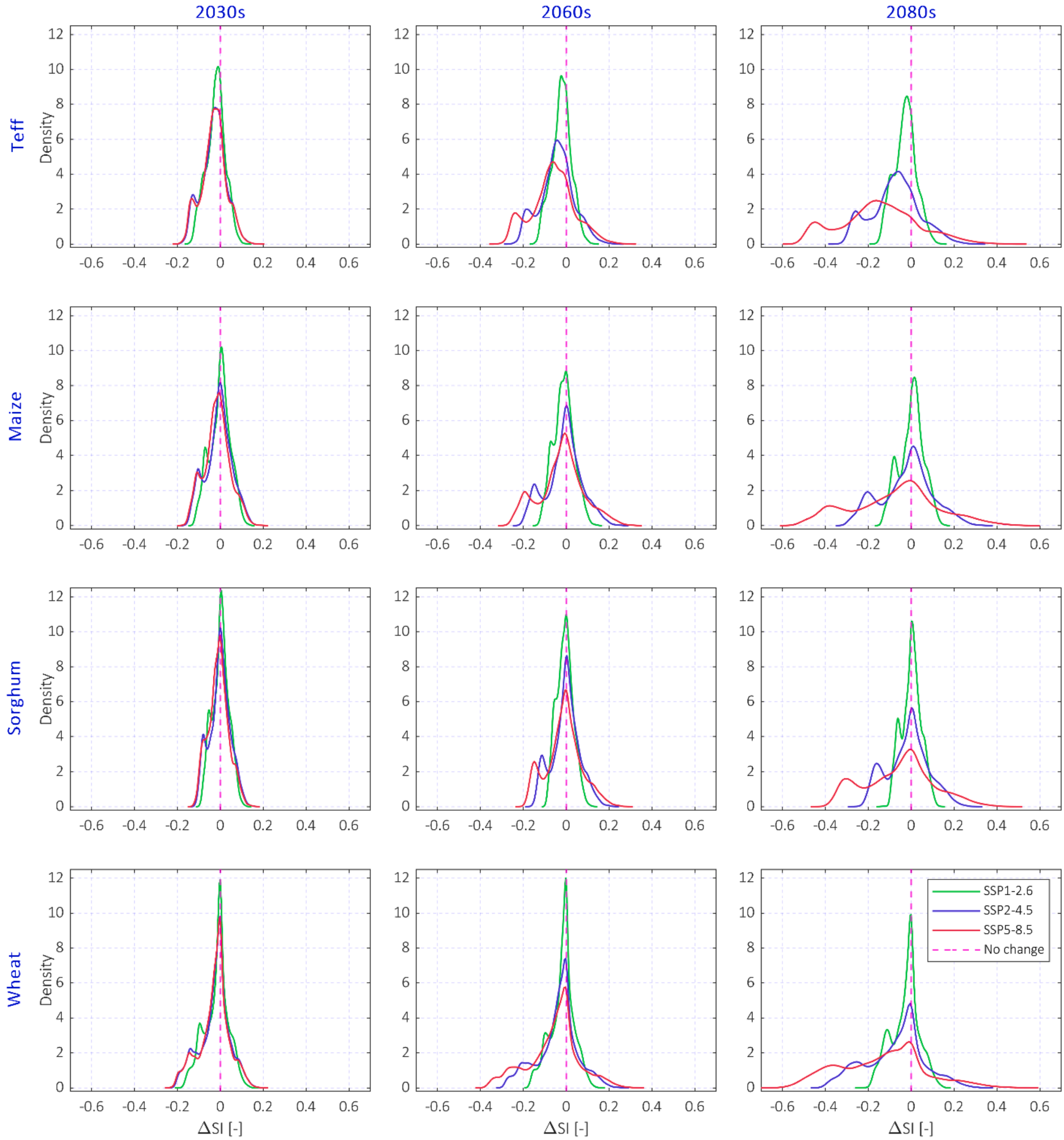

Fig. 6. Kernel-smoothed distributions of changes in the future cropland suitability (**Δ***SI*) for teff, maize, sorghum, and wheat under SSP1–2.6, SSP2–4.5, and SSP5–8.5 across all grid cells within the RFA region for the 2030s, 2060s, 2080s, from left to right.

among the four crops, with projected decreases in area of about 2.5 % and 5 % under low emission by 2030s and 2080s respectively. Under the high emissions, wheat areas are likely to decrease by 16 % and 32 % by the mid and end of the century. Changes in maize and sorghum areas are generally small under the low and intermediate emission scenarios in the 2030s and 2060s, suggesting that the changes are largely dominated by shifts in the suitable croplands as mentioned earlier. However, over 7 % and 24 % of the suitable areas of both crops are projected to be lost under intermediate and high emission scenarios, during the 2080s.

