Future Suitability of Arabica Coffee in Rwanda: Evidence from coffee suitability modelling using Downscaled Climate Data

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Future suitability of Arabica coffee in Rwanda: Evidence from coffee suitability modelling using downscaled climate data

Delice Izere[1], David Abigaba[2], Ananya Mazumder[2], Olivier Niyompuhwe[3], Janet Umuhoza[3], Kora Rösler[3], Sabine Undorf[2], Christoph Gornott[2,4], Sophie von Loeben[2]

[1]African Institute for Mathematical Sciences – Research & Innovation Center (AIMS-RIC), [2]Potsdam Institute for Climate Impact Research (PIK), [3]Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, [4]University of Kassel

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Table of Contents

List of Figures

List of Tables

1. Introduction

Rwanda's agriculture sector, which directly sustains more than 70% of the rural population, is almost entirely rain-fed and therefore highly vulnerable to climate variability in rainfall timing, temperature, and seasonal patterns (Minagri, 2022). Over recent decades, climate change has intensified these risks across East Africa through rising temperatures, erratic rainfall, prolonged droughts, and more frequent extreme weather events (Intergovernmental Panel on Climate Change, 2021).

Global climate models (GCMs) provide broad trend data but operate at coarse spatial resolutions of around 50 km, insufficient to capture Rwanda's complex, hilly topography (Fick & Hijmans, 2017; Frieler et al., 2017). Downscaled climate data addresses this gap by offering higher spatial resolution, enabling more accurate local assessments of how changing conditions affect agricultural suitability. When made available to farmers, planners, and policymakers, such information can underpin more sustainable and climate-resilient agricultural planning.

Crop suitability entails the extent to which climatic conditions and environmental factors in a given area enable the growth of a specific crop, completing the growth cycle. It can serve as a critical planning tool for matching the right crops to the right locations. Even modest shifts in temperature or precipitation can significantly alter suitable growing zones. Research across East Africa has shown that climate change is already driving suitability for crops such as coffee and beans away from traditional lowland areas toward higher altitudes (Bunn et al., 2015; Chemura et al., 2021; Ricciardi et al., 2021). Rwanda, with its steep terrain and dependence on rain-fed agriculture, is particularly exposed to such shifts.

Understanding these changes is essential for adaptation planning at both national and subnational levels. Agriculture sits at the centre of Rwanda's economy and features prominently in key policy frameworks, including the Green Growth and Climate Resilience Strategy and the National Adaptation Plan (Republic of Rwanda, 2019). Crop suitability assessments can directly inform land-use decisions, identify vulnerable regions, guide crop diversification, and support extension services.

This study focuses on coffee, which is Rwanda's most economically significant export crop, cultivated predominantly by smallholder farmers in high-altitude regions, to assess how climate change may reshape its suitability across the country. Given coffee's sensitivity to temperature and rainfall, it serves as an ideal indicator crop for evaluating broader climate-agricultural dynamics in Rwanda.

2. Context of Rwanda and Study Area

Rwanda is a small, landlocked country in East Africa with a total land area of 26,338 km² (Republic of Rwanda, 2018). It is bordered by Uganda to the north, Tanzania to the east, Burundi to the south, and the Democratic Republic of Congo to the west. With a population of more than 13.2 million and an average population density exceeding 500 inhabitants per km2, Rwanda is one of the most densely populated countries in Africa (Republic of Rwanda, 2018).

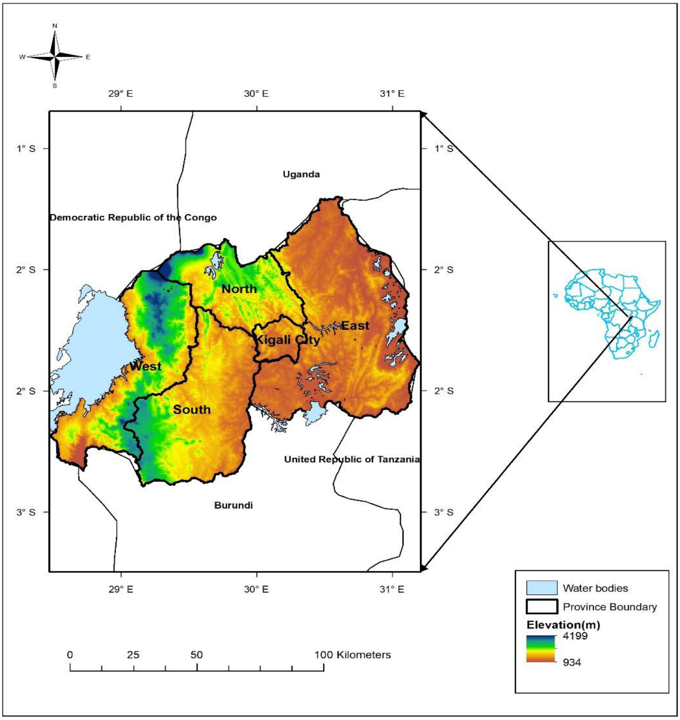

Figure 1. Study area map of Rwanda showing elevation, provincial boundaries, neighboring countries, and the location of Rwanda within Africa.

2.1. Coffee production in Rwanda

Nearly three quarters of the population live in rural areas and agriculture remains the backbone of the economy, employing about 70% of labor force and contributing 25-30% of GDP (Austin, 2020; Country official statistics, 2025; World Bank, 2021). Most farming is carried out by smallholder households who rely almost entirely on rainfall and cultivate on steep, terraced hillsides. The dominant food crops are bananas, beans, cassava, maize, sweet potatoes, Irish Potatoes and sorghum, while coffee (predominantly high-quality Arabica) and tea are leading export crops and major sources of foreign exchange. Rwanda's steep hills and landscapes have given the country the name "Land of a Thousand Hills." The country's elevation varies significantly, starting from about 900 meters above sea level in the east and rising to around 4,507 meters in the volcanic area in the north (Republic of Rwanda, 2019). The varying elevation in the country makes some areas warmer or wetter than others. Rwanda has a tropical highland climate with two rainy seasons: one from March to May and another from September to November. Rainfall also differs across the country, from less than 800 mm in some eastern areas to more than 1,500 mm in the western highlands (World Bank, 2024).

Arabica coffee is one of the most important export crops in Rwanda and is very central for both farmers and the national economy. According to the National Agricultural Export Development Board (NAEB), coffee brings in a large part of the country's agricultural export earnings, with annual revenues usually between 60 and 70 million USD, depending on global market conditions (NAEB, 2025). More than 400,000 smallholder farmers depend on coffee as their main source of income. Rwanda produces about 16,000 to 21,000 metric tons of coffee each year, mostly Arabica (Food and Agricultural Organization (FAO), 2026).

Coffee is mainly grown in the Western, Northern, and Southern provinces, where altitude is between 1,200 and 2,000 meters, and cool temperatures and fertile volcanic soils provide good conditions for its growth.

