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RESEARCH

Securing the future of Colombian cacao: projected suitability changes and adaptation strategies under climate change

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Abstract
Colombia is an emerging frontier in fine-flavour cacao production, but its potential is threatened by climate change. This study assesses climate-driven shifts in suitability for commercially cultivated and wild cacao using a combination of different ensemble habitat suitability models (i.e. ensemble-of-ensemble models). To guide the sourcing of planting material and zone-specific adaptation measures, suitable areas were categorized into ecogeographical zones with similar environmental conditions. To identify populations that may harbour climate change–tolerant genotypes, an outlier analysis was carried out to pinpoint localities at the margins of cacao's environmental niche. For commercially cultivated cacao, the ensemble models predict that around 20% of currently suitable areas may become unsuitable by 2050, with the most vulnerable regions concentrated in the lowlands in the north and northeast of the country. However, most areas along the Andean foothills, currently most important for cacao production, are predicted to remain suitable. The models also predict a 3% expansion of suitable areas, primarily shifting to higher elevation areas. For wild cacao, forecasts are more optimistic, with more expansion than contraction, suggesting a potentially important role for wild cacao genetic resources in climate-smart breeding, and stressing the importance of conserving wild cacao populations. In light of these predictions, a number of adaptation measures are proposed in each of the ecogeographical zones, emphasizing the broader adoption of agroforestry and the identification of climate change–tolerant genotypes in areas where cacao occurs at the margins of its climatic niche.

Keywords Cacao · Climate change · Distribution modelling · Suitability modelling · Climate change–tolerant genotypes · Adaptation

Introduction

The Americas account for approximately 20% of global cacao production, which is mostly concentrated in Côte d'Ivoire and Ghana (ICCO 2022). Colombia is the 10th largest producer globally, producing around 60,000 tons in 2023 (Ortega 2024), with cacao production supporting the livelihoods of around 65,000 families, mostly smallholders,

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and generating more than 150,000 direct and indirect jobs (MADR 2021). While production is still primarily aimed at domestic consumption (Ortega 2024), the country is an emerging player in the fine-flavour market (Escobar et al. 2020), and exports have more than tripled between 2011 and 2020 (MADR 2021). Due to its complex biogeography, Colombia's cacao-growing regions have been subdivided into 54 different areas (González-Orozco and Pesca 2022), each characterized by different environmental conditions and likely to experience differential climate change impacts. Therefore, scaling up cacao production and improving the livelihoods of cacao farmers require a better understanding of these impacts. The recent surge in cacao prices, partly driven by weather-related failed harvests in West Africa, highlights the crop's climate vulnerability (Tabe-Ojong et al. 2024).

Climate change can affect cacao production in a myriad of ways. Among the direct effects, shifts in climate and weather patterns may affect plant survival and vigour, as well as flowering, fruit set, and maturation (Lahive et al. 2019). Among the indirect effects, climate change may also alter the incidence of pests and diseases (e.g. Plasencia-Vázquez et al. 2022). Studies in other regions have yielded mixed results regarding suitability changes for cultivated cacao in response to climate change, ranging from net reductions (Läderach et al. 2013; Schroth et al. 2016; de Sousa et al. 2019; Ceccarelli et al. 2021; Heming et al. 2022) to net increases (Ariza-Salamanca et al. 2023; Ceccarelli et al. 2024; Asante et al. 2025). However, most have focused on countries outside cacao's native range, i.e. the Amazon Basin, and none has assessed climate change impacts in Colombia.

As the distribution of cultivated cacao is strongly influenced by human intervention, as opposed to wild cacao whose realized niche is shaped mostly by evolutionary processes, suitability modelling needs to assess both separately. In the light of climate change, wild cacao populations may possess adaptive traits that cultivated ones lack, such as resilience to floods or heat stress. For example, studies in Peru and Ecuador have reported that climate change may negatively affect the suitability for cultivated cacao in the Amazon lowlands, whereas wild populations may benefit through range expansion (Ceccarelli et al. 2021, 2024). In Colombia, most cacao cultivation occurs along the Andean foothills and valleys, outside the range of wild populations. In the Amazonian departments of Caquetá and Putumayo, a variety of wild cacao populations has been documented alongside other crop wild relatives pertaining to the *Theobroma* genus (González-Orozco et al. 2022). These populations are often overlooked and little is known about their diversity (González-Orozco et al. 2021b), but they could serve as a valuable genetic resource for breeding efforts aimed at enhancing the climate resilience of cultivated cacao.

