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Coupled Impacts of Soil Acidification and Climate Change on Future Crop Suitability in Ethiopia

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Abstract: Agricultural sustainability faces challenges in the changing climate, particularly for rainfed systems like those in Ethiopia. This study examines the combined impacts of climate change and soil acidity on future crop potential, focusing on Ethiopia as a case study. The EcoCrop crop suitability model was parameterized and run for four key food crops in Ethiopia (teff, maize, barley and common wheat), under current and mid-century climate conditions. To assess the impacts of soil acidification on crop suitability, a simulation study was conducted by lowering the soil pH values by 0.5, 1.0 and 1.5 and re-running the suitability model, comparing the changes in the area suitable for each crop. Our evaluation of the model, by comparing the modeled suitable areas with reference data, indicated that there was a good fit for all the four crops. Using default soil pH values, we project that there will be no significant changes in the suitability of maize, barley and wheat and an increase in the suitability of teff by the mid-century, as influenced by projected increases in rainfall in the country. Our results demonstrate a direct relationship between the lowering of soil pH and increasing losses in the area suitable for all crops, but especially for teff, barley and wheat. We conclude that soil acidification can have a strong impact on crop suitability in Ethiopia under climate change, and precautionary measures to avoid soil acidification should be a key element in the design of climate change adaptation strategies.

Keywords: soil pH; agriculture; climate adaptation; soil quality; EcoCrop; sustainability

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1. Introduction

Over the past few decades, the impacts of climate change facing the planet and humanity have come to the fore [1]. Climate change is causing changes to both atmospheric and biophysical conditions, with significant impacts on crop growth and productivity [2–7]. There is a mounting need for climate adaptation measures to ensure crop yields are maintained at levels sufficient to sustainably provide food and other products to society. However, there is also potential for maladaptation, where some adaptation measures could contribute to other environmental degradation challenges. In Ethiopia, soil acidification emerges as a prominent challenge, posing a significant threat to food security and constraining agricultural productivity [8–11]. This issue stems from a variety of complex factors, encompassing both anthropogenic and natural elements. Inadequate land management practices, including suboptimal fertilizer application, overgrazing and the insufficient incorporation of organic manures into the soil, instigate the exacerbation of soil acidification [12,13]. Furthermore, the occurrence of acid rain [14,15], a consequence of natural atmospheric phenomena intensified by anthropogenic activities, biological processes [16,17] and the decomposition of organic matter from plant residues and microbial activities [18], significantly contributes to soil acidification.

Soil acidification is a critical bottleneck for crop production in Ethiopia as it is expanding in area and magnitude and severely limiting crop productivity [19,20]. The central western Ethiopian regions are already showing signs of higher soil acidification that is close to the lower bound limits for most crops. Several studies [10,19,21] indicate that there has been a significant rise in soil acidity throughout the region, which is posing a challenge to sustainable crop production. This region is known for its extensive agricultural activities and widespread crop production due to its favorable biophysical and biochemical conditions. A rise in soil acidity can affect the availability of plant nutrients and increase the uptake of toxic elements (e.g., aluminum, manganese and hydrogen) and the leaching of essential plant nutrients (e.g., calcium, magnesium, sodium and potassium) below the root zone [9,22,23]. In addition to reducing crop yields, soil acidification lowers crop quality and predisposes plants to other biotic and abiotic stress factors [24,25]. Soil acidification unevenly affects various crop species and varieties and can lead to a vicious cycle where farmers either increase the use of fertilizers to gain lost yields or invest in expensive corrective measures such as liming. However, assessing the impact of soil acidity changes on distinct crops is crucial for planning and implementing targeted agricultural interventions in response to a changing climate.

Climate change is the other component of the equation, exerting a significant impact on crop suitability and production. Seasonal and interannual rainfall variability are a leading cause of crop failure and drought in most parts of Ethiopia [26–28]. As the impacts of climate change become more apparent, certain regions in Ethiopia, previously unsuitable for certain crops, are now becoming more suitable, while other regions that were once ideal for those same crops are now becoming less favorable [29]. Several studies have assessed suitability changes at the watershed [30–32] and country [29] scales, while other studies have investigated the dynamics of soil acidity in Ethiopia, considering the causes, the extent of the problem, effects on crop production and potential methods for amelioration [21,33–35]. These studies stress the significance of climate factors and of soil quality in determining crop yields and production potential in Ethiopia. To our knowledge, no studies have assessed the intersection or interaction between these two important factors under current or projected climatic conditions as they have, to date, been considered separately.

There is a need to juxtapose the projected changes in climatic conditions and soil acidity changes on agricultural potential to ensure that agricultural development in Ethiopia (and elsewhere) is sustainable, productive and profitable and remains within planetary boundaries. The aim of this study is to assess the impact of increases in soil acidity on crop suitability in a changing climate in Ethiopia using scenario-based simulations in a crop suitability model that was run with climatic and soil data. Specifically, the objectives are to (i) determine the current suitability extent of four key food crops in Ethiopia, (ii) model the impacts of climate change on the suitability of these food crops by the mid-century and (iii) assess the potential effects of soil acidification on changes in crop suitability for each food crop under climate change using scenario-based model iterations over the crop suitability assessments. Our findings contribute to an enhanced understanding of the interaction between climate change and soil acidity with regard to future crop suitability, which is missing in the current literature. Such information is required by policy makers, extension systems and farmers to design and implement more robust resilience pathways that enhance crop yields and quality without degrading soil resources. Our study also provides insights into potential climate change adaptation challenges, aiming to mitigate the risk of maladaptation.

2. Materials and Methods

2.1. Study Area

Located in East Africa, Ethiopia boasts a diverse topography that spans from 116 m below sea level to towering mountains reaching 4600 m high [36–38], as shown in Figure 1. The country's northern, central and western regions and part of the eastern region are classified as highland plateaus, while the eastern, southern and western areas are predominantly lowlands [36]. The annual rainfall amounts vary significantly across the country, ranging from 2400 mm in the southwest to 500 mm in the northeast. The mean temperature fluctuates from 5 °C in the highlands to about 40 °C in the lowlands [39]. Agriculture, especially crop production, is crucial in Ethiopia as it provides food for the population and contributes approximately 40% of the gross domestic product (GDP). Moreover, an estimated 75% of the country's workforce is employed in the agricultural sector [40].