2.2. The role of Rwandan women in coffee production

In Rwanda, women play a central role in the agricultural sector, with 63.9% of women employed in agriculture, forestry and fishing (NISR, 2023). Compared to other countries, women in Rwanda also enjoy greater access to financial services and a relatively lower time burden; the country scored 0.91 on the Women's Empowerment in Agriculture Index (Rosenbach et al., 2023). Understanding the role that women play in agriculture is an important step toward understanding how climate change disproportionately affects vulnerable populations, as women farmers often face compounded risks from shifting weather patterns, resource scarcity, and reduced crop yields, while simultaneously being key agents in building climate-resilient agricultural systems. Despite their high participation, women are disproportionately engaged in subsistence farming, while men dominate commercial agriculture (Nsengiyumva et al., 2022).

Women are central to Rwanda's coffee production. Approximately 70% of all workers in the coffee sector are women (Lloyd-Sherlock et al., 2015), as cited in van Kollenburg and van Weert (2024). Rwanda's coffee is cultivated primarily by 400,000 smallholder farmers and their families, with family members playing a crucial role in caring for coffee trees and hand-picking cherries (van Kollenburg & van Weert, 2024). Women's participation spans multiple stages of the production process, from planting and weeding to harvesting and transport to washing stations. However, women are predominantly concentrated in the lowest-paid roles, such as working at coffee washing stations, while men tend to dominate higher-paid activities including sorting, buying coffee beans, and managing companies (Center for the Promotion of Imports (CBI), 2019). This gendered division of labour means that despite their indispensable contributions, women remain largely confined to the lower rungs of the coffee value chain.

Understanding the structural position of women in Rwanda's agricultural and coffee sectors sets the stage for a deeper examination of how gender shapes vulnerability and resilience. The following section explores the specific dimensions of gender inequality in Rwandan agriculture that both reflect and reinforce women's constrained capacity to adapt to climate change.

3. Crop suitability modeling

Crop suitability modeling is a spatial analytical method that evaluates the potential of a given area to support the growth of specific crops based on their environmental requirements. It integrates biophysical parameters including soil properties, climatic variables (temperature, precipitation), topography, and land use to assess crop-environment compatibility and delineate areas where a crop is likely to perform well (Estes et al., 2013; Kihoro et al., 2013; Tümer et al., 2026).

Contemporary approaches increasingly combine geographic information systems (GIS), remote sensing, multi-criteria decision methods such as the Analytic Hierarchy Process (AHP), and machine learning techniques to produce objective, spatially explicit, and data-driven suitability maps (Tümer et al., 2026). Among these, species distribution models such as MaxEnt, originally developed for ecological applications, are now widely applied to crops, as they can effectively capture complex, nonlinear relationships between crop occurrence and environmental conditions (Phillips et al., 2006). Ensemble modeling approaches, which combine outputs from multiple methods, further improve reliability by reducing prediction uncertainty (Breiner et al., 2015).

Together, these tools make crop suitability modeling an essential instrument for agricultural planning, supporting evidence-based decisions on crop selection, spatial zoning, and adaptation to climate variability and change.

4. Research objectives

The main objective of this study is to assess how climate change may influence the suitability to grow arabica coffee in Rwanda using down-scaled climate data. The specific objectives are:

1. To model the suitability of coffee under both present and projected climate scenarios.

2. To identify potential shifts in suitable growing areas and provide insights that can support climate-resilient agricultural planning.

5. Literature review

5.1. Climate change impacts on agricultural systems

Sub-Saharan African agriculture is particularly susceptible to climate change owing to its heavy dependence on rain-fed production systems and limited adaptive capacity (Gebrechorkos et al., 2019; Niang et al., 2014). Extreme events such as droughts and floods already pose significant threats to regional crop production, pressures that are further compounded by rising temperatures and increasing rainfall variability (Gebrechorkos et al., 2019). These climatic stresses are projected to intensify throughout the twenty-first century, with far-reaching negative consequences for food security and rural livelihoods (Gebrechorkos et al., 2019; Intergovernmental Panel on Climate Change, 2021).

Rwanda's agricultural sector is especially sensitive to climatic shifts given the country's pronounced mountainous terrain (Iradukunda et al., 2024). Altered rainfall patterns disrupt planting calendars and crop development cycles, while rising temperatures are gradually pushing favorable growing conditions to higher altitudes, rendering the lowland areas where agriculture has historically been concentrated increasingly less viable (Ovalle-Rivera et al., 2015). Addressing these challenges requires fine-scale analysis capable of informing adaptation strategies tailored to local conditions. This calls for the integration of high-resolution climatic data with analytical methods that adequately account for Rwanda's complex topography and diverse microclimates, improving the precision with which future shifts in crop suitability can be projected (Fick & Hijmans, 2017).

5.2. Gender specific vulnerabilities to climate change

The climate shocks described above are projected to disproportionately affect women farmers. Their capacity to adapt is shaped by pre-existing structural disadvantages; as those who typically hold the least land and have the most limited access to productive assets, women face significant constraints in adopting climate adaptation (Bizoza, 2016; Clay & Yurco, 2024). Female-headed households are particularly affected, as lower incomes and smaller landholdings frequently prevent them from making the investments that adaptation requires (Nsengiyumva et al., 2022).

Agricultural policies also tend to overlook gender dimensions due to an incomplete understanding of food security dynamics and household decision-making structures. Weather information, for instance, is commonly disseminated through television on the assumption that it reaches farmers broadly as a mass communication medium. However, evidence shows that women farmers are considerably less likely than men to access information through this channel, relying instead on peer networks and community-based sources (Gumucio et al., 2020).

5.3. Climate sensitivity of arabica coffee

Arabica coffee (Coffea arabica) is among the most climatically sensitive commercial crops, with temperature and rainfall exerting strong influence over both yield and bean quality. In Rwanda, production is concentrated in high-altitude zones between approximately 1,200 and 2,000 meters above sea level, where cooler temperatures (18–22°C) and well-distributed rainfall create favorable growing conditions. Even modest temperature increases, however, can reduce productivity and quality, particularly in lower-lying areas already operating near the climatic thresholds for viable Arabica cultivation (Magrach & Ghazoul, 2015).

Projected climate changes are expected to drive a significant upward shift in suitable growing areas across Rwanda and East Africa more broadly. Estimates suggest that up to 56% of currently suitable Arabica zones could become less viable by 2050, while new potential areas emerge at higher elevations (Bunn et al., 2015; Magrach & Ghazoul, 2015; Ovalle-Rivera et al., 2015). Beyond temperature, altered rainfall patterns pose additional risks by disrupting flowering and fruit development cycles (DaMatta et al., 2007). Warming conditions are also expected to expand the range of pests and diseases, including the coffee berry borer (*Hypothenemus hampei*), which can colonize higher altitudes as thermal barriers diminish (Jaramillo et al., 2011).

While higher-altitude areas may gain suitability, many of these zones coincide with ecologically sensitive environments, including montane forests. This raises important concerns about land-use conflict between agricultural expansion and environmental conservation (Magrach & Ghazoul, 2015). In Rwanda's context, poorly managed suitability shifts could place significant pressure on mountain ecosystems, underscoring the need for spatially informed planning.

