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Climate change and tropical crops: Disruption in the geography of coffee and cocoa

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Abstract

Assessing the impact of climate change on high-value tropical crops such as coffee and cocoa is essential for long-term proactive adaptation planning. A coherent approach which integrates climate change and climate-related hazards into a single suitability assessment enables the development of adaptation strategies for the coming decades, while acknowledging that climate-driven impacts will vary significantly across different geographical regions and require differentiated adaptation measures. In this study, we identified the most and least suitable areas for coffee and cocoa production over a 30-year horizon, employing an agroclimatic zones approach and the latest CMIP6 (Sixth Assessment Report on Climate Change – CMIP6) climate projections.

This analysis was supported by the integration of Random Forest models with occurrence data, bioclimatic variables for precipitation, temperature and evapotranspiration; and key agro-climatic indices- such as the Number of Dry Days (NDD), Number of Days with Temperature above 30°C (NTx30), and Number of Water Logging Days (NDWL0). These variables were focused on their behavior relative to presence points through a categorical data reclassification process. These variables act as vital indicators for crop distribution, providing the scientific evidence needed to prioritize climate resilience interventions and steer the transition of perennial production systems over the coming decades. NDD showed more dry days in Southeast Asia and Oceania, but fewer in Andean and Central American mountains. NTx30 projections revealed widespread warming, especially in the Andes and North-Central Africa. Meanwhile, NDWL0 indicated increased waterlogging in Central and South America, while West Africa's cocoa regions faced a slight reduction in these events.

Our main findings showed that coffee will experience a net loss of suitability, most notably in countries like Indonesia, Tanzania, Southern Mexico and regions in Brazil and Bolivia. In contrast, Colombia, Perú, Honduras and Uganda are expected to remain suitable for production. As for cocoa, the overall suitable area remains largely stable, but we observe a widespread internal shift in agroclimatic zones toward warmer conditions, where comprehensive adaptation is the dominant impact category. While most regions would stay suitable, changes in climatic hazards will require a substantial overhaul of local farming practices to adapt to climate change – a phenomenon particularly evident in Colombia, Venezuela, Perú and Central Africa. Meanwhile, Ecuador, Côte d'Ivoire, and Ghana stood out for maintaining higher future suitability compared to other regions.

Introduction

Coffee and cocoa are agricultural commodities of global importance that are increasingly threatened by climate change (Rahn, Bunn & Craparo., 2025). As perennial crops, decisions taken today create dependencies towards the future, since a tree's productive optimum life generally spans from 15 to 20 years, with many regions characterized by even longer turn over cycles of 20+ years. Future climate projections data are important sources for future-orientated decision taking (Rising, J., & Devineni., 2020, Giraldo et al., 2023). By integrating them into Climate Information Services (CIS) as decision-support tools, farmers and value chain actors can assess and manage future risks (Malakar et al, 2024). Significant research has analyzed the impacts of climate risks (Bunn et al., 2015; Bunn et al., 2017; Castro-Llanos et al., 2020) and changes in crop suitability (Ovalle-Rivera et al., 2015; Schroth et al., 2016).

Risks from climate change can be differentiated into (i) long-term climate trends, (ii) acute climate hazards, and (iii) latent changes in suitability. These dimensions are not independent. Climate hazards – such as heat waves, droughts, waterlogging and occupational heat stress – can be quantified through composite climate indicators (Solaraju-Murali et al., 2021). In this study, rather than analysing hazards separately, we embed these indicators as agroclimatic indices directly into an ecological suitability model, so that hazard signals inform the assessment of latent suitability change. Such models typically define, in a first step, clusters using supervised or unsupervised machine learning (Breiman, 2001), which are then projected under current and future climate.

Material and Methods

We used data from CHIRPS (Funk et al., 2020) and CHIRTS (Verdin et al., 2020) as baseline during 1995-2014. Daily data were aggregated to a monthly scale, climatologies were estimated for precipitation and minimum and maximum temperature, and from these we computed a set of bioclimatic variables – 11 related to temperature, 8 to precipitation, 8 to potential evapotranspiration, and 4 to water balance – together with 5 agroclimatic indices: (i) Number of Dry

Days [NDD], (ii) Number of Days with Temperature above 30°C [NTx30], (iii) Number of Waterlogging Days [NDWL0], (iv) Human Heat Stress [HSH], and (v) Thornthwaite Aridity Index [TAI]. For future conditions (2026-2055) projections from five GCMs under the CMIP6 SSP3-7.0 scenario (Eyring et al., 2016) were first downscaled and bias-corrected following the delta method described by Navarro-Racines et al. (2020), and the same climatologies, bioclimatic variables, and agroclimatic indices were subsequently derived from the downscaled data. Because many of these predictors are strongly correlated, we reduce the set before modelling, starting from the full pool of 36 variables, screened for multicollinearity using the Variance Inflation Factor (VIF; Marquardt, 1970), iteratively removing the variable with the highest VIF and recomputing the remaining values until all fell below a threshold of 10.