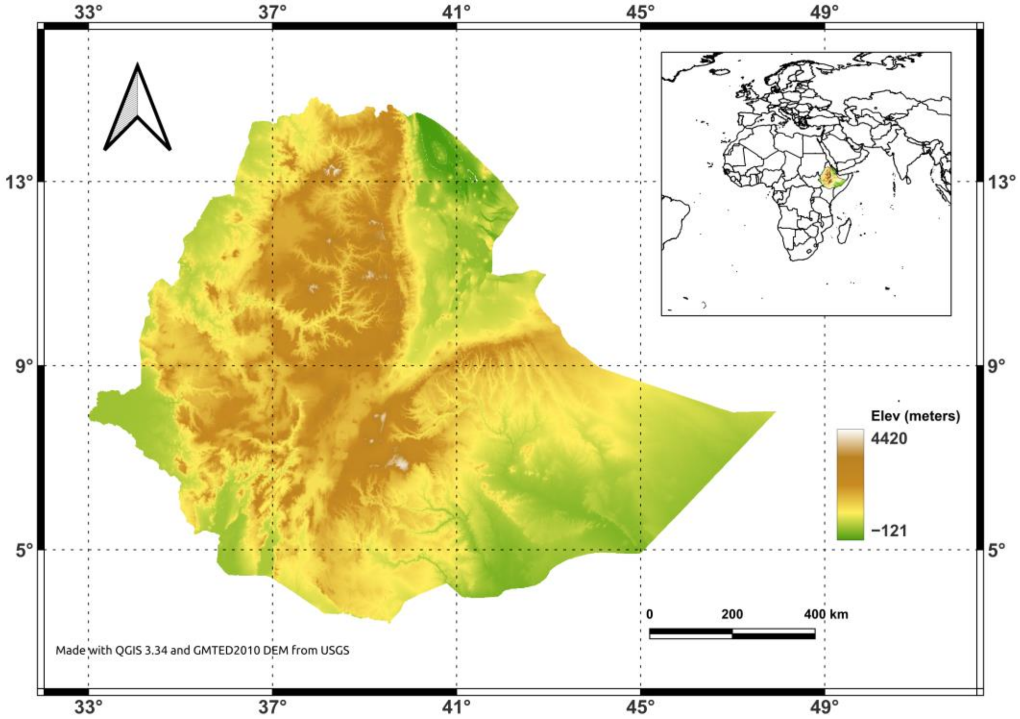

Figure 1. Location of the study area and topographic features of the country.

2.2. Climate and Soil Data

The study used climatic variables such as rainfall and temperature from the WorldClim database (www.worldclim.org). This database provides historical and future (based on Coupled Model Intercomparison Project Phase 6 (CMIP6) Shared Socio-economic Pathways (SSPs) projections) monthly data of rainfall, temperature and other variables at high spatial resolutions (30 s, 2.5 min, 5 min and 10 min). The dataset was calibrated, assuming high spatial autocorrelation, and was generated by computing the absolute or relative difference between global climate model (GCM) outputs for baseline periods (1960–1990) and target years (e.g., 2041–2060), with global cross-validation correlations of 0.99 for temperature and 0.86 for rainfall [41]. Thus, we specifically employed the WorldClim version 2.1 dataset at a spatial resolution of 2.5 min. We opted to use the 2.5 min spatial resolution because of the large-scale nature of the study that covers the whole country. The model was set up for historical (1970–2000) and mid-century (2041–2060) periods under the SSP370 scenarios. The mid-century was selected to align the results with the Nationally Determined Contributions of the Paris Agreement that set 2050 as the target year for climate outcomes. We selected SSP370 as it is now the most realistic pathway considering current greenhouse gas (GHG) emission trends and policy directions. It represents a "Rocky Road" with regional rivalry and high challenges to mitigation and adaptation as countries focus on achieving energy and food security goals within their own regions at the expense of broader-based development. This scenario estimates that global warming will reach 2.1 °C by the 2050s [42]. We selected seven general circulation models under the scenario (Table 1) for this analysis based on their known performances in East Africa. These models were CMCC-ESM2, GFDL-ESM4, INM-CM5-0, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0 and UKESM1-0-LL.

Table 1. Climate model outputs employed for future climate analysis.

Climate Models	Model Descriptions	Refs.
GFDL-ESM4	Geophysical-Fluid-Dynamics-Laboratory-Earth-System-Model	[43]
MPI-ESM1-2-HR	Max Planck Institute for Meteorology, Earth System Model	[44]
MRI-ESM2-0	Meteorological Research Institute (MRI) of Japan, Earth System Model	[45]
UKESM1-0-LL	UK Earth System Model	[46]
INM-CM5-0	Institute for Numerical Mathematics, Climate Model	[47]
CMCC-ESM2	Centro Euro-Mediterraneo sui Cambiamenti Climatici, Earth System Model.	[48]
IPSL-CM6A-LR	Institut Pierre-Simon Laplace, Climate Model	[49]

The topsoil pH data for Ethiopia was obtained from the ISRIC-World Soil Information databases, recognized for providing an extensive and consistent large-scale soil information resource derived from observed soil profiles [50]. The operational framework of ISRIC encourages inclusive and collaborative efforts for assembling, collating and generating global soil information applicable across diverse fields, with a specific emphasis on crop modeling in agriculture [51–53]. This dataset spans the African continent with a spatial resolution of 250 m, encompassing measurements at six standard soil depths: 0–5 cm, 5–15 cm, 15–30 cm, 30–60 cm, 60–100 cm and 100–200 cm. In this study, we employed the topsoil layer (0–5 cm) pH level.

2.3. Crop Suitability Modeling

We used the EcoCrop model for assessing current and projected crop suitability in Ethiopia. EcoCrop is a simplified tool that assesses the crop-specific cropland suitability of various crops by analyzing their ideal ranges of rainfall and temperature during the growing season. It uses the Sprengel–Liebig Law of the minimum to evaluate the most limiting factor for environmental variable responses [54]. EcoCrop is a rule-based model that estimates absolute environmental suitability for each crop type from a combination of dynamic weather variables (monthly) and static soil predictors. For all variables, default parameters indicate the extreme minimum and maximum value beyond which the crop cannot grow (suitability is zero) and a minimum and maximum optimal value within which suitability is one [55,56]. In the midst of extreme and optimal values, suitability is determined with linear interpolation between zero and one. It therefore shows where a species can be grown without major environmental constraints. This model was selected because the EcoCrop crop suitability model is effective for evaluating the suitability of diverse crops, considering the prevailing climatic conditions and soil pH levels. The EcoCrop model requires few crop-specific parameters to run and can be set up for many crops, including those where less detailed ecophysiological information is available to run process-based modeling [57]. It also provides map outputs for spatialized impact and targeting and accommodates scenario-based simulation iterations to visualize how agricultural systems work and identify important drivers of change. The model also requires relatively fewer input data to produce reliable results that match with those models with more sophisticated inputs. In addition, EcoCrop considers the important genotypic variation related to crop growth duration and thermal- and water-related tolerance limits without providing the detailed variety-level information [58]. Table 2 shows the crop types, species, area harvested and yield of four major food crops commonly grown in Ethiopia that we have conducted a suitability analysis on.