These dynamics reinforce the value of rigorous crop suitability assessment as a basis for evidence-based decision-making in coffee production and land-use policy. As established earlier in this study, global climate models operate at spatial resolutions too coarse to capture the microclimatic variation driven by Rwanda's complex terrain. Downscaled climate data, aggregated across seasons, addresses this limitation by resolving local temperature and rainfall gradients with greater precision. This produces suitability maps that more faithfully represent actual growing conditions, improving the reliability of model outputs and their utility for identifying priority areas for agricultural planning and climate adaptation.

5.4. Crop suitability studies in Rwanda and East Africa

Global suitability projections show that climate change is expected to reduce the area suitable to grow Arabica and Robusta coffee by half by 2050 (Bunn et al., 2015; Grüter et al., 2022; Magrach & Ghazoul 2015; Ovalle-Rivera et al., 2015)"plainCitation":"(Bunn et al. 2015; Grüter et al. 2022; Magrach and Ghazoul 2015; Ovalle-Rivera et al. 2015. Some of these studies highlight East Africa as one of the world's region least impacted and potentially profiting from climate change to some extent, with possibilities to shift coffee production to higher altitudes thereby offsetting suitability losses in lower altitudes (Bunn et al. 2015; Grüter et al. 2022; Ovalle-Rivera et al. 2015) the likely effects of future climates are already a concern. Forward-looking research on adaptation is therefore in high demand across the entire supply chain. In this paper we seek to project current and future climate suitability for coffee production (Coffea arabica and Coffea canephora. However, these regional projections obscure significant challenges at the farm level. Most coffee farmers in East Africa are smallholders cultivating less than one hectare of land, for whom even marginal shifts in suitability carry direct consequences for income and food security. Unlike large-scale commercial producers, smallholder farmers cannot readily relocate production to newly suitable areas at higher altitudes, as this would require access to land, capital, and infrastructure that most do not possess. Furthermore, the upward expansion of agricultural land into higher-altitude zones raises serious concerns about deforestation and the degradation of montane ecosystems, creating tension between agricultural adaptation and environmental conservation goals.

de Aquino et al. (2022) found that Robusta coffee production in eastern Congo and western Uganda was particularly vulnerable to the impacts of climate change. In Ethiopia, a decline of 39-59 % of the current suitable areas is projected by 2100, which could be more than offset by relocation of coffee production within the country (Moat et al. 2017), though this would carry the deforestation and land-use pressures noted above. However, Chemura et al. (2021) find that while the overall suitability to grow coffee in Ethiopia will increase, the suitability to grow specialty coffee will decrease. East Africa is also expected to experience an increase in the number of coffee pests due to climate change: Jaramillo et al. (2011) project an increase in the coffee berry borer in the Arabica producing regions of Ethiopia, the Ugandan part of the Lake Victoria region, the Mount Elgon region in Uganda and Kenya, as well as the Mt. Kenya region.

In Rwanda, there are still no studies that use high-resolution (1 × 1 km) climate data to study crop suitability under future climate conditions. Most studies in the country focus on staple crops like beans, maize, and cassava. For example, a report by International Fund for Agricultural Development (2020) shows that climate change may reduce productivity in lowland areas and improve conditions in higher areas.

This indicates an important research gap. Even though coffee is very important for Rwanda's economy, there is still limited research using detailed spatial models to understand how climate change may affect where coffee can grow in the future. This study aims to fill this gap by using downscaled climate data and spatial modelling to give a more detailed and location-specific analysis of future coffee suitability in Rwanda. This can help support better planning and adapt to climate change in the coffee sector.

6. Data and Methodology

6.1. Climate and soil data

6.1.1. Climate data

Climate data used in this study were derived from the downscaled climate projections presented in the Rwanda Climate Hazard Profile developed by MeteoRwanda, GIZ and the Potsdam Institute for Climate Impact Research (PIK). The analysis in the climate hazard profile is based on an ensemble of nine global climate models from the latest phase of the Coupled Model Intercomparison Project (CMIP6), bias-corrected through the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) framework and further downscaled to approximately 1 km spatial resolution using the CHELSA approach to account for topographic variation in Rwanda. Climate projections were evaluated under three shared socioeconomic pathway (SSP) scenarios. These include SSP126, which represents a low-emission pathway, SSP370, which reflects an intermediate-to-high emission pathway, and SSP585, which represents a high emission pathway. The climate data used in this study were available for three yearly seasons September–January season (SONDJ), February–June season (FMAMJ), and the annual season (JFMAMJJASOND), corresponding to Rwanda's main climate patterns. Considering seasonal conditions is important in agricultural studies because crop development is closely related to changes in temperature and rainfall throughout the growing seasons. Climate variables, based on temperature and precipitation that are relevant for crop growth were obtained from the climate datasets.

Table 1. Climate indices used in the suitability analysis

Index	Abbreviation	Description
Temperature	Tmean	Annual and growing season average of daily mean near surface temperature
Heat	nTgt30degC	Number of days with maximum temperature above 30 °C, representing heat extremes
	TX5x	Maximum daily temperature recorded during the hottest consecutive five-day period
Precipitation	psrum	Total precipitation accumulated during the analysis period
Extreme Precipitation	nprgtp95	Number of days with precipitation above the 95th percentile, indicating heavy rainfall events
Meteorologi-cal drought	ndry	Total number of days with no recorded precipitation
	n5daydry	Number of events with five consecutive dry days
	n5daydry1mm	Number of dry spell events defined using a precipitation threshold of 1 mm

The climate indices used in this study are shown in Table 1. Mean temperature (Tmean) describes the general temperature of the area. Other indices, such as the number of days above 30 °C, (nTgt30degC) and the maximum temperature over five days (TX5x), show short periods of very high heat, which is forecasted to affect coffee growth and reduce yields. High temperatures, especially during the growing season, can lower coffee production when they become too high (Kasongi et al., 2024). Total precipitation (prsum) shows the total amount of rainfall. Other indices, such as heavy rainfall events (nprgtp95), number of dry days (ndry), and long dry periods (n5daydry), describe how rainfall changes over time. These patterns are important because too much rain during flowering or too little water during growth can affect plant development and reduce crop production (Kasongi et al., 2024).

6.1.2. Soil and elevation data

In addition to climate variables, we incorporated soil and elevation related data since they are major determinants of coffee growth across regions. Data on soil pH, cation exchange capacity (CEC), nitrogen content, soil organic carbon (SOC), and soil texture components such as clay, sand, and silt were retrieved from the ISRIC Soil grids database ISRIC World Soil Information; Poggio et al. (2021).

6.2. Suitability model setup and evaluation

The suitability of coffee was modeled using a species distribution model approach (Figure 2) that was applied in the R environment. A combination of four machine learning algorithms Maximum Entropy (MaxEnt), Random Forest (RF), Boosted Regression Trees (BRT) and Support Vector Machines (SVM) were used. These techniques are appropriate for modelling non-linear and complex relationships between environmental variables and species distributions (Elith et al., 2006) and have been widely used in coffee suitability modelling.

The models were trained using coffee presence points obtained from a coffee mapping study in Rwanda (Mukashema et al., 2014). The data was cleaned, and spatial thinning applied to retain almost one point per grid to reduce model overfitting. A subsampling method was used to divide the dataset with 70% used to train the models and 30% used to test the models. Environmental predictors multicollinearity test was determined before fitting the model. Selection of variables was performed using Variance Inflation Factor (VIF), and subsequently, the removal of highly correlated variables was performed based on the VIF-count to ensure model stability and reduce model over fitting. This was applied for both historical and future projections.