3.3.4. Future changes in the major producing zones

The CLS changes and their climatic drivers in Ethiopia's major producing zones (ranked based on the observed yield data) in 2060s are summarized in Fig. 9, and altitudinal shifts and areal changes associated with the changes in suitability are presented in Fig. 10. The magnitude of changes in CLS increases with greenhouse gas emissions. Here, we present the changes under the high-emission scenario (SSP5–8.5). The major teff producing zones considered here are likely to experience rather small changes ranging from −0.04 to +0.04 (on a scale of 0 to 1) under SSP5–8.5 during 2060s (Fig. 9a). As a result, the areas of teff croplands are likely to remain nearly stable in most of the zones with the

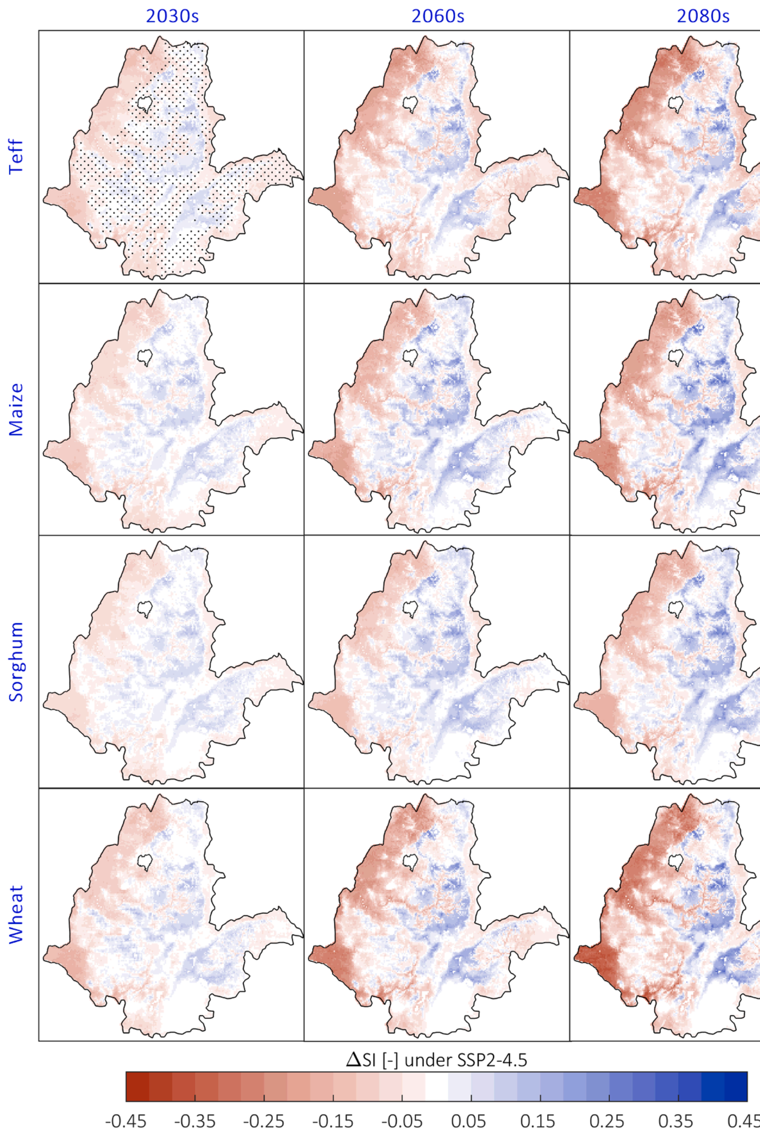

Fig. 7. Change maps of the cropland suitability for teff, maize, sorghum and wheat comparing SSP2–4.5 to the current climate during the three future periods. The dots in the first map show the midland areas (altitude range of 1300 – 2500 masl).

exception of West Hararge where the teff area is projected to decrease by up to 13 % under SSP5–8.5 in 2060s (Fig. 10b), and this decrease in suitability is linked to a decrease in temperature suitability (Fig. 9c). The slight increases in suitability in zones like Southwest Shoa and South Wollo are linked to an increase in temperature suitability (Fig. 9c) in the highland regions, which is also evident from the increases in the mean altitude (Fig. 10a). Other major teff producing zones like North Shoa of the Amhara Regional State, and West Shoa are likely to experience altitudinal shifts of about 50–100 m, but with only slight or no changes in the suitable area.

CLS for maize is likely to decrease considerably in the major producing zones across the western part (East Gojam and East Wollega) and northwestern part (Awi and Metekel) of the RFA regions (Fig. 9d). In Awi and Metekel in particular, highly suitable (SI $\geq$ 0.8) maize cropland area is projected to decrease by about 48 % and 69 % under SSP5–8.5 by the mid of the century (Fig. 10d). A decrease in rainfall suitability is highly evident in the major producing zones in the western part of the RFA region (Fig. 9e). High altitudinal shifts are expected in Awi and Metekel zones suggesting rapid maize cropland retreats towards the highlands (Fig. 10c). Maize areas in West Shoa and Gurage zones in the central part of the RFA region on the other hand, are projected to expand by over 12 % (SSP5–8.5) in 2060s, mainly due to an increase in temperature suitability.

The major sorghum-producing zones like West Shoa (central part), East Gojam (north central), and West Hararge (east) showed an increase in suitability under all SSPs in the mid of the century (Fig. 9g–i). In moisture-limited climates like in West Hararge, increases in rainfall suitability are likely to improve CLS, even by reversing the direction of the altitudinal shifts towards the lowlands. This is evident from the decreases in the average altitude and increases in the area (by about 4 % under SSP5–8.5) of the suitable croplands in this zone (Fig. 10e, f). In West Shoa and East Gojam, increases in suitability are associated with an increase in temperature suitability for sorghum. On the contrary, negative impacts on the CLS for sorghum are expected in the major producing zones such as Kamashi, East Wollega, and West Gojam in the western side of the RFA region, especially under the high emission scenario. Consequently, sorghum croplands are projected to decrease by about 21 % in Kamashi, and 12 % in East Wollega under SSP5–8.5.