Table 2. Key food crop types and species considered in this study.

Crop Name	Scientific Name	Area Harvested (000 ha) [59]	Yield (t/ha) [59]
Teff	*Eragrostis tef* (Zucc.) Trot	3017	1.71
Maize	*Zea mays* L. s. mays	2530	4.24
Barley	*Hordeum vulgare* L.	960	2.45
Wheat	*Triticum aestivum* L.	1950	2.67

2.4. Model Calibration and Validation

We evaluated the model for accuracy by comparing the suitability with reference data. We developed and implemented a comprehensive evaluation of the produced suitability maps as this is important for building confidence in the produced crop suitability maps for climate change and agriculture policy applications. The reference data used for the evaluation was the Global Biodiversity Information Facility (GBIF, www.gbif.org) data. To evaluate our model, we extracted the reported ‘occurrence’ of each crop from 2000 to align with the baseline period, then compared it to the modeled suitable area for that crop. We computed the detection accuracy by evaluating the ratio of GBIF points located within the suitable area to the total number of GBIF points. Subsequently, we converted the absolute suitability values into binary classifications through a suitability analysis based on the model’s performance. To determine the threshold values, we considered geographic locations with observations of a particular crop species exceeding 70% (i.e, model accuracy greater than 0.7) are suitable for that crop.

2.5. Assessing Impacts of Soil Acidification on Crop Suitability under Climate Change

For the EcoCrop input, we used climatological data for the dynamic environmental variables (i.e., rainfall and temperature) for twelve time steps corresponding to the 12 months of a year and static soil pH levels to determine a suitability index ranging from zero to one. To emulate the impacts of acidification on crop suitability, we ran the suitability model with current soil pH values (baseline, bl), and then, we acidified the soil by reducing the soil pH by 0.5 (bl-0.5), 1.0 (bl-1.0) and 1.5 (bl-1.5) while the future climatic data remained the same. These values were selected to encompass the observed ranges of soil acidification over recent decades, arising from a combination of natural processes and anthropogenic factors, such as the suboptimal utilization of inorganic fertilizers [24,35,60]. By combining the rainfall and temperature data with each soil acidity level, we conducted a crop suitability analysis for future climate scenarios (i.e., 2050).

3. Results

3.1. Climate, Soil pH and Crop Suitability in Ethiopia under Current Climate

Figure 2 presents an overview of the baseline (1970–2000) rainfall and temperature climatology and soil pH distribution across Ethiopia. There is a clear contrast given that the rainfall amount is high in the western mountainous parts, whereas it is low in the lowland eastern regions (Figure 2). The temperature is also lower in the central highlands; conversely, it is higher in the country’s eastern areas and along the western boundaries. There are distinct soil pH levels in the country’s western ($pH < 6$), central ($6 < pH < 7.5$) and eastern ($pH > 7.5$) regions.

Table 3 presents the environmental and soil pH requirements based on FAO’s crop ecological requirements database, ranging from minimum to upper optimum values for the four crops considered in this study [61].

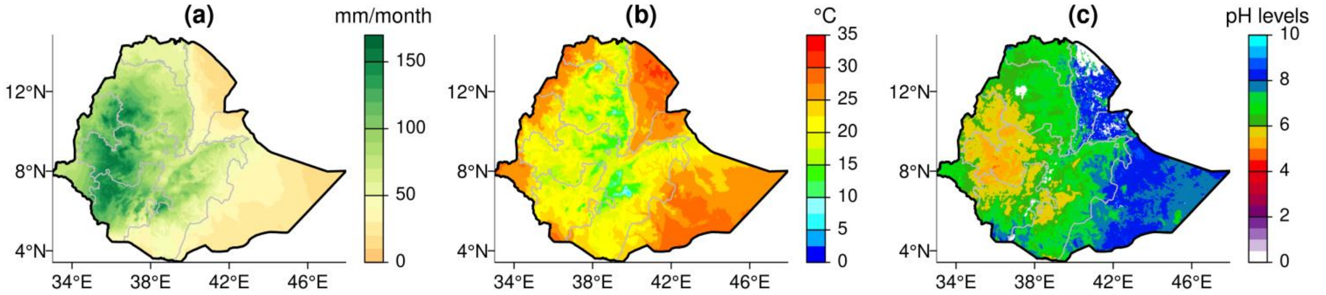

Figure 2. Baseline (**a**) rainfall and (**b**) temperature climatology (1970–2000), and (**c**) current soil pH distribution across the country.

Table 3. Environmental and soil pH requirements for the four crops (teff, maize, barley and wheat).

Crops	Precipitation Range (mm/Month)	Temperature Range (°C)	pH Ranges
Teff	65–389	2–28	5.0–6.5
Maize	49–180	10–33	4.5–7.0
Barley	31–200	2–20	6.0–7.5
Wheat	45–174	5–23	5.5–7.0

Using EcoCrop, we determined the suitability values of each crop in Ethiopia. Figure 3 shows the current suitability of teff, maize, barley and wheat based on the environmental and soil pH level requirements specified in Table 3. The degree of crop suitability has been delineated by the range of values between zero and one. Our results indicate that teff, maize, barley and wheat are all suitable crops for specific regions of the country. Teff, in particular, thrives in areas with high rainfall amounts (90–170 mm/month), moderate temperatures (12.5–22.5 °C) and a soil pH level between 5.0 and 7.0. Similarly, barley and wheat are grown in high-rainfall and modest-temperature regions, although they tend to prefer neutral pH levels along the central and eastern highlands. Maize is a bit more flexible regarding soil acidity levels and is commonly grown in the southwestern parts of the country and along the East African Rift Valley ridges where soil pH levels are between 4.5 and 7.0.