Model performance was assessed using Area Under the Receiver Operating Characteristic Curve using the Area under the curve (AUC). The AUC metric was used to assess the performance of individual models and determine the relative contribution of each algorithm to the ensemble model (Elith et al., 2011; Marmion et al., 2009). Besides the evaluation of the AUC, a confusion matrix was used to evaluate the model accuracy using the spatial production model (SPAM) as the reference. The confusion matrix is based on comparison of predicted suitability and reference data and gives measures of model performance including sensitivity and specificity. The relative contribution of individual environmental variables was assessed using the permutation method. The built ensemble model generated suitability maps with values of 0 to 1, with higher values indicating the regions that are more suitable for producing coffee. The continuous suitability values were further transformed into two categories: Suitable and unsuitable areas to simplify the process of interpreting the results using a threshold that maximizes model sensitivity and specificity. This classification assisted in determining the spatial location of the areas that would be viable in growing coffee and enabled us to study how these areas would be subject to change with the future climatic conditions.

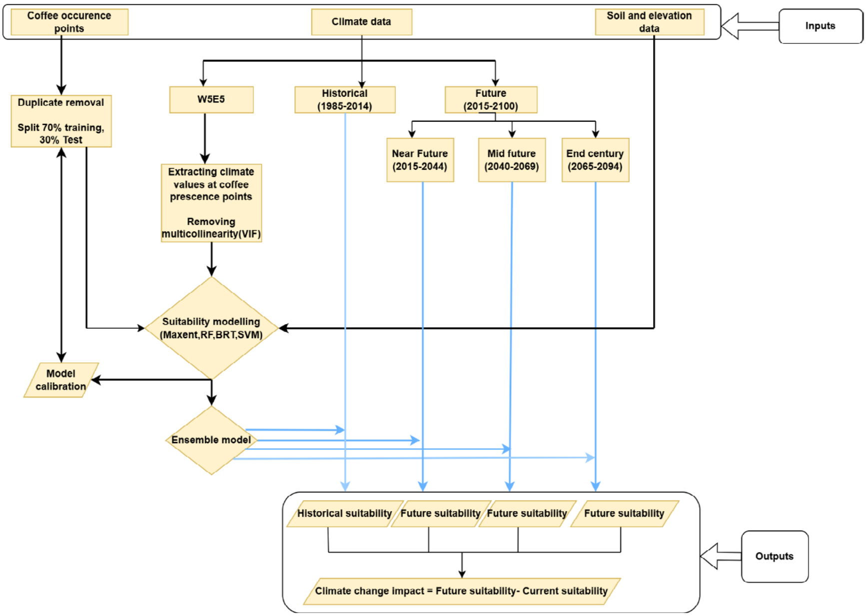

Figure 2. Methodology flowchart (from data preparation and preprocessing to suitability modelling data preparation and preprocessing to suitability modelling).

6.3. Assessment of climate change impacts on coffee suitability

The impact of climate change on coffee suitability was evaluated by applying the trained ensemble model to both historical and projected climate data. In this step, the climate variables in the model were replaced with climate projections, while other environmental predictors such as soil properties and elevation were kept constant. This allows the analysis to focus on how changes in climate may influence coffee suitability.

Future suitability was then projected using the same climate models under three Shared Socioeconomic Pathway scenarios (SSP126, SSP370, and SSP585). Predictions were generated for three future periods centered around 2030, 2055, and 2080. Results were averaged across GCMs for all time periods and SSPs. Climate change impacts were calculated as the grid-wise difference between future suitability and historical suitability.

7. Results

7.1. Model Performance and Evaluation

The performance of the four modelling algorithms using Receiver Operating Characteristic Curves is shown in Figure 3. For all four algorithms, we attained high model performance, as indicated by high AUC values of 0.97, 0.86 and 0.78, 0.86 for Random Forest, Boosted Regression, Support Vector Machine and Maxent respectively. Overall, the results indicate that all four algorithms had acceptable predictive performance and were therefore suitable for inclusion in the ensemble modelling framework and future predictions.

Figure 4 shows the relative importance of the environmental variables used to predict coffee suitability models. Elevation was the most significant variable, making the largest contribution to the model predictions (19%). Among the climate variables, total number of dry days (ndry) (13%) and total precipitation accumulated during the season (prsum) also had a strong influence on coffee suitability. Soil variables such as nitrogen content and Soil Organic Carbon (SOC) contributed moderately to the model results. Other soil properties, including sand, silt, clay, and CEC (cation exchange capacity) showed lower contributions. Overall, elevation and climate variables, relating to moisture, are very important in determining suitable areas for coffee cultivation. which This indicates that coffee suitability in Rwanda is mainly influenced by those variables which are critical for the growth of Arabica coffee.

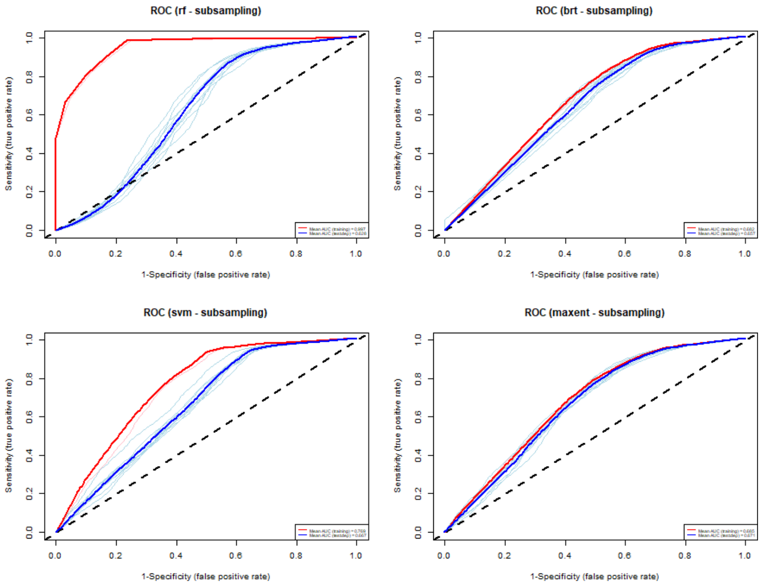

Figure 3. Receiver Operating Characteristic (ROC) curves showing the predictive performance of the four models (Random Forest, Boosted Regression Trees, Support Vector Machine, and MaxEnt).