Despite cacao's agricultural importance in Colombia, its emerging role in the fine-flavour market, and the country's complex biogeography, there are—to the best of our knowledge—no peer-reviewed studies that have modelled the current and future environmental suitability of cacao in this country. In this study, habitat suitability models were used to investigate the effects of climate change on the suitable areas for cacao in Colombia, as a first step for identifying areas where climate change adaptation strategies are most needed. The study aimed at (1) mapping current and future suitable areas for commercially cultivated and wild cacao, identifying those areas that may be most affected by climate change. For commercially cultivated cacao, we modelled the areas where cacao is currently cultivated for commercial purposes, for simplicity this will be referred as 'cultivated cacao' hereafter. To increase the robustness of the predictions, the study employed a combination of different ensemble models (i.e. an ensemble-of-ensembles), rather than relying on a single algorithm or single ensemble model. As a secondary objective, more targeted at local decision makers, the obtained model predictions were compared with a national spatial planning strategy, based on an overlay of physical, socio-ecological and socioeconomic variables. The two other main objectives were (2) categorizing the areas suitable for cacao in ecogeographical zones with similar environmental conditions, to guide the sourcing of planting material and zone-specific adaptation measures, and (3) identifying localities at the margins of cacao's realized environmental niche, which may harbor climate change–tolerant genotypes. Based on our results, we discuss some climate change adaptation measures in each of the ecogeographical zones.

Methods

Habitat suitability modelling

To predict the distribution of suitable areas for cultivated and wild cacao, we used a novel approach consisting of a combination of several ensemble models, resulting in 'ensemble-of-ensemble models', following Ceccarelli et al. (2024). Details on presence points, environmental predictors, and model calibration and validation are given below.

Presence points

Presence points for cultivated cacao were obtained from a country-wide database maintained by FEDECACAO, data collected by AGROSAVIA (González-Orozco and Pesca 2022), Romero-Sanchez et al. (2022), and Castro and Bunn (2022), as well as several unpublished datasets collected by the Alliance of Bioversity International – CIAT, complemented with data from the Global Biodiversity Information

Facility (only records stating that the coordinates are from cultivated cacao) (GBIF; www.gbif.org). Wild cacao presence points were compiled from the Botanical Information and Ecology Network (BIEN; www.biendata.org), GBIF (only records stating that the coordinates are from wild cacao), and Motamayor et al. (2008). After cleaning the data and removing duplicates, the data comprised 31,467 and 352 points for cultivated and wild cacao, respectively.

Given the limited extent of international exchange of cacao germplasm, we opted to assess the impact of climate change on cultivated cacao using only presence data from Colombia. As both the environmental conditions and the cacao genetic resources in neighbouring countries are quite different (Thomas et al. 2023, 2024), including these may result in an overly broad estimated niche. Wild cacao populations, by contrast, represent a cross-border continuum across the Amazonian forests. In addition, data availability for wild cacao inside Colombia was more limited, so we also included points within Colombia's longitudinal and latitudinal extent (66.7°W–81.8°W; 15.9°N–4.2°S), resulting in the inclusion of points from neighbouring Ecuador and Peru, as well as a few points from Brazil.

Environmental variables

As listed in Table S1, the candidate predictor variables included 19 bioclimatic variables (Fick and Hijmans 2017), 11 soil variables (Hengl et al. 2017), and 6 terrain attributes (Hengl 2018), all at a resolution of 30 arcsec (ca. 0.9 km at the equator). To minimize multicollinearity, we performed an iterative variance inflation factor (VIF) analysis, retaining only those predictors with a VIF below 5 (indicated in bold in Table S1). This analysis was based on the values of the predictors extracted from both the presence and pseudo-absence locations used in the ensemble models (see details below), yielding a single set of predictors for both cultivated and wild cacao.

Model calibration and validation

For both cultivated and wild cacao, suitability modelling was performed using ensemble models composed of up to 11 modelling algorithms, implemented in the *BiodiversityR* package for R. The suite of algorithms included two maximum entropy algorithms (MAXENT and MAXNET), boosted regression trees (GBM), random forests (RF), stepwise generalized linear models (GLMSTEP), two versions of generalized additive models (GAM, MGCV), flexible discriminant analysis (FDA), neural networks (NNET), support vector machines (SVM), and multiple adaptive regression splines (EARTH). Among these, maximum entropy models are presence-only models, requiring background points (which do not distinguish between presence and absence), while all other algorithms require absences or pseudo-absences.