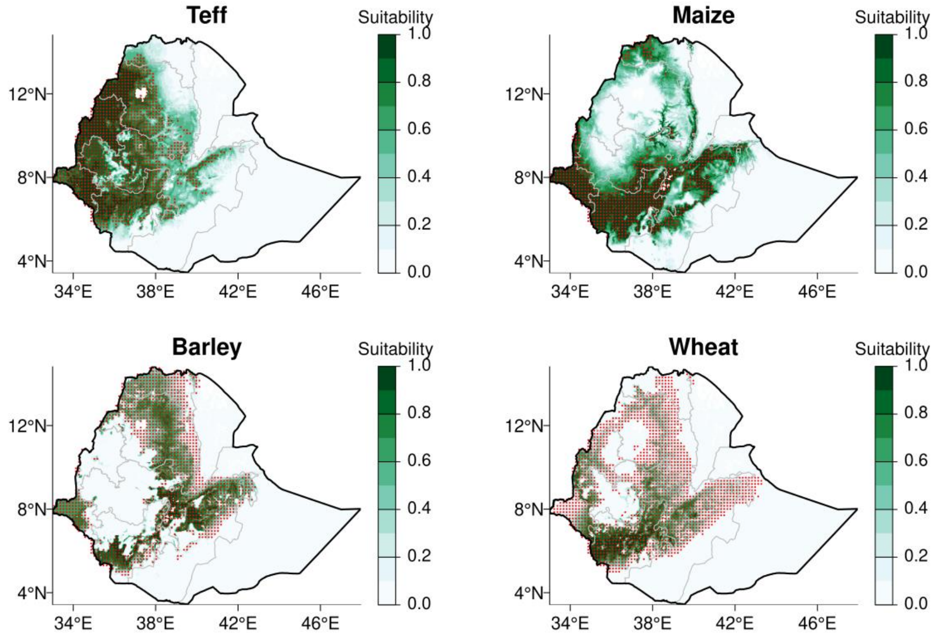

Figure 3. Current crop suitability maps for teff, maize, barley and wheat across Ethiopia. Red hatches overlayed on the maps indicate GBIF observed data points.

3.2. Projected Climate and Crop Suitability in Ethiopia

The future climate change expected by the 2050s is projected lead to a rise in rainfall of up to 18 mm/month in the central north and eastern highlands of Ethiopia (Figure 4). However, no significant rainfall changes are projected for the southeastern and northeastern parts of the country, which are known dry areas (Figure 4a). The temperature is also projected to increase throughout the country with higher warming rates up to 2.1 °C in the northern, south central and western regions by 2050 (Figure 4b).

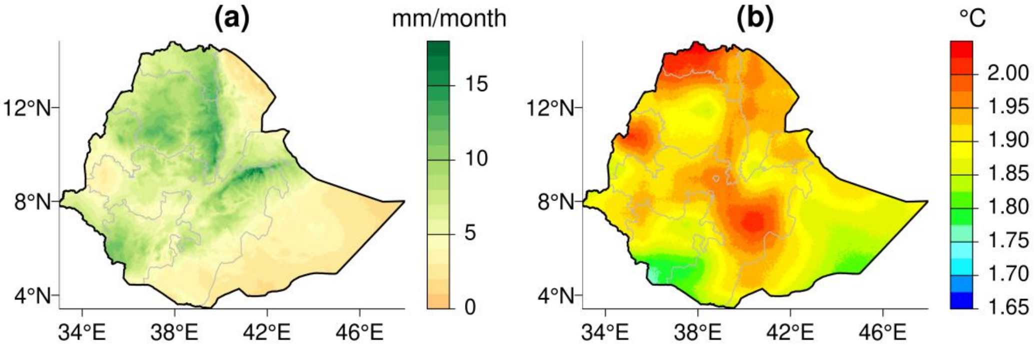

Figure 4. (**a**) Rainfall and (**b**) temperature changes by the middle of the 21st century (2041–2060) in Ethiopia with respect to the historical period (1970–2000).

Figure 5 illustrates the difference in suitability between future (2050) and current crop land areas for four distinct crops in Ethiopia, maintaining consistent soil pH levels with the present distribution across the country. According to the projected 2050 climate data, the findings suggest that teff, maize and barley will thrive in land area along the East African Rift Valley ridges (specifically, along the tips of northeastern highlands), as these regions are anticipated to become more favorable due to increased rainfall and a moderate temperature rise. However, the suitability of wheat appears scattered, primarily in the central eastern highlands.

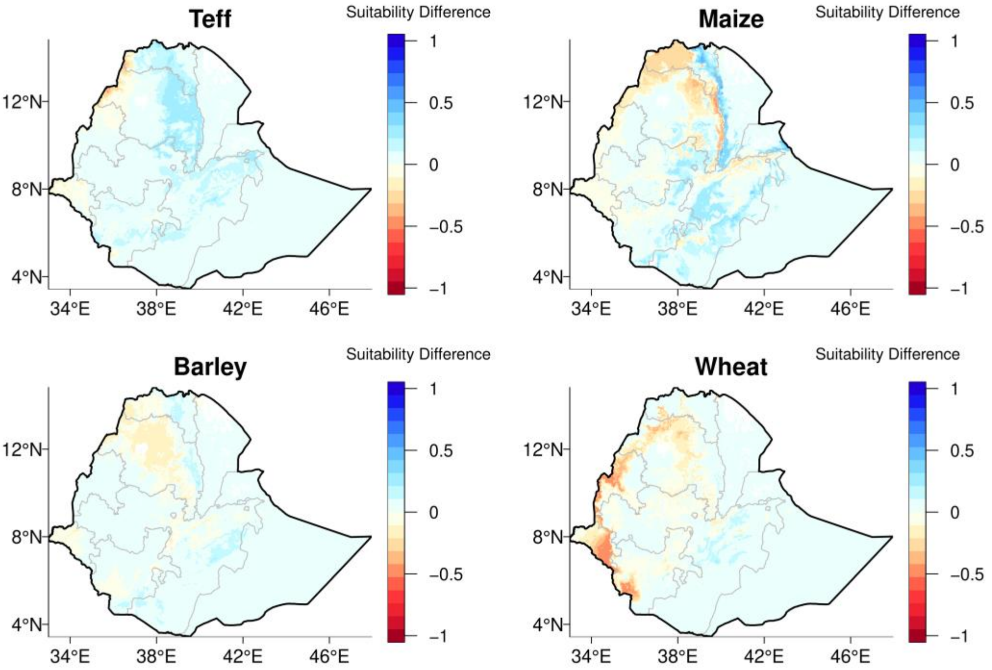

Figure 5. Changes in future crop suitability by the 2050s with respect to the current suitability using SSP370 future climate scenario for rainfall and temperature data, while the soil pH levels are the same as the present soil pH distribution across the country.