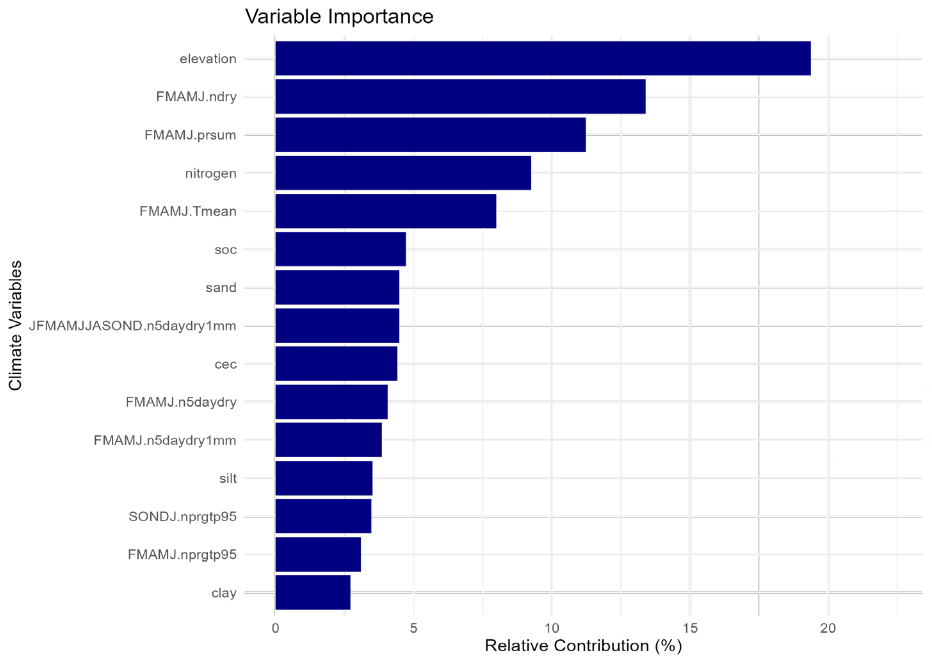

Figure 4. Relative importance of environmental variables used in the coffee suitability model.

7.2. Current Suitability to cultivate coffee across Rwanda

Under current climate conditions, Arabica coffee shows a clear and expected pattern of suitability across Rwanda. The continuous suitability map (Figure 5) indicates that the central, western, and northern highlands are highly suitable, while suitability drops markedly in the warmer and drier eastern and southern lowlands. Approximately 71.06% of Rwanda's land area is currently suitable for Arabica coffee cultivation (Figure 6). This distribution closely reflects the well-known preference of Arabica coffee for cooler, wetter highland environments and aligns well with the main coffee-growing regions in the country today. These results are in line with previous studies on coffee in Rwanda, which also show that coffee is mainly grown in highland areas and not in lowland regions (Clay et al., 2018; Nzeyimana et al., 2014).

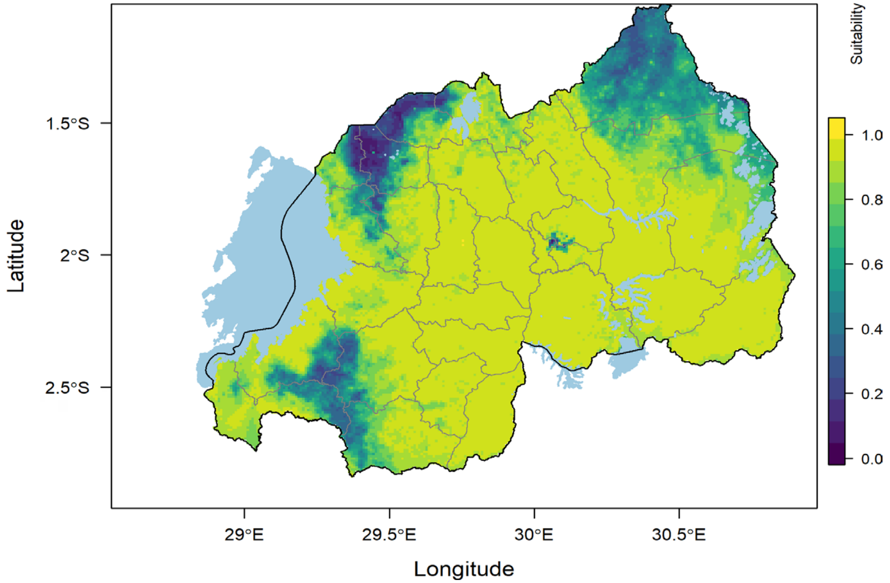

Figure 5. Current suitability for Arabica coffee across Rwanda as derived from an ensemble suitability model.

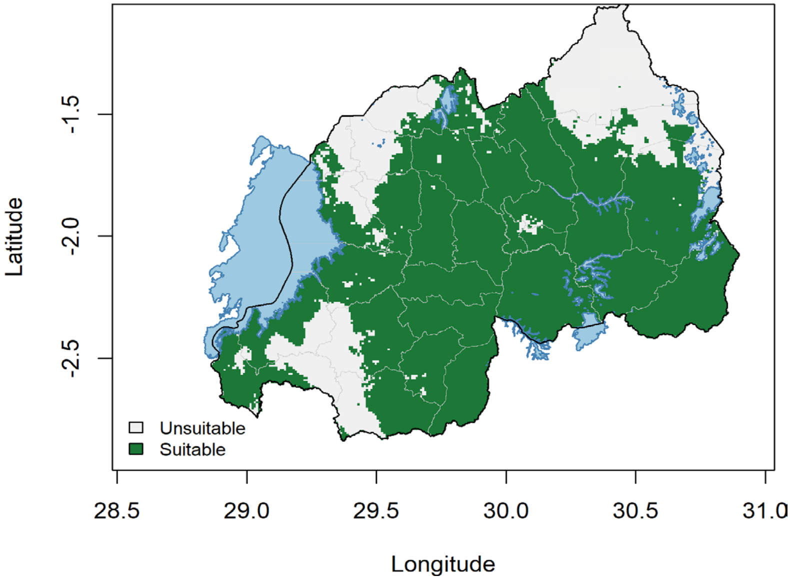

Figure 6. Classified coffee suitability map under current climate (green = suitable, grey = unsuitable).

7.3. Future Suitability of Coffee under Climate Change (2030–2080)

At the country level, models show that coffee suitability is projected to remain broadly stable under the low-emission pathway but declines more noticeably under the higher-emission pathways, and the effects increase with time. Results show both gains and losses (Figure 8 and 9) across the country with differential magnitudes across different scenarios. Model results show minimal changes in suitability over time with relatively minimal reductions under the low emission scenarios starting from midcentury (Figure 7). The spatial patterns show that suitability losses are concentrated mainly in the eastern and southern lowland areas, particularly by 2055 and 2080, whereas the central and northern highlands generally remain suitable. Under SSP126, most of the country is still suitable, with only small changes. By 2055, losses become more evident under SSP370 and SSP585, while SSP126 exhibits only modest change. By 2080, the strongest decline occurs under SSP585, with suitability loss reaching about 3% of the current suitable areas compared with gains of roughly 1.2%, producing the largest net reduction. Overall, the findings suggest that climate change is likely to shift coffee suitability toward cooler high-altitude zones, while lowland areas become increasingly marginal for Arabica coffee cultivation.