Wheat CLS are projected to increase or remain nearly stable in the 2060s across the seven major-producing zones we examined as shown in Fig. 9j. In particular, in the wheat corridors of Ethiopia (Bale and Arsi), the wheat-suitable croplands are expected to expand by 41 % and 49 %

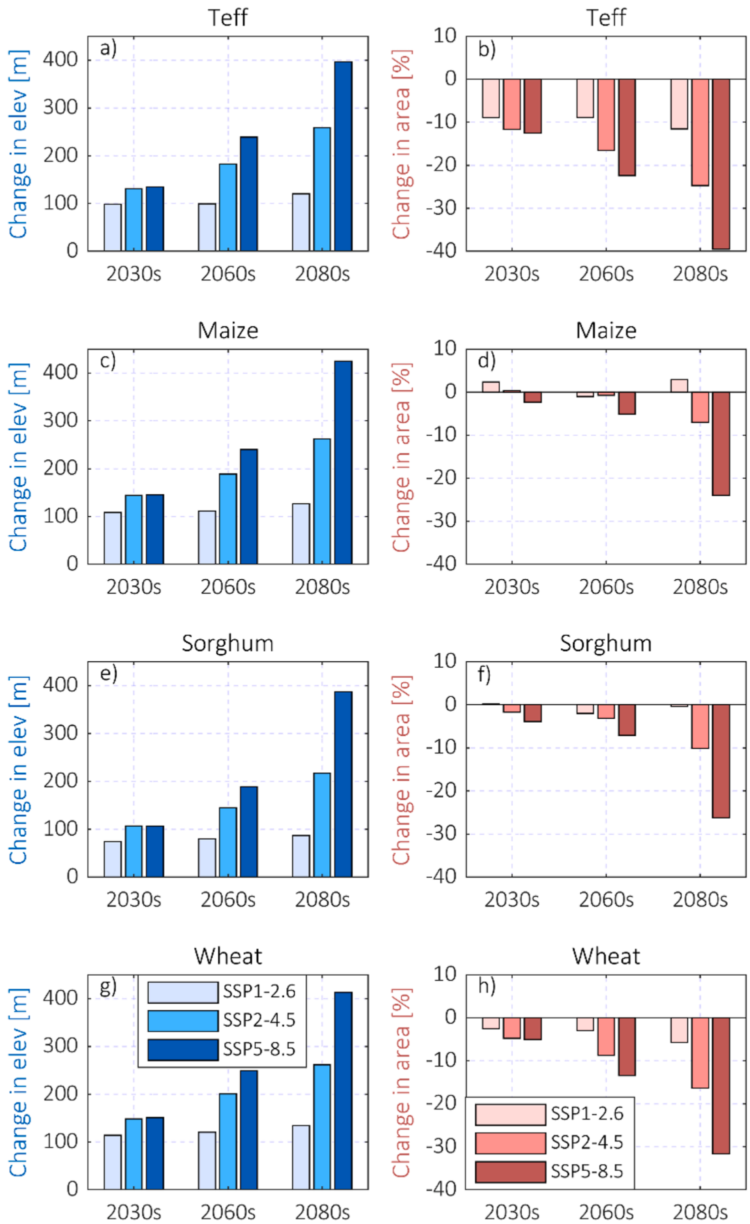

Fig. 8. Average changes in the altitudes (left) and average changes in the areas (right) of moderately and highly suitable teff, maize, sorghum, and wheat croplands in the RFA region of Ethiopia. The changes were calculated comparing the future versus current suitabilities considering all grid cells with **SI** ≥ 0.6.

respectively under SSP5–8.5 (Fig. 10h), mainly due to the projected increase in rainfall suitability in Bale and increases in both rainfall and temperature suitability in Arsi. Similarly, wheat areas are projected to expand in East Shoa, Southwest Shoa, and Gurage under all SSPs, for example by up to 11 % under SSP5–8.5 by the mid of the century. Only in Hadiya and Kembata-Tembaro zones, the wheat-suitable areas are likely to decrease slightly by <5 %. As one can expect, the increases in the suitable areas are largely associated with altitudinal shifts towards the higher elevations, especially in Arsi (~185 m) and East Shoa (~130 m) as shown in Fig. 10g. The exception is in Bale zone, where a decrease in the elevation of suitable croplands is projected, especially under the low emission scenario and this decrease is attributed to the projected increase in rainfall suitability (Fig. 9k), which in turn increases the overall suitability in the mid-altitude croplands.

3.4. Sensitivity of CLS to rainfall and temperature

The results suggest that cropland suitability across the Ethiopian RFA region may be affected by rainfall and temperature changes in different ways. Therefore, it is important to examine the sensitivity of CLS to each factor. The OAT sensitivity analysis results in Fig. 11 show that the relative sensitivity β_{ratio} is high (blue) in semi-arid climates across the southern, southeastern, eastern, and northeastern margins, and in hyper-humid climates in the western parts of the RFA region. This indicates that changes in CLS in these regions are predominantly driven by changes in rainfall suitability. Changes in CLS in semi-arid and dry sub-humid climates of the Rift Valley corridor (dashed line in Fig. 11) are also sensitive to rainfall, especially for maize, sorghum, and wheat. The rainfall limitations in the dry climatic regions are linked to moisture deficit during the growing season that considerably reduces crop yields. Soil conditions further exacerbate this limitation, as these regions are largely characterized by coarse-textured soils with low organic matter content (Fig. S3d, f), limiting the soil water storage capacity (Rawls et al., 2003). In the hyper-humid regions, problems associated with excess rainfall including waterlogging and soil nutrient erosion (as discussed in Table 1) are the main constraints and are highly noticeable,