Additionally, the changes in the suitability due to climate change are shown by the area density plots in Figure 6. Highly suitable areas (>0.8) for teff will increase compared to the current climatic conditions, but these will decrease for barley and wheat, with no changes for maize. Our results show that no major shifts are projected in already marginal areas where suitability is below 0.25 between the current and the future climatic conditions, but shifts will happen in areas that have moderate (between 0.5 and 0.75) suitability. The density distribution for maize is quite distinct, with most regions being either highly suitable or unsuitable. Both the highly suitable areas (>0.75) as well as the moderately and marginally suitable areas (>0.5) will likely increase for maize under future climate change (Figure 6).

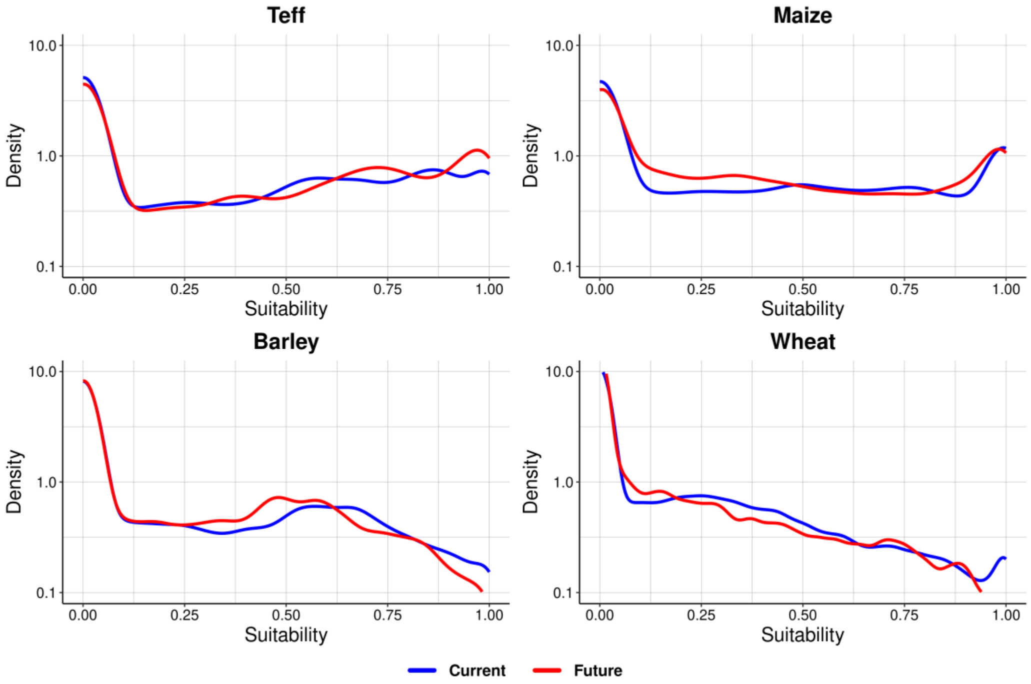

Figure 6. Density plots showing the changes in the distribution of the suitability for teff, maize, barley and wheat in Ethiopia between the current and projected climate. When the blue line is above the red line, it shows that the area with that suitability is higher under current conditions and vice versa. The Y-axis has been scaled to log10 to improve visibility.

3.3. Effect of Different Levels of Soil Acidification on Changes in Crop Suitability under Climate Change

As future soil acidity levels are expected to increase due to natural processes, suboptimal inorganic fertilizer usage and improper land management practices throughout the country [10], we simulate the potential impacts on crop suitability. According to Figure 7, by the 2050s, there will be changes in crop suitability as the soil pH level decreases by 0.5 from its current levels. Teff is expected to lose a significant size of suitable land in the western central regions. Similarly, barley and wheat will become less viable in most areas in the west. On the other hand, maize has gained more favorable land areas along the central eastern highlands and southwestern tips (Figure 7). The unsuitability for teff, barley and wheat is because the soil acidity level will drop below the lower limit of these crops in most parts of the western regions (Figure 7). However, maize's suitability in the country's western areas will not be much affected due to its lower pH limit, which can be as low as 4.5. In addition, maize is gaining more territories over the central eastern region due to the decrease in pH level that renders the soil pH level within the requirements for maize growth.