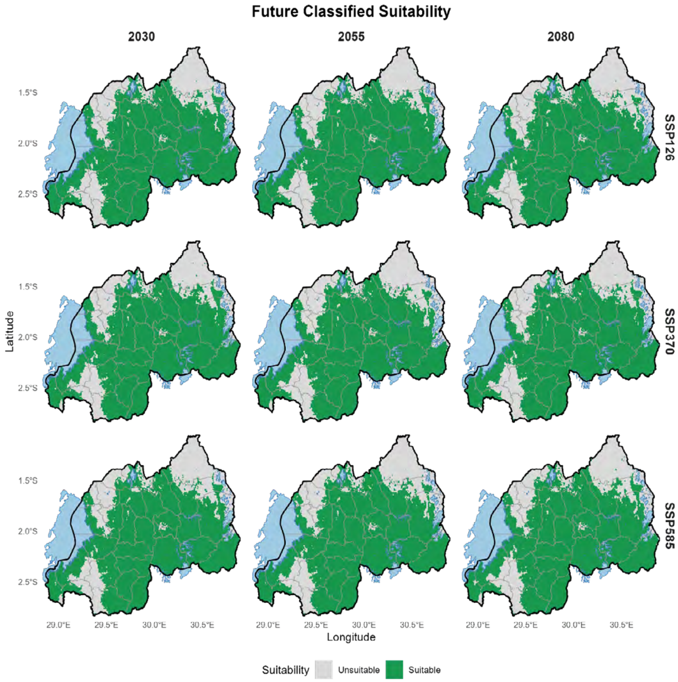

Figure 7. Future classified suitability for Arabica coffee in 2030, 2055 and 2080 under SSP126, SSP370 and SSP585 (green = suitable, grey = unsuitable).

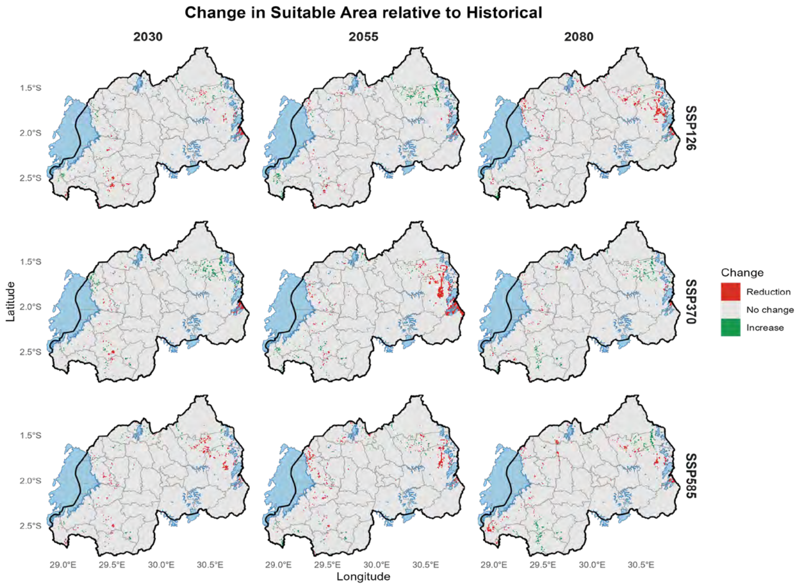

Figure 8. Projected changes in suitability of Arabica coffee relative to current conditions for 2030, 2055, and 2080 under three climate scenarios (SSP1-2.6, SSP3-7.0, SSP5-8.5). Red indicates decreased suitability, green indicates increased suitability, and gray shows no change.

As shown in Figure 9, the differences between the scenarios are mainly due to how much temperature and rainfall change. In the low emission scenario (SSP126), the bars show that gains and losses are more balanced. In the higher emission scenarios (SSP370 and SSP585), the figure shows larger losses, especially over time, because temperatures increase more, particularly in lowland areas. The figure also shows some gains, for example under SSP370 in 2080. This happens because some higher-altitude areas become suitable as temperatures rise. However, these gains are smaller than the losses, which is why the overall pattern in the figure still shows a decrease in total suitable area.

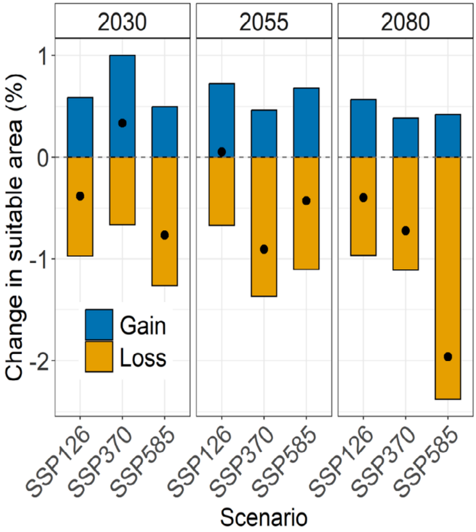

Figure 9. Percentage gain, loss, and net change under different scenarios

7.4. Gender-specific vulnerabilities to climate change

Understanding the structural position of women in Rwanda's agricultural and coffee sectors sets the stage for a deeper examination of how gender shapes vulnerability and resilience. The following section explores the specific dimensions of gender inequality in Rwandan agriculture that both reflect and reinforce women's constrained capacity to adapt to climate change.

7.4.1. Land access and Input Usage

Land is a critical asset in agriculture, yet gender disparities persist in land ownership and control. When it comes to land access, Rwanda is one of the very few countries in Sub-Saharan Africa that has a policy such as the Land Tenure Regularisation (LTR) which attempts to settle questions of land settlement, keeping in mind the rights of women to inherit. Further, Rwanda has laws allowing for women to own land under their own name (Abbott et al., 2018). Progressive reforms notwithstanding, there are however, several notable distinctions between agricultural households headed by men, and agricultural households headed by women. For one, female headed agricultural households report higher rates of poverty, with 28.7% of female headed agricultural households as poor, in comparison to 25.2% of male headed agricultural households, according to the Agricultural Household Survey, 2024. While female headed agricultural households rent less land in comparison to their male headed counterparts, 39.9% and 43.2%, respectively, with a higher percentage of women, 88.3% outright owning the land, most of this land is less than 0.5 ha. It is the same for male headed agricultural households, 75.4%. However, the percentage of female headed agricultural households is higher in comparison, with 84.7% reporting land of less than 0.5 ha. Additionally, women report a slightly lower right to the land, defined through the access to use land and the right to sell/use the land as a guarantee for a loan. This seems indicative that although women might have improved access, there are barriers to their use of the land (National Institute of Statistics of Rwanda, 2025).

These constraints are mirrored in the coffee sector specifically. A study conducted in Huye province revealed notable disparities between female- and male-headed households engaged in coffee farming. Female heads of household tended to be older than their male counterparts, a pattern largely attributed to widowhood and other family losses, and faced significant resource constraints: smaller plots of land, fewer productive coffee trees, and considerably lower incomes (Gerard et al., 2024).

When it comes to usage of agricultural inputs, referring to Figure 10, female headed households use less percentages of improved seeds, organic fertilizers, inorganic fertilizers and pesticides relative to male headed households. This pattern is also evident in coffee farming, where female-headed households reported lower investment in key farm inputs including weeding, mulching, pruning, and manure application, yet recorded a higher rate of seedling planting than male-headed households, suggesting that despite systemic disadvantages, women remain active and engaged contributors to production (Gerard et al., 2024).