We applied two different methods to select these background and pseudo-absence points: a random sampling approach for cultivated cacao and the target group approach for wild cacao, based on Ceccarelli et al. (2021). The target group method, where background or pseudo-absence points are drawn from grid cells containing records of species belonging to a group (i.e. the 'target group') of species similar to the modelled species (Phillips et al. 2009), has proven an effective way to counteract the impact of spatially biased presence points (Barber et al. 2022). Methodological details on how these approaches were implemented are provided in Supplementary Text S1. For simplicity, both background and pseudo-based points will be referred to as 'pseudo-absences' hereafter.

To ensure robust evaluation of the algorithms, we used the *blockCV* package (Valavi et al. 2019) to implement a spatial block cross-validation, in which presence and pseudo-absence points were divided into training and validation sets across 10 folds, each composed of one or more 200-km wide squared blocks. A key strength of this spatial cross-validation approach, which was used to calculate the area under the receiver-operator curve (AUC) of each of the candidate algorithms, is that it evaluates model performance in areas that were not used for training, offering a more reliable estimate of the model's transferability, which is especially important when projecting models to future climatic conditions (Wenger and Olden 2012). The weight of each algorithm in the ensemble models was then determined using the 'ensemble.tune' function from the *BiodiversityR* package, which adjusts the algorithm weights by maximizing the AUC value through a factorial optimization process (Kindt, 2018). Final suitability predictions were generated using the full dataset of presence and pseudo-absences, applying the previously optimized algorithm weights. These continuous suitability predictions were then converted into binary presence-absence maps using a 10% omission threshold.

For both cultivated and wild cacao, we generated six ensemble models using different filtering methods to mitigate the effects of spatial sampling bias in the presence data. Three ensemble models applied only geographic filtering, at spatial resolutions of 5 arcminutes (ca. 9 km at the equator), 10 arcminutes, and 20 arcminutes, while the remaining three models combined geographic filtering at the same resolutions with environmental filtering. Geographic filtering involved randomly selecting a single presence point within each grid cell at the specified resolutions, while environmental filtering was carried out using the envSample function (https://github.com/SaraVarela/envSample), implementing the method described by Varela et al. (2014). This method overlays a grid on a multivariate environmental space and then retains one presence point per grid cell. For this analysis, we constructed a three-dimensional grid using the first three principal components derived from a PCA of environmental variables at the presence locations.

For both cultivated and wild cacao, we finally combined the predictions of the six ensemble models using a majority-vote approach; i.e. grid cells were deemed suitable if at least four out of six ensemble models predicted suitable conditions. In this way, the resulting predictions are those of an 'ensemble-of-ensemble models'.

Future projections under climate change

Each of the six ensemble models for cultivated and wild cacao was projected to future conditions (2050; average for 2041–2060) under two climate change scenarios: the shared socioeconomic pathways SSP2-4.5 and SSP3-7.0, the former being more optimistic than the latter. Downscaled future climate projections were derived from five general circulation models (GCMs): ACCESS-CM2, GISS-E2-1-G, INM-CM5-0, MIROC6, MPI-ESM1-2-HR. We selected these based on a model ranking by Brunner et al. (2020) that combines both GCM performance (referring to their ability to predict observed climatic conditions) and independence (dissimilarity), selecting the top five GCMs available through the WorldClim v2.1 database (Fick and Hijmans 2017).

For each ensemble model, future suitable conditions were predicted using a majority-vote approach, identifying suitable conditions where at least three out of five GCMs predict suitable conditions. Next, the predictions of the different ensemble models were combined for each SSP scenario, again using a majority-vote approach, identifying suitable conditions where at least four out of six ensemble models coincide. Statistics on contraction, expansion, and net change in suitable area were then calculated with the area of each grid cell factored into these calculations. In addition, we calculated these statistics for each of the municipalities in the distribution range of cultivated cacao.