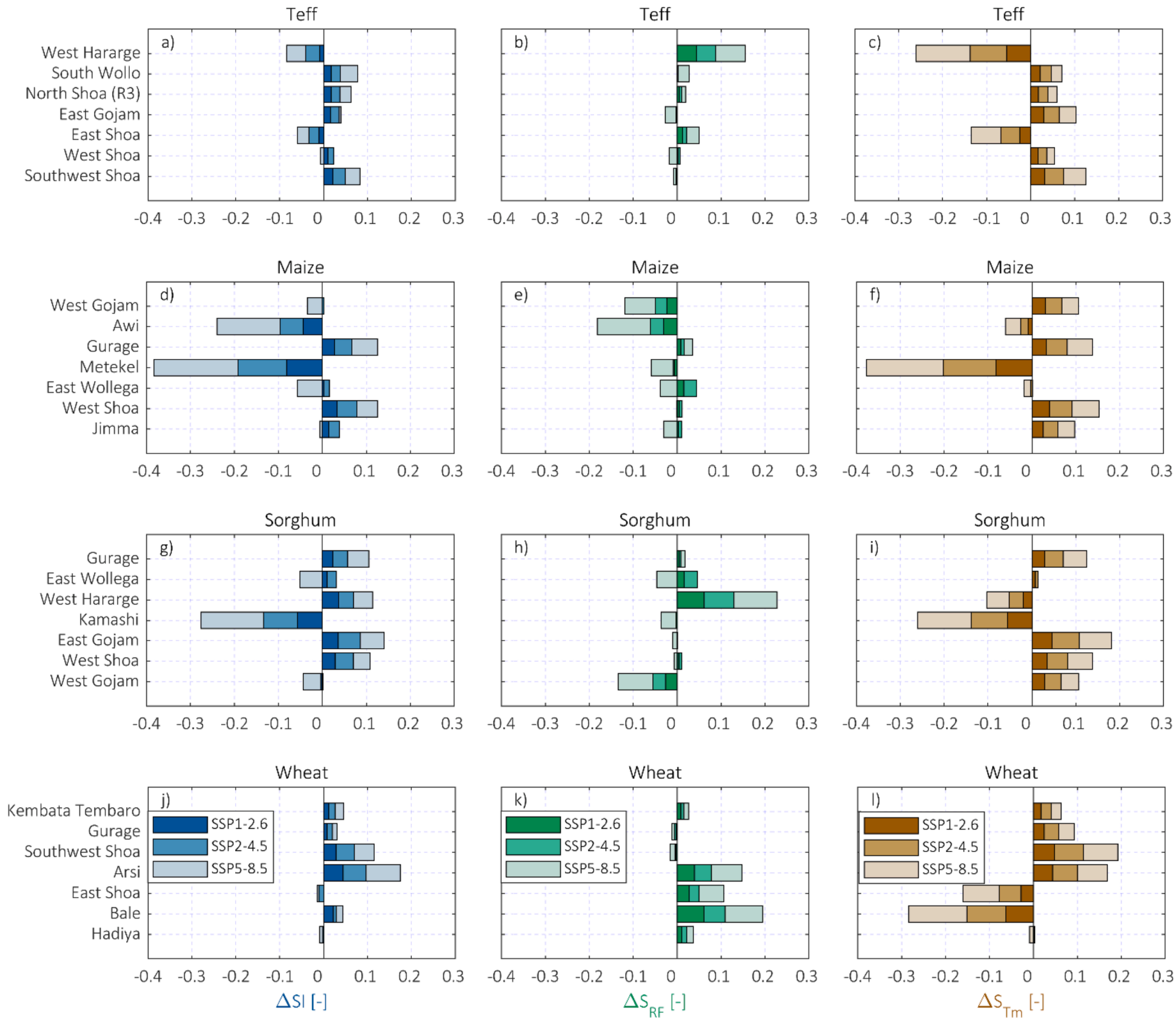

Fig. 9. Changes in overall cropland suitability (left), rainfall partial suitability (center), and temperature partial suitability (right), for teff, maize, sorghum, and wheat in the major producing zones (the y-tick labels) under SSP1–2.6, SSP2–4.5 and SSP5–8.5 by 2060s. The top-producing zones were identified based on the observed multi-year average crop yields. R3 stands for the Amhara Regional State in which the North Shoa zone is found.

especially for teff and wheat CLS. Clay soils like nitisols, luvisols, and vertisols are the dominant soils across the hyper-humid areas in the western part of the RFA region (Ali et al., 2022), making the region susceptible to waterlogging problems.