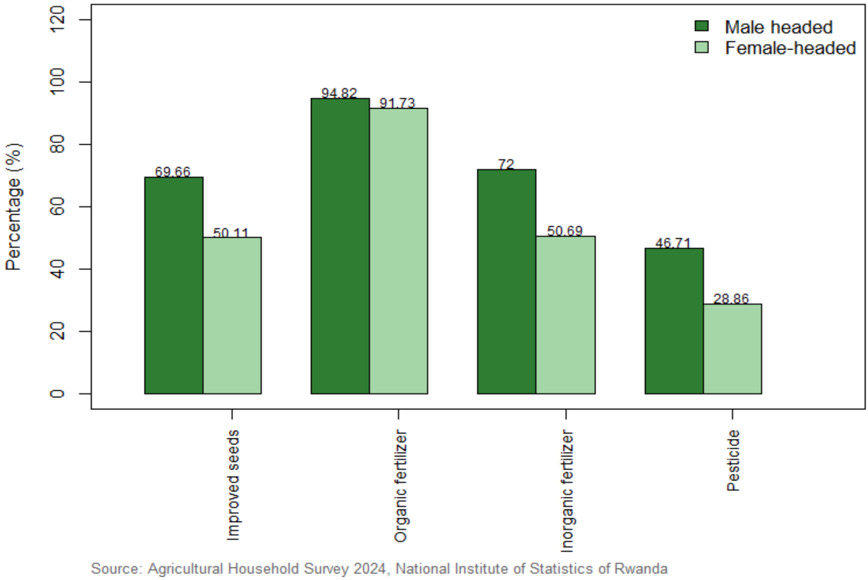

Figure 10. Percentage of agricultural households by different agricultural inputs used (National Institute of Statistics of Rwanda, 2025)

Turning to land use patterns, female-headed households show lower rates of forest plantation and fallow land relative to their male-headed counterparts, while rates of cropping and fodder cultivation are broadly similar across both groups (see Figure 11).

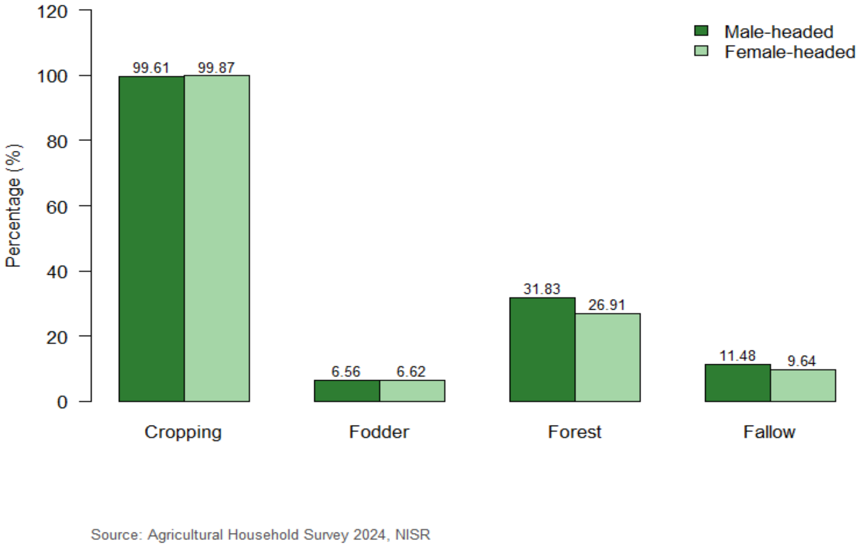

Figure 11: Percentage of agricultural households by land use type (National Institute of Statistics of Rwanda, 2025)

7.4.2. Decision-Making

Intrahousehold decision-making emerges from a complex interplay of gender norms, bargaining power, and familial customs (Agarwal, 1997) and is a critical determinant of agricultural outcomes. An analysis of Rwanda's Land Tenure Regularization Program by Santos et al. (2014) offers important insights into how these dynamics play out along gender lines. Women in monogamous marriages reported relatively high levels of decision-making power across a range of agricultural matters including how land is used, which crops are sold, how proceeds are allocated, whether land is rented or used as collateral, and who ultimately inherits it. Nevertheless, in each of these domains, husbands retained greater decision-making authority than their wives. The disparity was starker in non-monogamous households, where women reported significantly less agency, with husbands making unilateral decisions about land inheritance in nine out of ten cases (Santos et al., 2014). Structural factors compound these inequities further: women in polygamous arrangements frequently lack registered marriages, and since land inheritance is contingent on formal marital registration, they are rendered particularly vulnerable to dispossession (Illien, 2024). Notwithstanding these constraints, Rwanda's broader gender landscape shows signs of progress. According to the Women's Empowerment in Agriculture Index, Rwandan women report relatively high levels of agency in agricultural decision-making, including decisions about food and cash crop farming, as well as fisheries and livestock (Rosenbach et al., 2023).

7.4.3. Why gender matters for climate change adaptation

The vulnerabilities documented in the preceding section do not merely shape women's present livelihoods. They directly determine how well women can respond to future shocks. Chief among these is climate change, which threatens to deepen existing inequalities by placing the greatest burden on those already least equipped to cope. Women are expected to bear a disproportionate share of the projected climate change impacts: with less land, fewer productive assets, and lower incomes, they have fewer resources to draw upon when shocks occur and less ability to invest in mitigation strategies (Nsengiyumva et al., 2022). Compounding these material constraints is a systemic failure in how climate information reaches women. Agricultural policies frequently overlook gender dynamics, reflecting a limited understanding of household decision-making. Weather information, for instance, is typically disseminated through television, but evidence shows that women farmers are significantly less likely than men to access information this way, relying instead on peer networks (Gumucio et al., 2020). When critical climate information fails to reach women through the channels they use, their ability to respond in a timely and informed manner is further undermined.

8. Discussion and implication of the results

8.1. Shifts in coffee suitability and Land-Use Constraints

Consistent with findings reported in other studies (Abigaba et al., 2024; Bilen et al., 2022; Bunn et al., 2015; Ovalle-Rivera et al., 2015), the results of this study indicate a clear shift in coffee suitability toward higher elevations, while low-lying areas gradually lose suitability over time. This pattern is principally driven by the already elevated baseline temperatures in low-lying areas, which under continued warming are likely to exceed the optimal thermal range for Arabica coffee growth. As temperatures rise, these areas face increasing heat stress, reduced moisture availability, and deteriorating growing conditions, with adverse effects on flowering, fruit set, and overall yield. Higher-elevation areas, by contrast, are projected to remain within climatically suitable ranges for longer, positioning them as the primary zones for future Arabica production. Although the projected net reductions in suitable areas may appear modest in aggregate, their implications for smallholder livelihoods and national income from coffee exports could be considerable.

Although the results indicate that large areas of Rwanda remain suitable for Arabica coffee, these findings should not be interpreted in isolation from existing national policies, land-use planning frameworks, and conservation priorities. In particular, some areas projected to gain suitability are located within or near protected landscapes, including national parks in the eastern and south-western parts of the country, where agricultural expansion would conflict with biodiversity conservation and ecosystem protection objectives (Republic of Rwanda , 2020). This concern is further reinforced by the EU Deforestation Regulation (EUDR), which requires that coffee placed on the European market has not been produced on land subject to deforestation or forest degradation, adding a significant trade compliance dimension to any expansion of coffee cultivation into forested or ecologically sensitive areas. Suitability alone is therefore insufficient as a basis for land allocation decisions; it must be assessed alongside legal, environmental, and socio-economic considerations to ensure that future coffee development is ecologically sound and institutionally appropriate.