Comparison with national planning strategy for commercial cacao cultivation

To inform local decision-making, we compared our results with the spatial planning strategy for commercial cacao cultivation adopted by the Colombian government (UPRA 2018). Rather than being based on correlative habitat suitability modelling (our approach), the map is based on a multicriteria analysis of spatial layers consisting of a weighted overlay of layers expressing a series of physical, socioecological, and socioeconomic conditions relevant for commercial cacao cultivation (Flórez et al. 2018). Areas are categorized in 'suitable' areas (further subdivided in low, medium, and high suitability), 'not suitable' areas, and 'legal exclusion' areas, where crop cultivation is prohibited by law.

Ecogeographical zones

To categorize and map the diversity of growing conditions across the range of cultivated and wild cacao, we divided this range into distinct areas characterized by comparable environmental conditions, termed 'ecogeographical zones' following Parra-Quijano et al. (2012). Such zones can serve as seed (transfer) zones (Miller et al. 2011; Fremout et al. 2021), providing a framework for identifying locally adapted planting material. Within a given zone, genetic material can be exchanged or relocated with a low likelihood of maladaptation. By projecting these zones to future climatic conditions, they can inform the selection of planting material from areas that currently resemble the projected future conditions of target sites, anticipating the effects of climate change through seed sourcing (Fremout et al. 2021).

Ecogeographical zones were delineated following Fremout et al. (2021), using the Clustering Large Applications (CLARA) algorithm implemented in the *cluster* package for R (Maechler et al. 2022). Seven distinct zones were defined in agreement with expert knowledge on the biogeographical regions of Colombia (González-Orozco 2021). The clustering was based on geographic coordinates (longitude and latitude) and the first ten principal components derived from a PCA performed on normalized environmental variables (Table S1), covering the full current distribution of both cultivated and wild cacao. These components collectively accounted for over 90% of the total variance. Longitude and latitude were scaled so their variance matched the average variance of the selected principal components. For projecting the seed zones to future conditions, each grid cell was assigned to its nearest cluster in the ordination space made of the selected principal components, applying the 'cl_predict' function from the *clue* R package (Hornik, 2019).

To explore if and how climate change could have different impacts in the different ecogeographical zones, we calculated average changes in mean annual precipitation and temperature by 2050 (average for 2041–2060) within each zone and across the five GCMs mentioned previously.

Outlier analysis for potential climate change–tolerant genotypes

To identify the locations where genotypes adapted to extreme conditions and therefore potentially tolerant to climate change may be present, we conducted an outlier analysis similar as in Ceccarelli et al. (2021) and Ceccarelli et al. (2024), which is based on the assumption that populations at the margins of cacao's climatic niche could be good candidates to look for climate change–tolerant genotypes. To identify these outliers, we selected four variables expected to be relevant: high temperature (tolerance to heat), low rainfall (tolerance to drought), high rainfall (tolerance to floods), and high elevation (tolerance to chilling risk) (Table 2). As climate change will not only alter climate averages but also increase the occurrence of extreme events, we repeated the outlier analyses using both climatic averages and climatic extremes for the first three variables (Table 2).

For the outliers using climatic averages, high-temperature outliers were identified as those cacao presence points falling above the 99th percentile of the maximum temperature of the warmest month, using the BIO5 variable from WorldClim (Fick and Hijmans 2017). Low-rainfall outliers were identified as those presence points below the 1 st percentile of annual precipitation (BIO12), while high rainfall were identified as those exceeding the 99th percentile of this variable. Percentiles were determined after filtering the presence points to a resolution of 30 arcsec (ca. 0.9 km at the equator), resulting in a total of 10,944 locations considered in the outlier analysis.

For the outliers using climatic extremes, we used three variables representing interannual extremes in monthly based maximum temperature and interannual extremes (minimum and maximum) in annual precipitation. These rasters, with a resolution of 3 × 3 km, are based on interpolated daily records from 1980 to 2010 from 4438 weather stations in Colombia (Alzate-Velásquez 2017; Alzate-Velásquez et al. 2018). The grid cells in the maximum temperature rasters express the value of the warmest month over those 30 years, while those of the minimum and maximum precipitation rasters express the value of the driest and warmest year. Also here, outliers were identified using the 99th percentile (maximum temperature and maximum precipitation) or the 1 st percentile (minimum temperature).

Finally, to identify locations with genotypes that may exhibit greater tolerance to ‘chilling risk’, which may be useful when expanding cacao cultivation to higher elevations, we also identified high-elevation outliers, using a 30 arcsec digital elevation model (Hengl 2018), again using the 99th percentile of the elevation values extracted at the filtered cacao presence points.