In the highland and lowland (western and northwestern) regions, on the other hand, the changes in CLS are highly sensitive to temperature. In the lowland areas, teff and wheat CLS are more sensitive to temperature compared to maize and sorghum. The temperature sensitivity of CLS can be attributed to two combined limitations of temperature, namely thermal stress and evaporative stress limitations (Eyshi Rezaei et al., 2015; Lesk et al., 2022). Thermal stress (cold and heat stress) tolerance is the genetic property of a crop that determines the geographic niche of that crop species (Sutherst, 2003). The thermal ranges in which a crop can survive are often given by low- and high-temperature thresholds. Under the projected warming climate, temperature converges to and eventually surpasses the high-temperature thresholds of crops in lowland regions, resulting in frequent heat stresses and gradual abandonment of crops. In the highland marginal agroecosystems, temperature instead exceeds the low-temperature thresholds reducing cold stress frequencies, and thus widening the crop niches toward high altitudes. The evaporative stress limitations are linked to temperature effects on crop evaporative moisture losses. Lowland regions are energy-excess (water-limited) systems where crops often suffer from high water stress due to high evaporative losses driven by high temperature under a given moisture-limited condition, thus climate warming aggravates water stress conditions in lowlands. On the contrary, highland ecosystems tend to be energy-limited, thus crops transpire less due to stomatal closure under cold temperatures, which also means that CO_2 uptake and photosynthesis are limited. Climate warming overcomes the energy limits in the highland ecosystems, increasing photosynthesis and crop yields under available water conditions.

4. Discussion

4.1. Socioeconomic and environmental implications

We have presented the possible future changes in CLS for the major

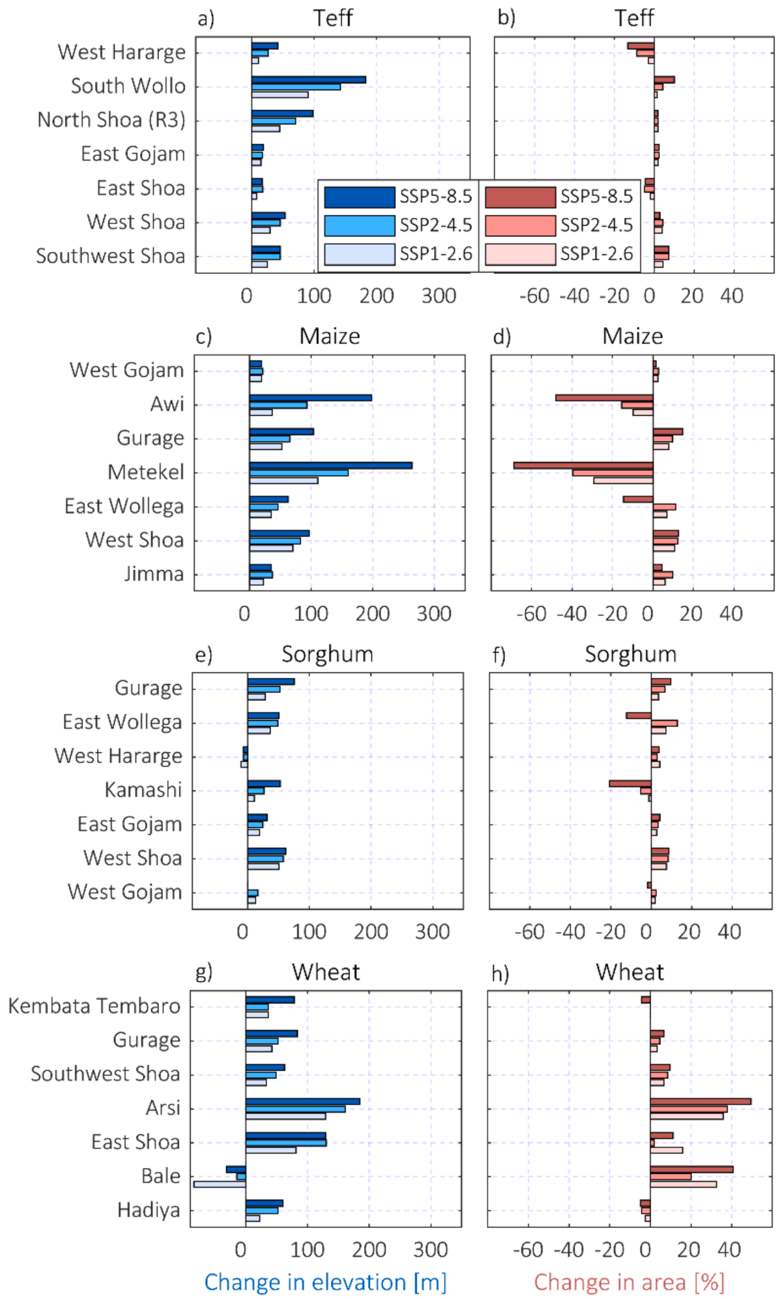

Fig. 10. Changes in mean elevation (left) and changes in area (right), of suitable croplands (SI ≥ 0.6) of teff, maize, sorghum and wheat in the major-producing zones under SSP1–2.6, SSP2–4.5, and SSP5–8.5 in the 2060s. The changes were computed considering all grid cells of each zone with SI ≥ 0.6.

staple food crops on climatological time scales in the RFA area of Ethiopia. It should be understood that these changes in CLS represent a response to climate change in the long term, which is different from responses to climatic extremes and interannual variability that often result in spontaneous short-term impacts on crop yield. While interannual variabilities in CLS are primarily driven by variabilities in rainfall suitability as illustrated in Fig. 12a, and temperature extremes (not shown here), the long-term changes in CLS are caused by both temperature and rainfall. In fact, temperature limitations are more severe in the long-term for the four crops, compared to rainfall limitations (Fig. 12b), which is also in agreement with the findings in previous studies (Akpoti et al., 2022; Holzkämper et al., 2013; Lobell & Burke, 2008; Schlenker & Lobell, 2010). The early sign of these changes can be a gradual decrease in the native crop productivity, as has already been witnessed by farmers across various regions in Ethiopia (Adimassu et al., 2014; Destaw & Mekuyie, 2022; Megabia et al., 2022; Moroda et al., 2018; Tesfahunegn, 2021; Teshome et al., 2021; Tessema, 2021). This is followed by a phase of generally low productivity where the native (existing) crop species retreat and new crop species emerge (Abera & Tesema, 2019; Hameso, 2018). The final stage is when the native crop is abandoned and the new crop is adapted, for example as observed in sub-humid and humid areas in central and northern Ethiopia (Taye, 2021; Tessema et al., 2019).