While climate change may open new potential growing areas, not all of these are available or appropriate for cultivation. Expanding production into higher-elevation zones risks disturbing fragile ecosystems and undermining biodiversity (Hylander et al., 2013; Meyfroidt et al., 2013; Ovalle-Rivera et al., 2015). Future planning should therefore prioritize already designated agricultural zones and degraded lands with lower conservation value, as identified in the national land use plan, rather than encroaching on ecologically sensitive areas. This approach would help minimize land-use conflicts, reduce pressure on vulnerable ecosystems, and support a more sustainable pathway for agricultural adaptation.

8.2. Farm-level adaptation strategies

At the farm level, adaptation will be essential. A range of measures have been identified as relevant to sustaining coffee production under changing conditions, including soil water conservation, microclimate management, and soil fertility improvement, alongside more transformative options where necessary (Pham et al., 2019). The adoption of alternative varieties, such as

Robusta coffee, which tolerates higher temperatures, remains a viable option in areas where Arabica cultivation becomes unviable, though this entails economic trade-offs given Robusta's generally lower market value. Agroforestry represents a particularly promising multipurpose strategy, capable of moderating microclimates, maintaining soil health, and supporting biodiversity simultaneously. Regardless of the specific measures adopted, adaptation interventions should be calibrated to local conditions and implemented with the active support of agricultural extension services.

8.3. Women as agents for adaptation

Despite the disproportionate climate vulnerabilities faced by women farmers in Rwanda, a range of emerging initiatives demonstrates that women are active agents in building resilience within the coffee sector. The following pathways illustrate how cooperative structures, certification schemes, and community-based approaches are beginning to shift gender dynamics in coffee production.

8.3.1. Cooperatives

While women seem to be disproportionately affected by climate change in Rwanda, women farmers are participating in initiatives that aim to change that. For example, in Rwanda, there exist several women-led cooperative women's associations in coffee, as well as initiatives such as Promoting Economic Empowerment for Women and Youth for Sustainable Coffee Production in Rwanda (PEESCoP), which work with women and youth to diversify income streams. The women's cooperatives formed with several objectives, including skill training, expanding their roles in the coffee production process, and generating off-season income. Expanding their roles in the coffee production process involves bringing women into underrepresented, yet higher income generating activities, such as transport, sales and factory processing. Diversification of income streams involved skill-training in embroidery/weaving, beekeeping and diversified cropping etc. (Luna et al., 2025; van Kollenburg & van Weert, 2024). Their involvement in these associations and initiatives seems to have had bearing on their empowerment, with increased voice, agency and economic decision-making as consequences.

8.3.2. Certification

Certification schemes represent another potential pathway toward greater agency for women in coffee. Standards required by certification bodies, including provisions against gender discrimination, have been linked to increased participation of women in Fair Trade certified cooperatives. An unexpected spill over from certification is the accumulation of a kind of social capital among coffee growers (Elder et al., 2012). Nova Coffee, which employs predominantly women farmers and holds Rainforest Alliance certification, offers a concrete example of how certification and gender inclusion can be pursued together.

8.3.3. Community Initiatives

Addressing the structural exclusion of women from mainstream agricultural markets is a further avenue for empowerment. Effective community-based approaches involve engaging directly with local farmers to understand their specific needs and co-designing context-appropriate solutions that incorporate local knowledge. Such initiatives ideally combine market access support with promotion of more sustainable production practices, including agroforestry, crop rotation, and seed preservation (Muhwezi & Turyasingura, 2025).

9. Summary and Conclusion

The results reveal clear spatial and temporal patterns in coffee suitability across Rwanda under both current and future climate conditions (2030–2080). Suitability is consistently highest in the central, western, and northern highlands, while the eastern and southern lowlands remain comparatively less suitable, reflecting a pronounced elevation-driven gradient that underlies the spatial distribution of viable growing areas.

Future projections suggest that changes in suitability, while relatively moderate in magnitude, are nonetheless meaningful. Losses marginally outweigh gains across most scenarios, producing a net decline in suitable areas that become more pronounced under higher emission pathways (SSP370 and SSP585) toward 2055 and 2080. These changes are spatially uneven: lowland areas bear the greatest losses, driven by rising temperatures and increasing moisture stress, while highland areas remain comparatively stable and, in some cases, register marginal gains in suitability. Although the overall magnitude of change is not dramatic, the consistent direction of these trends points to a gradual but consequential restructuring of Rwanda's coffee-growing landscape. Even modest reductions in suitability carry significant implications for farmers operating in already marginal areas, where productivity is particularly sensitive to climatic variability. As with all modeling exercises, these results are subject to inherent uncertainty and should be understood as indicative of general trends rather than precise local forecasts. Nonetheless, the findings consistently support the conclusion that coffee cultivation will remain viable in Rwanda, while acknowledging growing challenges in lowland regions.

From a livelihood perspective, farmers in areas of declining suitability face increasing production risks and will likely need to adopt targeted adaptation strategies, including improved agronomic practices, crop diversification, or, where feasible, gradual reorientation of production toward more suitable locations. However, upward relocation of coffee cultivation is not straightforwardly achievable for most smallholders, given constraints related to land access, capital requirements, and the environmental sensitivity of highland ecosystems. These challenges are likely to fall disproportionately on women farmers, who typically operate with smaller landholdings, more limited access to capital and extension services, and fewer formal land rights, constraining their ability to respond effectively to shifting suitability conditions. Ensuring that adaptation strategies are gender-responsive, and that women have equitable access to information, resources, and decision-making processes, is therefore not only a matter of social equity but a prerequisite for the long-term resilience of Rwanda's coffee sector. This study offers a baseline against which future coffee suitability assessments in Rwanda can be measured, and its methodology could usefully be extended to other complementary cash crops to build a more comprehensive picture of climate risk across the agricultural sector. While coffee production in Rwanda is expected to persist under projected future climate conditions, proactive and context-specific adaptation planning will be essential to sustain productivity, protect smallholder livelihoods, and safeguard the environmental resources on which the sector depends.

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Federal Ministry for Economic Cooperation and Development (BMZ)
BMZ Bonn
Dahlmannstraße 4
53113 Bonn, Germany
www.bmz.de

Scientific content developed by:
Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH
Potsdam Institute for Climate Impact Research (PIK)
Telegraphenberg A 31
14473 Potsdam, Germany
http://www.pik-potsdam.de

Scientific coordination:
Christoph Gornott (PIK)

Main Authors:
Delice Izere (AIMS RIC)
David Abigaba (PIK)
Ananya Mazumder (PIK)
Olivier Niyompuhwe (GIZ)
Janet Umuhoza (GIZ)
Kora Rösler (GIZ)
Sabine Undorf (PIK)
Christoph Gornott (PIK)
Sophie von Loeben (PIK)

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