Results

Suitable area for cultivated and wild cacao under current climate conditions

A summary of the ensemble model results, including the cross-validated AUC values, number of presence points, and algorithms included in each of the models, can be found in Table S3. For both cultivated and wild cacao, the boosted regression trees algorithm yielded the highest average weight in the ensembles, followed by Maxent (see Table S4 for the average weights of all the considered algorithms).

According to the ensemble-of-ensemble models, to which we will refer to as ‘ensemble models’ in the following for brevity, commercially cultivated and wild cacao presented markedly different predicted distributions under current climatic conditions (Fig. 1). Cultivated cacao mainly occupies the foothills of the eastern, central, and western cordilleras (mountain ranges), extending along the inner slopes of the Cauca and Magdalena River valleys as well as along the slopes of the Sierra Nevada de Santa Marta and the Serranía de San Lucas, with some suitable area extending into the Colombian Amazon and the Orinoquía region in the east (Fig. 1a). In contrast, wild cacao covers the southern Colombia Amazon lowlands, with high-suitability values in Serrania of La Macarena – Andean transition, Chiribiquete National Park, the upper and lower basins of the Caguán and Caquetá rivers, the middle and lower areas of the Putumayo River, along with the surrounding areas of the middle and lower Apaporis River and the Trapecio Amazonico in Amazonas (Fig. 1b). The predicted suitable areas for cultivated and wild cacao overlap only slightly (Fig. 1), confirming that they occupy largely distinct ecological niches in Colombia.

Comparison with national planning strategy for commercial cacao cultivation

Figure 2 compares the results of our ensemble models with a spatial planning strategy by the Colombian government (UPRA 2018), based on an overlay of layers expressing physical, socioecological, and socioeconomic conditions. Overall, this map identifies a smaller suitable area than our model, although it also includes suitable areas that are not identified as suitable by our ensemble models, mainly in the Orinoquía region in eastern Colombia. To evaluate how both maps correspond to current reality, we overlaid them with our compiled dataset of cultivated cacao. After filtering this dataset to a resolution of 30 arcsec (ca. 0.9 km at the equator), i.e. only retaining one farm per grid cell, we found that 51% of the farms ($n = 5563$) are located in areas classified as suitable in both models. This overlap indicates a substantial level of agreement between our environmental suitability estimates and current spatial planning priorities. However, 44% ($n = 4805$) are situated in areas predicted to be suitable by our ensemble models but classified as unsuitable by UPRA, which may reflect the fact that additional, non-environmental variables were taken into account by UPRA. Only 0.4% of the farms ($n = 41$) are found in areas deemed suitable by UPRA but predicted to be unsuitable by our ensemble models. In addition, 5% ($n = 488$) are located within legal exclusion areas, such as national parks, highlighting potential conflicts between current land use and conservation regulations.