In marginal croplands, the changes in CLS are largely unidirectional. For example, in lowland areas the emergence of new crop species is constrained by warm temperature extremes, thus the croplands are abandoned once suitability for the native crop diminishes, while in highlands temperature becomes more suitable and new croplands emerge (Burke et al., 2009; Dendir & Simane, 2021; Sloat et al., 2020). However, expansions toward the highlands are not only limited by other environmental factors such as soil and slope, but they are also

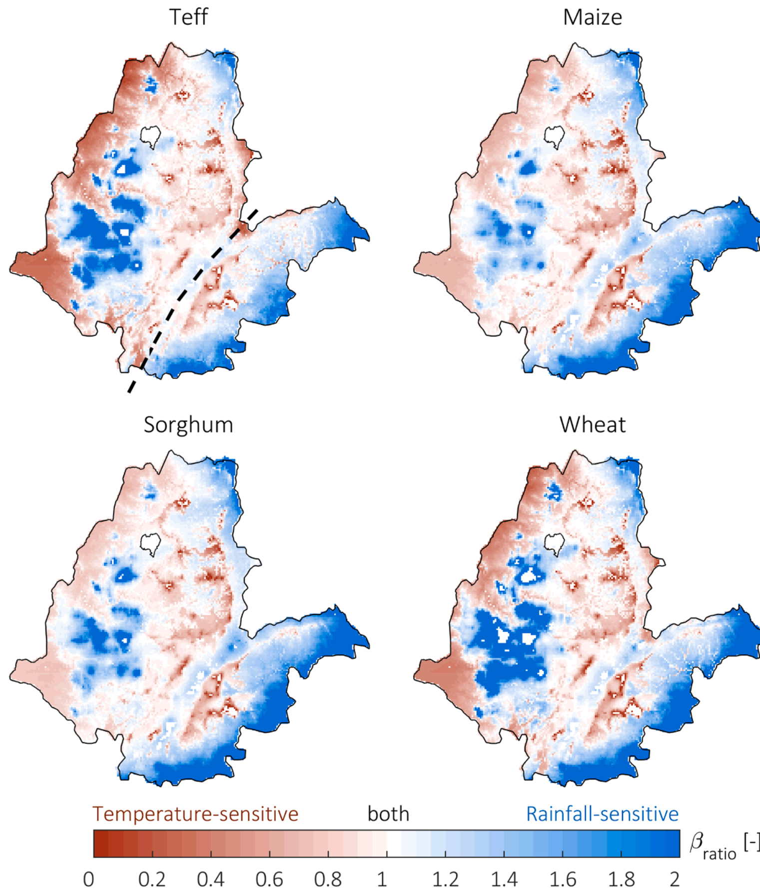

Fig. 11. Relative sensitivity (β_{ratio}) of cropland suitability to rainfall and temperature for teff, maize, sorghum and wheat. The β_{ratio} values mapped here are the average of nine OAT simulations – the combinations of three future periods (the 2030s, 2060s, and 2080s) under three SSPs (SSP1–2.6, SSP2–4.5, and SSP5–8.5).

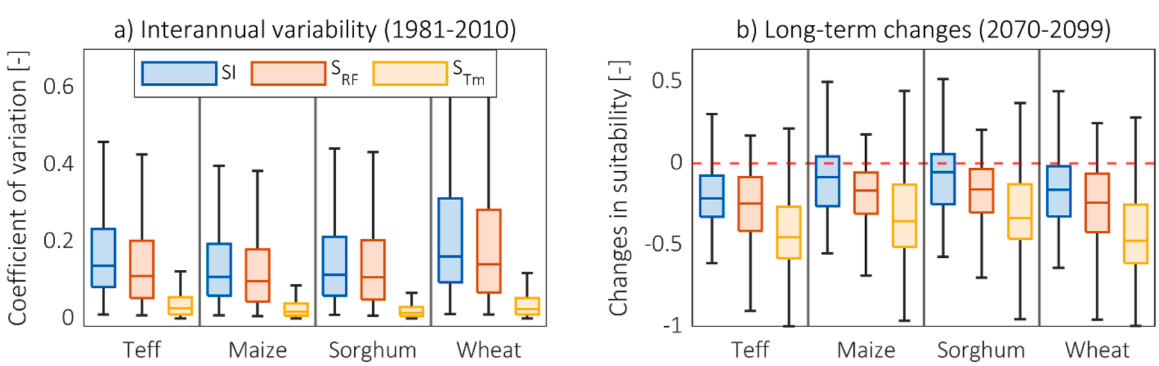

Fig. 12. (a) Interannual variability in suitability represented by boxplots of the coefficients of variation in the current climate, and (b) long-term changes in the suitability index (SI, blue), rainfall suitability (S_{RF}, orange) and temperature suitability (S_{Tm}, yellow) under future climate. The boxplots represent variations among the grid cells across the RFA region. The coefficients of variation were calculated from the annual SI, S_{RF} and S_{Tm} for the reference period (1981–2010). The long-term changes were computed as the differences between the future (2070–2099) suitability under SSP5–8.5, and the reference (present) suitability.

unsustainable as they trigger massive land conversion with serious environmental impacts including deforestation, biodiversity losses, and land degradation (Delelegn et al., 2018; Gidey et al., 2023; Moges, 2018), particularly in highly populated countries like Ethiopia. Since only a portion of the newly emerging croplands can realistically be exploited by farmers, our analysis represents a best-case scenario, which is unlikely to occur. Our analysis may therefore underestimate the overall negative impacts of climate change on future cropland areas in Ethiopia.