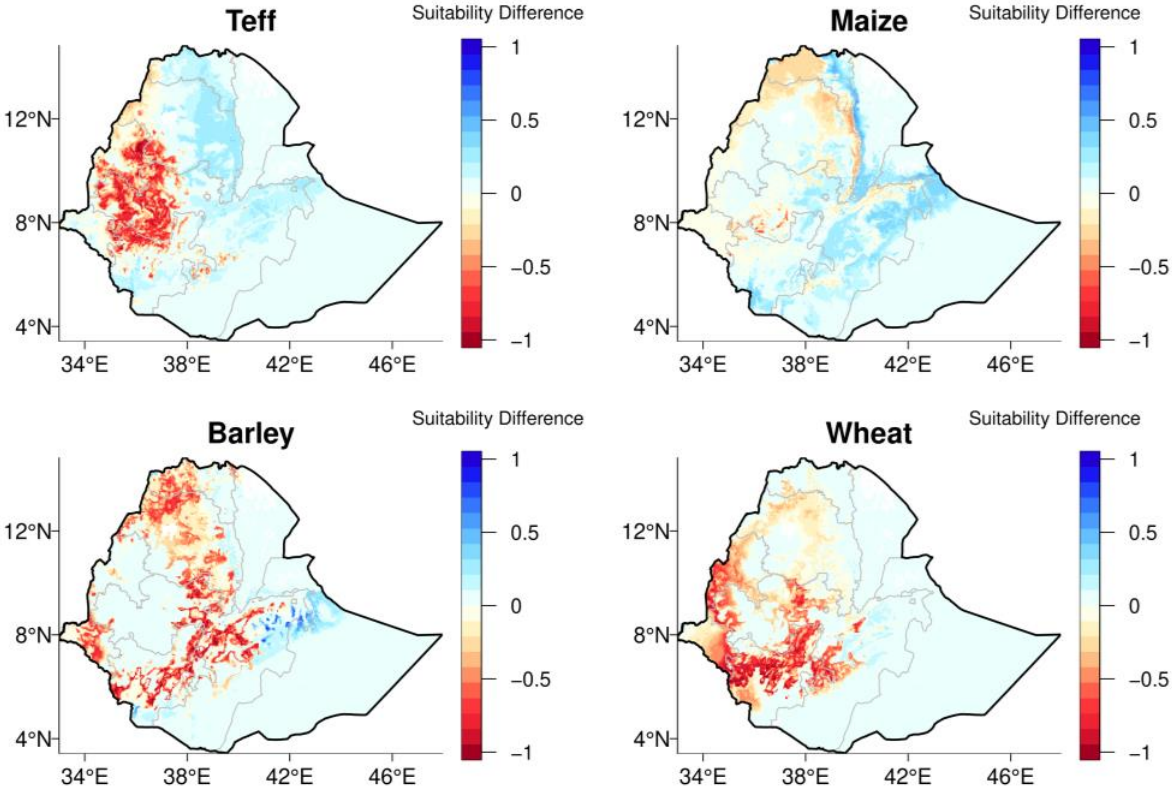

Figure 7. Changes in future crop suitability by the 2050s with respect to the current suitability using SSP370 future climate scenario for rainfall and temperature if the soil pH levels decrease by 0.5 from the current distribution.

As shown in Figure 8 (soil pH levels decrease by 1.0) and Figure 9 (soil pH levels decrease by 1.5), it is evident that a further increase in soil acidity would have a more negative impact on crops. The decrease in soil pH leaves most parts of the western region of Ethiopia acidic and unsuitable for all crops. Thus, there is a trend of crop suitability migrating towards the eastern highlands due to the decrease in soil pH level and a change in soil properties from basic pH to neutral pH levels. It has also been noted that soil pH levels in the northeastern and southeastern regions decline to neutral pH levels. However, the environmental variables (i.e., rainfall and temperature) required for these crops' growth do not meet the minimum requirements. Therefore, there is little or no enhancement in crop suitability in these regions.

Compared to the historical (1970–2000) period, due to a changing climate, we project increases by 5.1%, 0.08%, 1.8% and 0.4% for teff, maize, barley and wheat, respectively, in suitability by 2050 (Figure 10, dark blue bar). While the soil pH distribution is the same as the current state, climate change creates more favorable areas for all crops along the central and eastern highlands. The increase in suitable land arises because of an increase in rainfall and temperature over the highlands, which meets the basic environmental requirements of the crops. However, a slight increase in soil acidity by 0.5 (Figure 10, light blue bar) leads to suitable areas for teff, barley and wheat dropping by −3.1%, −9.0% and −11.7%, respectively. In contrast, suitable land for maize increases by 2.03%, which is due to soil pH level changes from basic to neutral pH levels in the central eastern highlands and the gain of new favorable land areas. Comparatively, maize suitability remains the same in the western regions due to its soil acidity tolerance up to the 4.5 pH level. Furthermore, teff, maize, barley and wheat lose −17.8%, −1.6%, −24.1% and −22.6% of their suitable area, respectively, by decreases in soil pH level by 1.0 (i.e., light red bar in Figure 10).

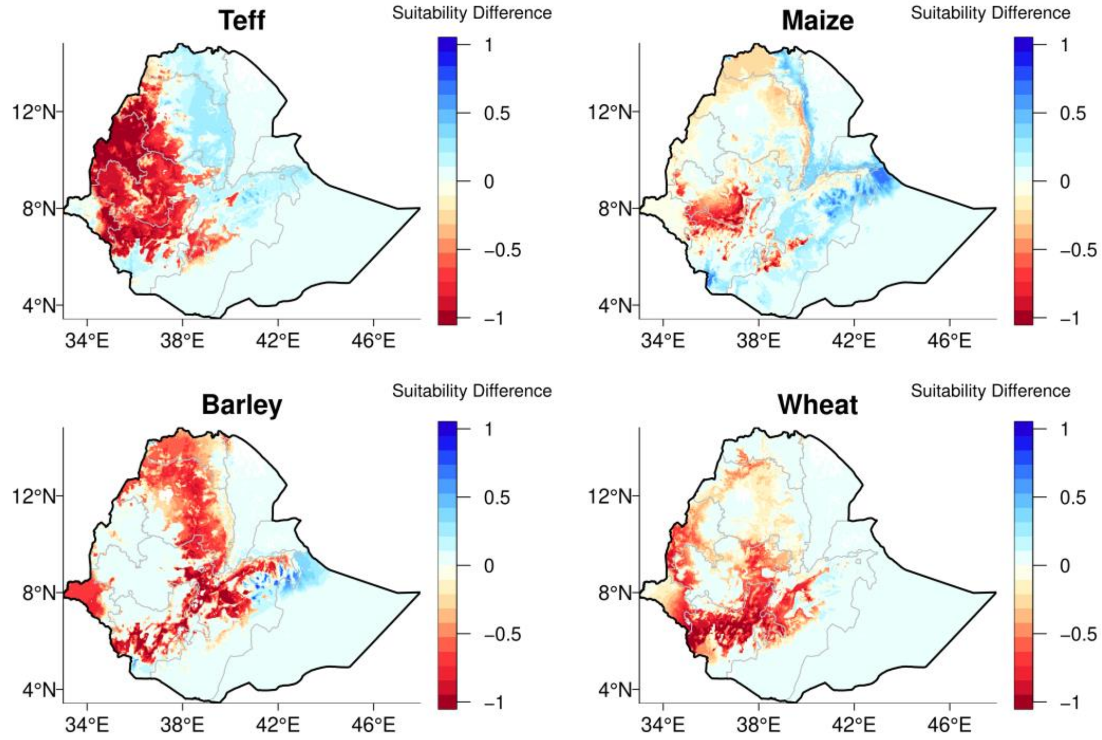

Figure 8. The same as Figure 7, but the soil pH levels decrease by 1.0 from the current distribution.