Crop presence data for coffee and cocoa were compiled from multiple research projects and from the Global Biodiversity Information Facility (GBIF). A Random Forest model was then trained on these presence records using the predictors retained after the VIF screening, and the resulting clusters defined the agroclimatic zones: two for coffee, corresponding to the Arabica and Robusta species, and five for cocoa, following the methodology of Bunn et al. (2015) to classify farms according to their climate-related behavior. The projected extent of each agroclimatic zone was then computed to characterize future conditions.

Results and Discussions

The agroclimatic zones for cocoa (Figure 1) are distributed along the equatorial belt in the Americas, Africa and Asia. In the Americas, suitability is concentrated primarily in the Amazon Basin of northern South America (Colombia, Ecuador, and Peru). Under climate change projections, a global transition toward warmer conditions is anticipated, dominated by the expansion of the "Hot – Dry" and "Very hot – Wet" classes. At the regional level, this redistribution combines wet and dry signals: an altitudinal shift of mixed zones in the Amazon; a pronounced drift toward very dry conditions ("Hot – Very dry") alongside an increase in mixed zones in West Africa; and the persistence of the "Cool – Very dry" class in Asia.

In terms of coffee cultivation (Figure 1), mountainous spatial patterns are evident in high-altitude regions for Arabica, concentrated along the South American Andean range, in Central America, and in the highlands of East Africa, in countries such as Tanzania, Uganda, and Madagascar. Robusta coffee exhibits a distinctly equatorial and lowland distribution; this species finds its main continuous belt in West and Central Africa (the Congo Basin and the Gulf of Guinea), complemented by specific pockets in the American plains (the southern Amazon rainforest in Brazil), the Caribbean coast, and the Colombian Orinoquia, as well as some scattered areas in countries such as Panama and Costa Rica; it also has a highly significant presence in the lowland and island regions of Southeast Asia (Vietnam, Laos, Indonesia, and southern India).

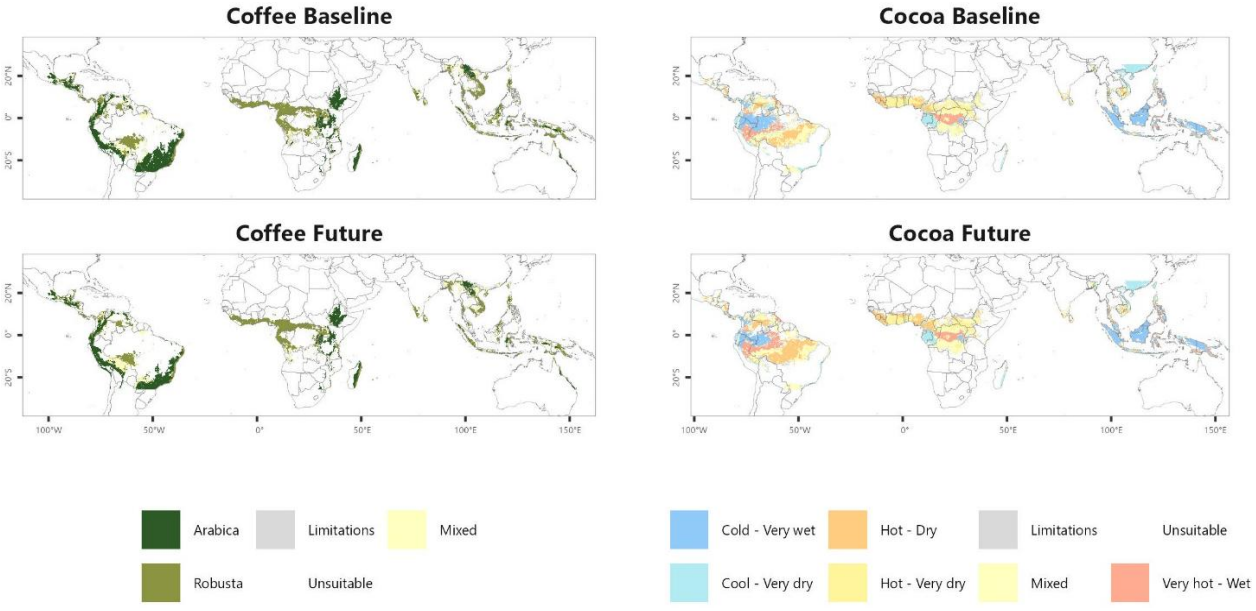


Figure 1 Agroclimatic zones for Coffee and Cocoa crops

Quantitatively, the dominant effect of climate change is internal redistribution of agroclimatic zones rather than a uniform loss of area, with contrasting patterns between crops. For cocoa, the total suitable area remains largely stable —the unsuitable class rises only from 66.2% to 66.7%— but reorganizes toward warmer conditions: the "Hot – Dry" class expands the most (from 3.58% to 5.50%), followed by "Very hot – Wet" (from 3.52% to 3.95%), whereas the cooler and wetter classes decline, particularly "Cold – Very wet" (from 5.50% to 4.51%) and "Cool – Very dry" (from 4.74% to 3.95%). In contrast, coffee shows a substantial net loss of suitability, with the unsuitable class increasing from 71.0% to 75.7% at the expense of both Arabica —the largest absolute loss, from 10.0% to 7.92% and Robusta (from 10.8% to 9.04%); only the transitional "Mixed" class expands (from 4.52% to 4.97%). Rather than a simple loss, this expansion may reflect a shift of formerly Arabica-suited areas toward conditions increasingly shared with Robusta, as warming blurs the climatic boundary between the two species.