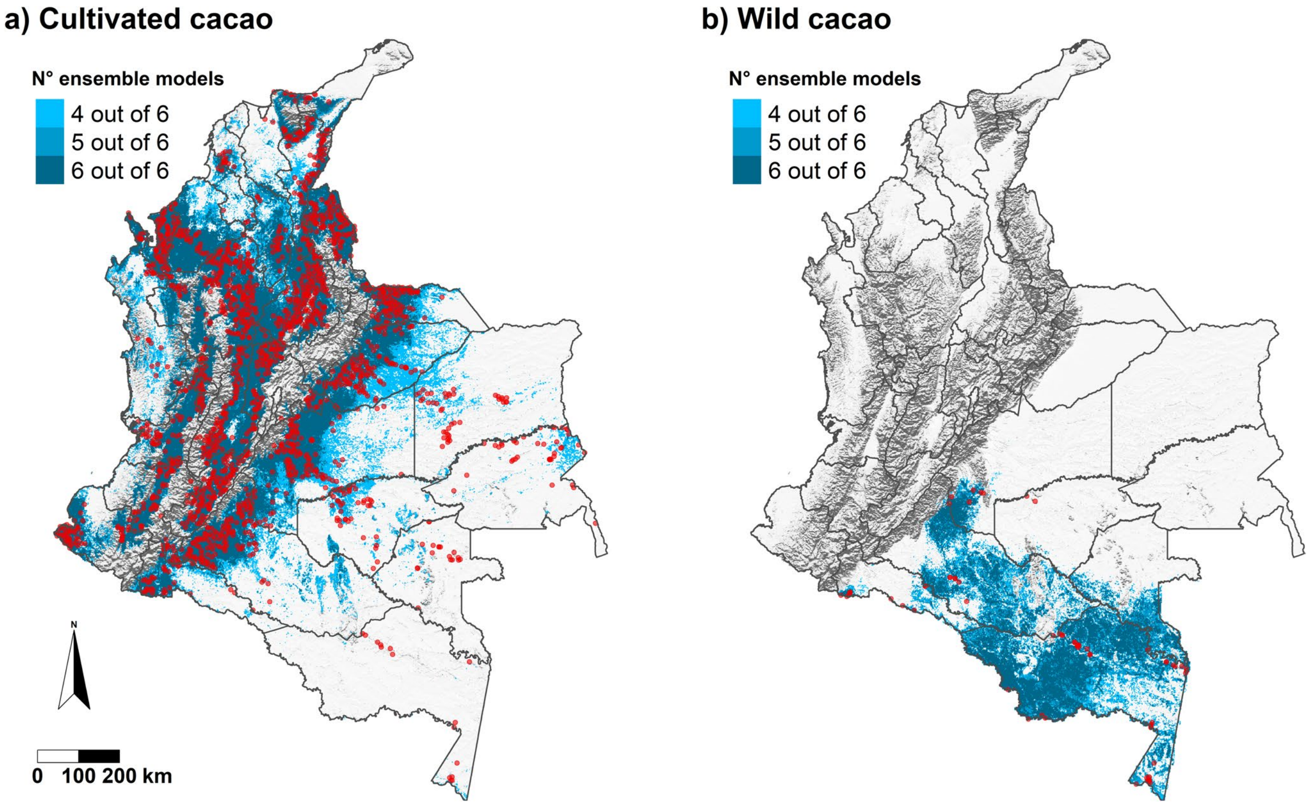


Fig. 1 Present predicted distribution of suitable habitat (shades of blue) and presence points (red dots) for cultivated cacao (panel **a**) and wild cacao (panel **b**) in Colombia. Colouring of suitable areas represents the number of ensemble models predicting suitable conditions, from four to six out of six ensemble models. Areas where less than four ensemble models predicted suitable conditions are considered not suitable and are not shown. The presence points for cultivated and wild cacao shown on the map are filtered at 5 arcmin (ca. 9 km) for visualization purposes. For wild cacao, we also used presence points from neighbouring countries (not shown) within the longitudinal and latitudinal extent of Colombia. The shown borders are the department borders

Future projections of suitable area for cultivated and wild cacao

Future projections for cultivated cacao predict a contraction of 19–20%, depending on the emission scenario (Fig. 3a, Table 1). However, most of the areas along the Andean foothills, where commercial cacao cultivation is currently concentrated, are predicted to remain suitable (Fig. 3), indicating that these regions retain climatic conditions close to the optimal range for cacao under future scenarios. In contrast, the greatest contraction is predicted in lowland areas with lower current habitat suitability, with 97% of areas predicted to lose suitability located below 400 masl, including some areas in northern Colombia, some parts of the Orinoquía plains in the northeast, and a few smaller areas along the Pacific (Fig. 3a). Our models also suggest slight expansion opportunities (3%; Table 1), mainly involving a shift to higher elevation areas. The 95th percentile of the elevation of all grid cells suitable for cultivated cacao increases from 1578 masl under present conditions to 1941 masl under the SSP2-4.5 scenario, and to 1956 masl under the SSP3-7.0 scenario.

Lowland areas below 300 masl are predicted to be the most affected by climate change (Fig. 3a), reflecting increasing exposure to temperatures exceeding the optimal range for cacao cultivation. For example, the departments of Santander, Colombia’s main cacao-producing zone, and César, the low-lying areas near the Magdalena River, are projected to experience some contraction, while the more hilly and mountainous areas are expected to remain suitable. Also, the nearby high-elevation cocoa cultivation zones in the department of Norte de Santander are predicted to remain suitable. Similarly, several other low-elevation zones in other northern departments, such as Bolívar and Córdoba, are predicted to lose a considerable portion of their currently suitable areas. In the surroundings of the Sierra Nevada de Santa Marta, most contraction is predicted along the southeastern foothills, while higher elevation areas are predicted to remain suitable. In most of the Andean cacao cultivation regions towards the centre and south of the country, such as