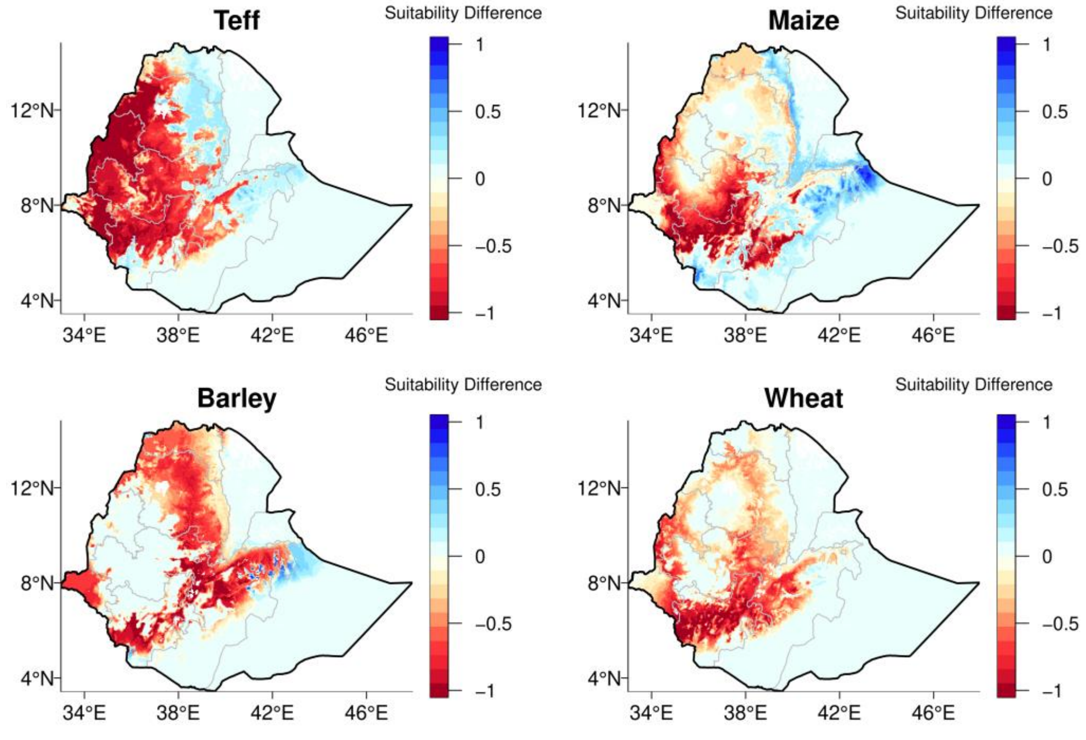

Figure 9. The same as Figure 7, but the soil pH levels decrease by 1.5 from the current distribution.

The worst-case scenario of declining soil pH level by 1.5 (i.e., red color bar in Figure 10) decreases the teff, maize, barley and wheat suitable land areas by −26.7%, −8.7%, −30.9% and −34.3%, respectively. Therefore, the increase in soil acidity is likely to leave the western and most regions of the country unsuitable for all crops once the soil pH level crosses the lower threshold limit of all crops.

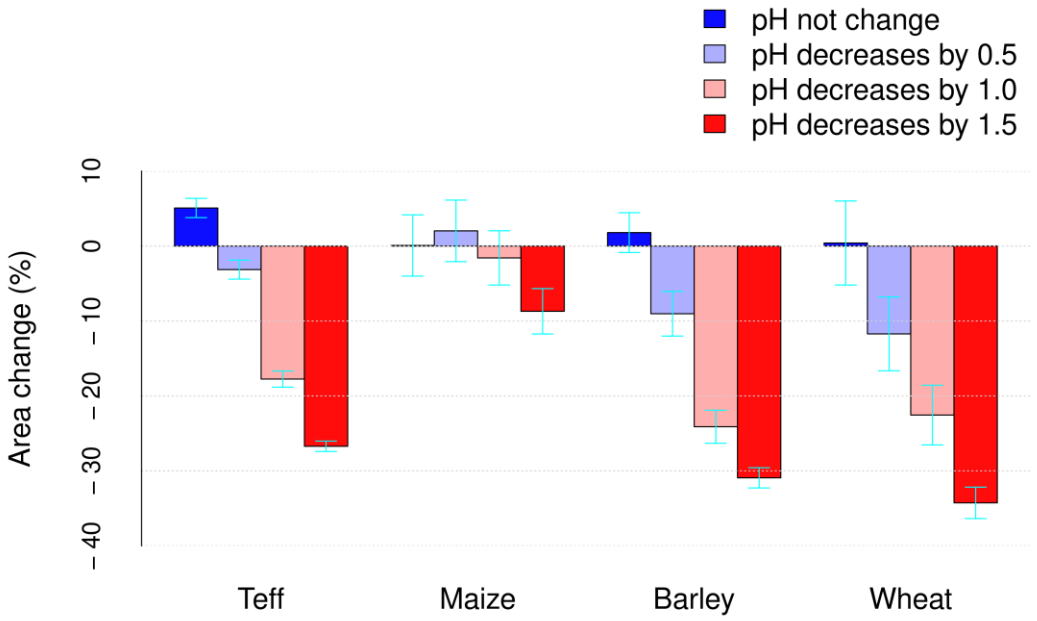

Figure 10. Changes in crop suitable areas across the country under the future climate (2050) and soil pH level changes.

4. Discussion

In this study, we investigated the combined effect of soil acidification and future climate change on crop suitability in Ethiopia. Our approach utilized a crop suitability model to assess the impacts of climate change on four key food crops (with and without adjusted soil pH parameters) under current and projected 2050 climatic conditions for Ethiopia. We selected Ethiopia as a case study because soil acidification is recognized as a prevailing issue in the country's most cultivable lands [8–11,19,21]. The noteworthy recent substantial increase in crop yields, attributed to intensified agricultural activities, underscores the increasing pressure on finite land to meet the rising demands imposed by a growing population, enhanced agricultural trade in the region, socioeconomic development and associated shifts in dietary preferences. Our study (i) provides a spatially explicit assessment of climate change impacts on four key food crops in Ethiopia; (ii) identifies where and for which crops soil acidification have impacts on crop suitability and (iii) provides an integrated study of the impacts of soil acidification and climate change impacts on cropping systems.

The climate of Ethiopia is spatially variable, as shown by the rainfall and temperature climatologies, with a significant influence on crop potential in the country. Considerable areas in the country are dry, with rainfall of less than 100 mm per month. These areas correspond with warm areas where temperatures are above 22.5 °C. This interaction between temperature and rainfall is important as it influences potential evapotranspiration which affects the climatic water balance that in turn determines the length of the growing period, crop water requirements and crop types to be grown [62–64]. In a country where less than 5% of the total cultivated land is irrigated [65], any spatial and temporal changes to this balance between temperature and rainfall are likely to have significant impacts on agricultural production. In this study, we confirm the link between rainfall and soil pH in Ethiopia, where soils in the high-rainfall areas are acidic, while those in the low-rainfall areas tend to be alkaline [19,35]. The highly acidic soils are the nitisols, alisols, and fluvisols, which encompass some of the most intensive crop production areas in Ethiopia [66].