Our results corroborate and qualify the global picture drawn by Bunn et al. (2015), the first multi-model assessment of climate suitability for both coffee species and a direct methodological foundation of this work. The geography is reproduced independently: Arabica resolves as a montane crop along the Andes, Central America and the East African highlands, while Robusta forms an equatorial lowland belt across the Congo Basins and the Gulf of Guinea with major extensions into mainland and island Southeast Asia – the same altitudinal separation that Bunn et al. (2015) traced to Robusta's requirement for the low intra-seasonal temperature variability, which confines it to low latitudes. The direction of change also agrees coffee loses. The magnitudes, however, diverge Bunn et al. (2015) projected the loss of roughly half the globally suitable area (49% of accumulated suitability score for Arabica and 54% for Robusta under RCP 6.0), whereas our relative losses are 20.8% and 16% respectively – approximately a third as large. The two figures are not directly commensurable. Bunn et al. summed a continuous suitability score across pixels, a metric that registers degradation *within* areas that remain nominally suitable; our zoning reports the share of area assigned to a discrete class, which changes only when a pixel crosses a class boundary. A continuous score therefore captures erosion that a class-based accounting absorbs silently — part of it visible here as the encroachment of the transitional Mixed class (4.52% to 4.97%) onto previously well-suited areas. The two assessments plausibly describe the same process at different resolutions rather than disagreeing about its severity. For cocoa, our results align closely – in both method and message – with Bunn et al. (2018), whose global case study on cocoa – producing regions employed the same architecture we adopt here: hierarchical clustering define agro-climatic suitability types, followed by Random Forest to extrapolate them under current and future climate.

Cocoa tells a complementary story. In agreement with Bunn et al. (2018), the dominant effect is not contraction but rather internal reconfiguration: the total suitable area essentially remains the same, but its composition shifts sharply towards the warm, moisture-limited end of the spectrum. The Hot – Dry zone expands by 54%, while the cooler, wetter zones recede. The two crops together present the two faces of a single climate signal: for coffee, latent suitability change manifests as a loss of area, whereas for cocoa it manifests as migration of production conditions between zones. This distinction matters for adaptation: a change of zone calls for management tailored to new conditions, not abandonment – guidance that only a zone-based framework can make explicit.

Conclusions

According to the CMIP6 SSP3-7.0 scenario, coffee production will face a substantial net loss of climatically suitable areas over a 30-year period. The proportion of unsuitable areas is expected to rise from 71.0% to 75.7%, affecting both species: Arabica production is predicted to contract from 10.0% to 7.92%, while Robusta production is expected to fall from 10.8% to 9.04%. Only the transitional mixed class expands, indicating the encroachment of marginal conditions onto areas that are currently well suited. These losses are unevenly distributed geographically: suitability declines most sharply in Indonesia, Tanzania, southern Mexico, and parts of Brazil and Bolivia. In contrast, Colombia, Peru, Honduras, and Uganda are projected to remain suitable and thus emerge as comparatively secure sources of coffee over the next few decades.

Cocoa follows a fundamentally different trajectory. While its total suitable area remains stable, with the unsuitable class shifting only slightly from 66.2% to 66.7%, its internal composition is shifting significantly towards warmer conditions. This is driven by the expansion of the Hot-Dry and Very Hot-Wet zones, alongside the decline of the cooler, wetter classes. Therefore, for cocoa, the dominant impact is not the disappearance of suitable land, but rather a redistribution of production conditions among agroclimatic zones. This is most evident in Colombia, Venezuela, Peru and Central Africa. In contrast, Ecuador, Côte d'Ivoire and Ghana stand out for retaining higher future suitability.

Taken together, the two crops reveal two aspects of a single climate signal: latent suitability change is manifested as a loss of coffee-growing area and as cocoa-growing zone migration. This distinction has clear methodological and practical implications. Our zone-based accounting and the continuous-score approach of earlier assessments (Bunn et al., 2015) describe the same underlying process at different resolutions, rather than disagreeing about its severity. More importantly, a location that remains suitable, but changes zone does not require abandonment, but rather management

that is tailored to its new agroclimatic conditions — a differentiated response that only a zoning framework can make explicit. All data and results from this study are openly accessible through the ACLIMATAR platform (link to website).

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