The contraction of suitable croplands will have adverse economic and food security implications in Ethiopia. A summary of the approximate changes in the annual production of the four crops in the 2060s under the intermediate emission scenario, assuming a linear relationship between production volume and cropped area is shown in Table 4. For example, under business-as-usual practices, i.e., rainfed small-scale farming practices with the same level of inputs, technologies, and services as present, the national teff production will decrease from the current volume of about 2.1 million tons to 1.8 million tons. Similarly, it is projected that maize production will fall from 2.8 million tons to 2.6 million tons due to the contractions of the suitable cropland areas (Fig. 8). The consequences of climate-driven changes in CLS for future crop production in Ethiopia could be even more significant if the

Table 4
Comparison of the current and future cereal production associated with the projected changes in suitable cropland areas during the 2060s under the intermediate emission scenario. The present (reference) production was assumed comparable to the average of productions in the years 2000, 2003–2007 and 2010.

	Current		Future (2060s) under SSP2–4.5	
	Production (10^6 tons)	Cropped area (10^6ha)	Production in (10^6 tons)	Crop area in (10^6ha)
Teff	2.09	2.14	1.76	1.80
Maize	2.80	1.41	2.77	1.40
Sorghum	2.10	1.39	2.04	1.35
Wheat	1.99	1.29	1.81	1.17

currently cultivated fertile croplands are affected more than the marginally suitable less fertile croplands. On the contrary, Ethiopia's population is predicted to climb from 73.8 million (2007 census) to about 171.8 million in 2050 (Bekele & Lakew, 2014). These concurrent challenges add to the severe food security status in the country (GHI, 2022; Mohamed, 2017) exacerbating the level of poverty and the risks of hunger and malnutrition in the future.

4.2. Adaptation

Our results suggest that climate-driven changes in CLS are relatively small under sustainable development pathways that lead to low GHG emissions compared to the intermediate and high emissions, indisputably implying that global GHG emission mitigation is vital. However, the impacts of these small changes even under the low emission targets are net negative and they can be impactful for society given the increasing food demand. For example, low emission pathways result in the reduction of teff cropland area by about 9 % by 2060s (Fig. 8b), which can be a substantial limitation to the efforts towards meeting the 'zero hunger' sustainability goal (Tilman et al., 2011). Context-based adaptation and sustainable intensification measures are vital to reduce these impacts and meet the food demand of the growing population. Our sensitivity analysis results are useful in defining the objectives and the types of adaptation measures that can be implemented at a given location.

In rainfall-sensitive agroecosystems, water management practices aimed at reducing crop water stress in rainfall-deficit areas and waterlogging and nutrient losses in rainfall-excess areas are needed. In particular, reducing water stress in rainfed farming systems consists of several measures ranging from locating optimal planting dates that maximize the total available moisture during the growing season, to optimal on-farm management of rainwater that allows maximum infiltration, storage, and plant water availability, and minimum evaporative losses. Several on-farm water conservation practices have proven to effectively reduce water stress in moisture-limited agroecological zones. These practices can be expanded in rainfall-sensitive semi-arid and dry sub-humid areas in the northeast, east, southeast, and parts of the Rift Valley. Among these on-farm (micro-catchment) infiltration-enhancing measures are various kinds of bunds (contour, semi-circular, and trapezoidal), terraces, trenches, tied ridges, mulching, and vegetative barriers such as strip grass or crops (Hurni, 2016; 1998; Studer, 2021; Studer & Liniger, 2013). However, the effectiveness of some of these measures varies with biophysical features like slope, soil depth, and climate. Hurni (2016, 1998) defined, through more than three decades of extensive research and field demonstrations, soil and water conservation measures suitable for the various agroecological zones of Ethiopia.

In temperature-sensitive lowland areas, it is the management practices which aim at reducing evaporative losses that are important to alleviate evaporative stress, but only within the thermal stress limits of crops. For example, mulching and windbreak trees are measures that reduce evaporative losses of moisture (Knoop et al., 2012). Improving crop tolerance to harsh agroecological conditions like thermal and water stress through plant breeding is a viable and widely used strategy for climate adaptation and yield improvement (van Etten et al., 2019). Microclimate regulation is another adaptation strategy that can be implemented to reduce heat stress in warm climates. In this regard, agroforestry systems provide multiple benefits including microclimatic regulation, water conservation, soil fertility improvement, pest control, and farmers' income stabilization (Lasco et al., 2014). Under limited adaptive capacity, which is likely for example in Metekel and Awi zones for maize, Kamashi zone for sorghum in the western part, and West Hararge for teff in the eastern part of the RFA region, gradual switching to more resilient crops and/or smooth transition to a suitable farming system is needed.