We also report a differential response to soil pH among the four crops in terms of their suitability in Ethiopia. Teff is distributed across highly acidic areas, while maize, barley and wheat are less commonly found in acidic soils. The finding that maize is not suitable in acidic areas is not surprising; as a crop, it is known to prefer soils with a near-neutral pH. Indeed, grain yield reductions of between 3 and 71% have been attributed to acidic soils in maize field trials [67,68]. The variation in yield reduction under low soil pH is explained by the level of acidity in the soil, the agro-climatic conditions of the environment and the genotypes of maize varieties. It was expected that common wheat would be similarly or more acidic-soil-sensitive than maize [69]. More studies on the genotype X environment interactions in relation to the soil acidity responses of both maize and common wheat genotypes in Ethiopia need to be performed.

Our assessment of changes in climate variables shows an increase in both temperature and rainfall by 2050, in line with many reported projections. While the increases in temperature are apparent due to emissions-driven global warming, the increase in rainfall for Ethiopia and the whole East African region is surprising, especially when it is not aligned to observed trends (the East Africa Paradox). Similar increases in precipitation have been reported in other studies [65,70,71]. An evaluation by [72] of ERA5 data shows positive changes over East Africa in rainfall and concludes that the representation of the cycle of precipitation is substantially improved in the most recent general circulation model. It is in this context of increasing rainfall and temperature where crop suitability models are required to investigate if, where and by how much suitability thresholds for crop growth and performance are crossed under climate change.

Our findings suggest no major changes in crop suitability for maize, barley and wheat in Ethiopia by the mid-century using current soil pH values, while climate change will benefit teff suitability. Positive crop production outcomes under climate change have previously been reported for Ethiopia, influenced by the projected increases in rainfall [73–76]. The findings from this study are noteworthy in two ways. Firstly, the country can position itself to become a regional food basket, leveraging the increasingly favorable climatic conditions for major crop production. This is possible by building the capacity of farmers in the remaining and newly suitable areas through supporting agricultural inputs and extension services, while establishing value chains and markets to harness the outputs. This is an important finding because much of the current research on climate change reports negative impacts, without recommendations on how to deal with projected positive climate change impacts such as those reported in our study. Secondly, while the overall results show a positive or no impact of climate change on the crop suitability of the four crops, spatially explicit models such as those used in this study show some areas as having negative impacts. Therefore, "broad brush" adaptation planning should not be used as a blunt instrument based on national trends, but should be targeted towards where adaptation interventions are most needed at the local level. Thus, locations with projected negative impacts on crop suitability (especially for maize and teff) are revealed in our results where adaptation planning should focus to strengthen resilience. Targeting adaptation interventions based on scientific evidence is important for generating expected outcomes, avoids maladaptation and ensures the best investment of scarce resources to address the climate change. For example, we suggest agricultural systems' transformation where farmers begin to grow the most suitable crops in their areas to meet their food requirements and/or for markets, with possible transport and storage systems enabling exchange and trade in agricultural commodities between regions made possible or easier or less costly. The development and distribution of crop varieties that are more tolerant to the climatic and soil conditions will also help in ensuring sustaining agricultural production.

Our most significant finding is that neglecting to address soil pH will lead to more pronounced climate change impacts on all crops in Ethiopia, potentially transforming projected positive impacts into negative ones, especially for teff, barley and wheat. Certainly, this impact increases with the severity of the soil acidification and there is a need to design and implement intervention measures to avoid this outcome. Indeed, it has been demonstrated that it is not possible to supply food, feed, fiber and fuel to support a growing world population in a changing climate without taking care of soil health [77]. In support of this view, [78] indicated that it is important for agricultural intensification and land management efforts to focus on soil health management to realize multiple benefits at multiple scales for crop production, ranging from water use and quality, human health, animal health, climate and biodiversity. Our study demonstrates a crucial interactive link between climate and soil pH, influencing crop potential in tropical regions. Hence, it is imperative to include soil health in the ongoing discourse on the impacts of climate change on crops. Soil health management strategies such as the use of organic amendments, conservation farming methods and others should be considered as integral aspects in agricultural resilience building.

We applied a crop suitability model to investigate the impact of soil acidity on crop suitability under climate change in Ethiopia. While our results are robust based on the data and model used, users of such results should consider some caveats associated with our presented approach. Our future projections of crop suitability are produced by combining a mechanistic understanding of crop requirements with climate and soil data. However, other factors such as agronomic practices (e.g., precision agriculture, alternative N sources, e.g., legumes) are not explicitly captured, and yet they may be important at localized levels of farms and fields. In our study, we provide wide-scale results for agricultural planning purposes, which would need to be further downscaled for each localized area in each grid pixel. Our modeling also assumes that the established equilibrium between current climate and soil data with crop requirements remains the same under the future climate. Yet, this may change due to genetic improvement in crops for new environments and biophysical conditions over time. Lastly, since our study is a national-scale study, the area suitability calculations also include other land that may not be available for agricultural production because of the resolution, and this should be factored in when using the results for decisions.

5. Conclusions

We investigated the combined effect of soil acidity and climate factors in determining the potential of four key food crops (teff, maize, barley and common wheat) in Ethiopia under changing climate conditions. Our study is important for agricultural resilience building, as integrated studies that consider both soil health and climate are rare. We conclude that by 2050, the climate in Ethiopia is projected to undergo shifts characterized by increases in both rainfall and temperatures. The interaction between these climatic changes and shifting soil pH is anticipated to impact crop suitability. Using default soil pH values, we project that there are no significant changes in the suitability of maize, barley and wheat, while an increase in the suitability of teff by 2050 will occur due to projected increases in rainfall in the country. However, and perhaps most importantly, the no change and positive changes in suitability under climate change is eroded if the soil acidifies, with the severity of the change corresponding to the magnitude of the change. It is therefore recommended that due consideration be given to soil acidity in planning agricultural adaptation strategies. Intensification measures that lead to increased soil acidity could potentially reverse expected benefits. Future research should consider understanding the relative weights of climate versus soil factors in determining crop suitability to identify what to focus on more in terms of designing and implementing adaptation investments. It will also be important to understand the mechanisms of impact of soil pH on crop suitability by using process-based models that explain the limiting pathways of the variables on crops (as this is not shown with our models). It would also be worthwhile to upscale our study to regional, continental and global scales to further understand how the interaction between the soil and the climate factors will play out in influencing crop suitability under climate change at larger supra-national scales.

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