Effective adaptation entails holistic measures including policy, appropriate technology, informed decisions, social transformation, and multi-stakeholder actions. These measures would unlock the untapped potential for adaptation and resilience by filling the current yield gaps thereby increasing production, for example by about 24 million tons (8 times more) for maize in Ethiopia (van Dijk et al., 2020). Institutional-level efforts are very crucial in Ethiopia to coordinate knowledge generation, evidence-based adaptation planning, decision-making, implementation, monitoring, and financing of climate adaptation. Because in Ethiopia climate change poses multiple impacts that differ in their types, occurrence probability, and severity, adaptation goals and plans need to be site-specific and comprehensive, and go beyond climatic emergency responses (Conway & Schipper, 2011). Adaptation goals that target to improve resilience at farm and landscape levels considering interannual variability of rainfall, droughts, as well as long-term changes in cropland suitability, are necessary. Awareness of the diversity of future climate impacts should be created within the agricultural community to build readiness and flexibility for farmers to adjust to the changes and practice a diversified family economy.

4.3. Study limitations and future directions

The spatial maps presented here are limited by the spatial resolution of the climate data (0.05° x 0.05°), and thus sub-grid (e.g., landscape, farm, and field scale) details are not explicitly represented. In particular, terrain characteristics like slope and aspect have not been considered in the suitability model, as their effects are impossible to capture at this coarse spatial resolution. As a result, the estimated potential suitability and projected cropland expansion toward highlands have not been topographically constrained and thus might be overestimated. Our framework however allows the inclusion of topographic limitations into the assessment of crop suitability, and this could be a useful direction for future research. Ultimately, local scale plans and decisions, for example cropland intensification, should be based on future suitability assessments at a higher spatial resolution.

Another limitation is that the effects of rainfall and temperature on crop suitability in our model were represented in a generalized way, i.e., as growing season total rainfall and mean temperature. The influences of other rainfall characteristics, such as the onset and duration of the rainy season, and additional temperature characteristics, such as cold and warm extremes, should be considered in future studies. A late onset of the rainy season leads to a significant reduction in seasonal crop production in most of the Ethiopian RFA region (Wakjira et al., 2021). This effect can be exacerbated by the increased rainfall uncertainty expected under future climate scenarios (Adhikari et al., 2015), thus the associated impact on CLS could be significant. In this regard, our assessment may underestimate future changes in CLS, especially in semi-arid regions where CLS is rainfall-sensitive. One important future research direction is to estimate the future changes in the timing and duration of the rainy season as well as the temperature extremes, and how these changes may influence future croplands by using process-based crop models in addition to statistical approaches as implemented in other case studies (Flückiger et al., 2017; Sultan et al., 2019). Future research in Ethiopia should also be extended to the Belg growing season, because the secondary rainy season may provide new opportunities as well. Despite these shortcomings, our analysis provides a valuable first-order assessment of the agroecological impacts of climate change on cereal crop production in the RFA area of Ethiopia, with a view towards understanding the implications as well as adaptation actions that need to be taken especially at institutional level in the country.

5. Conclusions

The impact of climate change on rainfed agriculture poses a significant challenge to future food security and livelihoods, particularly in vulnerable countries like Ethiopia. We investigated the impacts on cropland availability by modelling cropland suitability under current and projected future climate conditions. We show that the warming climate and variable rainfall conditions in Ethiopia's rainfed agricultural area will cause suitable cropland areas to experience altitudinal shifts toward the highlands, leading to a loss of viable farming areas in the lowlands and a gain in the highlands. However, due to strong evaporative and heat stresses in the moisture-limited lowland areas, it is expected that suitability losses in the lowlands will outweigh the gains in the highlands. Thus, even under the low-emission climate scenario, the net projected effects on cropland areas will be negative. This could have serious implications for food security in Ethiopia, especially given the expected high demographic growth and increasing food demand in the coming years. The impacts of intermediate and high emission scenarios are more severe, and cropland suitability conditions will worsen with time.

In some parts of the rainfed agricultural region, the current cropland suitability is constrained by low soil suitability, for example, due to high clay content (thus poor internal drainage) and acidity in the western humid agroecologies, coarse-textured soils with low organic matter content in large parts of the semi-arid areas (thus low water storage capacity and fertility), and high soil alkalinity in the eastern and southeastern parts of the rainfed agricultural region. It is possible to increase productivity in these regions using effective management and technologies that can improve the suitability of the soil. The management and technologies that will help overcome climatic limitations can be selected based on the rainfall and temperature sensitivity of the croplands. Because lowland areas are more sensitive to temperature change, management interventions that reduce heat and evaporative stress are particularly necessary. In contrast, management of excess rainwater such as agricultural soil drainage in hyper-humid regions and conservation of moisture in dry regions can significantly improve cropland suitability in these areas. In dry regions, land management practices that enhance soil organic matter and reduce soil erosion are crucial for improving soil water holding capacity and fertility. The significant limitation of solar radiation in the forest-dominated southern part of the RFA region necessitates measures like selection of crop species with high radiation use efficiency, and proper choice of the growing season to ensure optimal radiation inputs, and moisture and temperature conditions. Our analysis provides comprehensive information for such climate adaptation planning and policymaking mainly at a national level. However, our work also stresses that reliable local adaptation plans should be based on high-resolution site-specific information about future climate, soil, and local farming contexts.

CRediT authorship contribution statement

Mosisa Tujuba Wakjira: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Nadav Peleg:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Conceptualization. **Johan Six:** Writing – review & editing, Visualization, Validation, Methodology, Conceptualization. **Peter Molnar:** Writing – review & editing, Visualization, Supervision, Resources, Project administration, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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Data availability

Data will be made available on request.

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