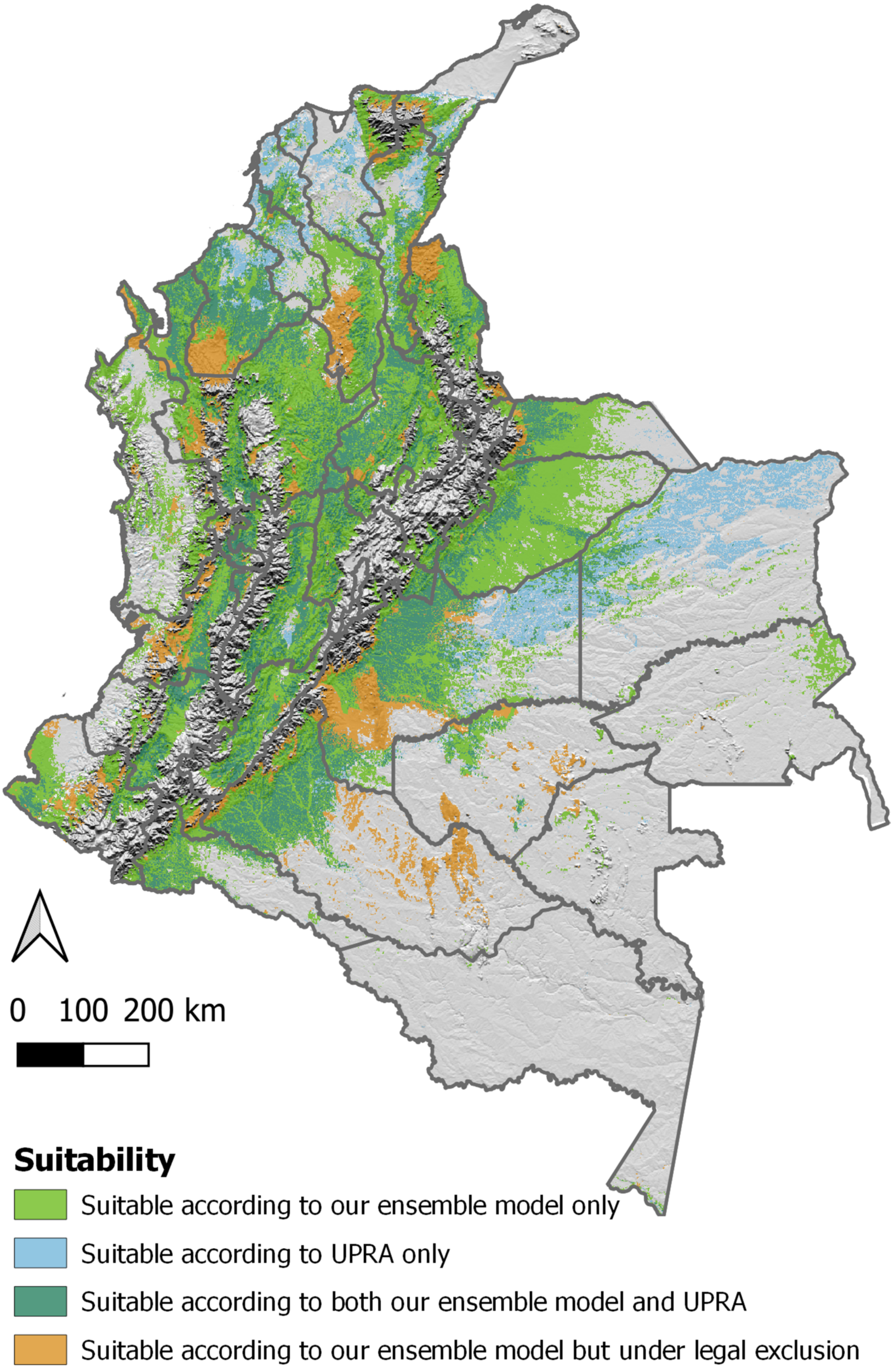
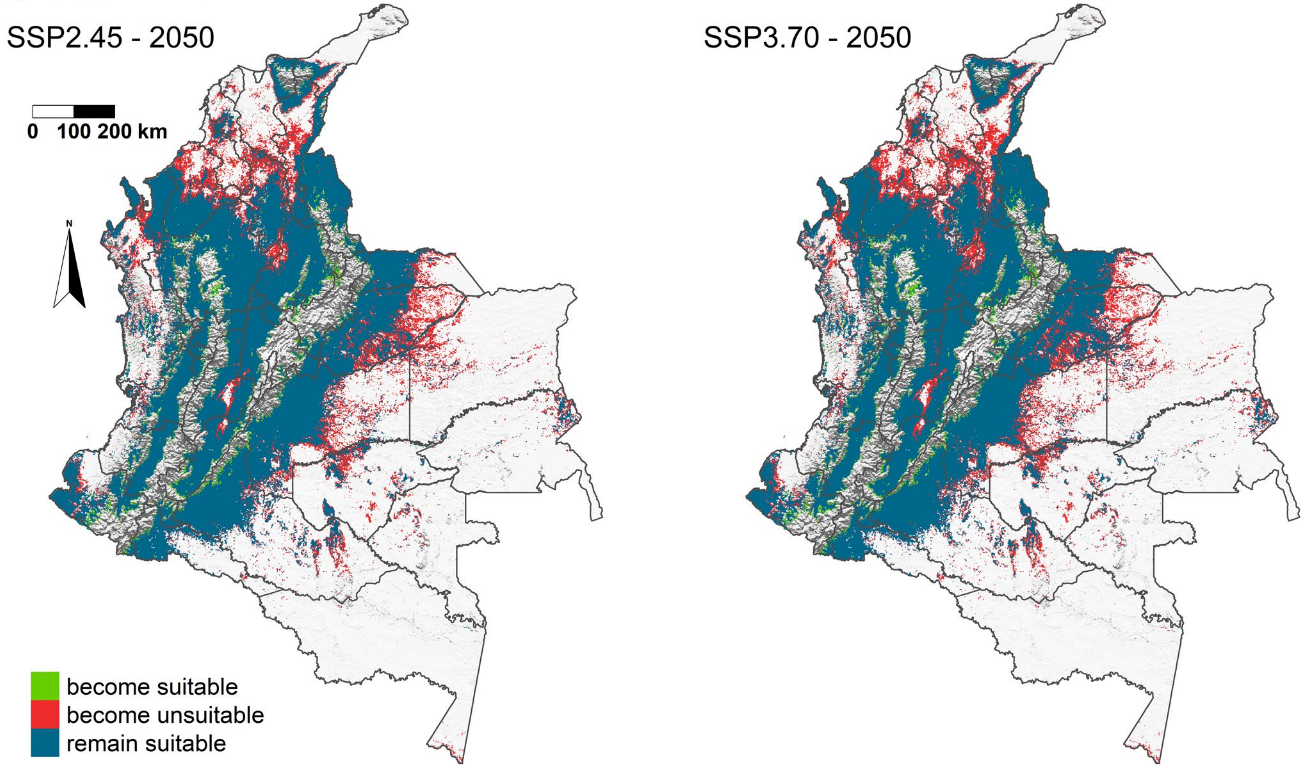


Fig. 2 Suitability map of cultivated cacao in Colombia: comparison between our ensemble modelling results and the areas suitable according to the spatial planning strategy for commercial cacao cultivation of Agricultural Rural Planning Unit (UPRA) of the Colombian Government (see the "Comparison with national planning strategy for commercial cacao cultivation" section). The ensemble models predict a larger distribution, although the areas currently most important for cacao cultivation along the Andean foothills largely overlap. The UPRA map also identifies some areas not identified as suitable by our model, mainly in the northeast and the north of the country. The shown borders are the department borders

the departments of Tolima and Huila, most suitable areas are predicted to remain suitable, except for some lowland areas in the Magdalena valley north of Neiva. In the west, the Cauca valley is predicted to remain suitable, as is the case for most cacao-growing zones of Tumaco in the coastal plains of Nariño. East of the Andes mountain ranges, significant contraction is anticipated in the Orinoquía region in the northeast, while the Andean foothills and lowlands of the departments of Caquetá and Putumayo in the south are predicted to remain largely suitable (Fig. 3a).

Detailed statistics describing changes in suitable area for all 983 municipalities that currently are at least partly suitable for cacao cultivation are provided in Table S4. The departments with the highest relative contraction

a) Cultivated cacao



b) Wild cacao

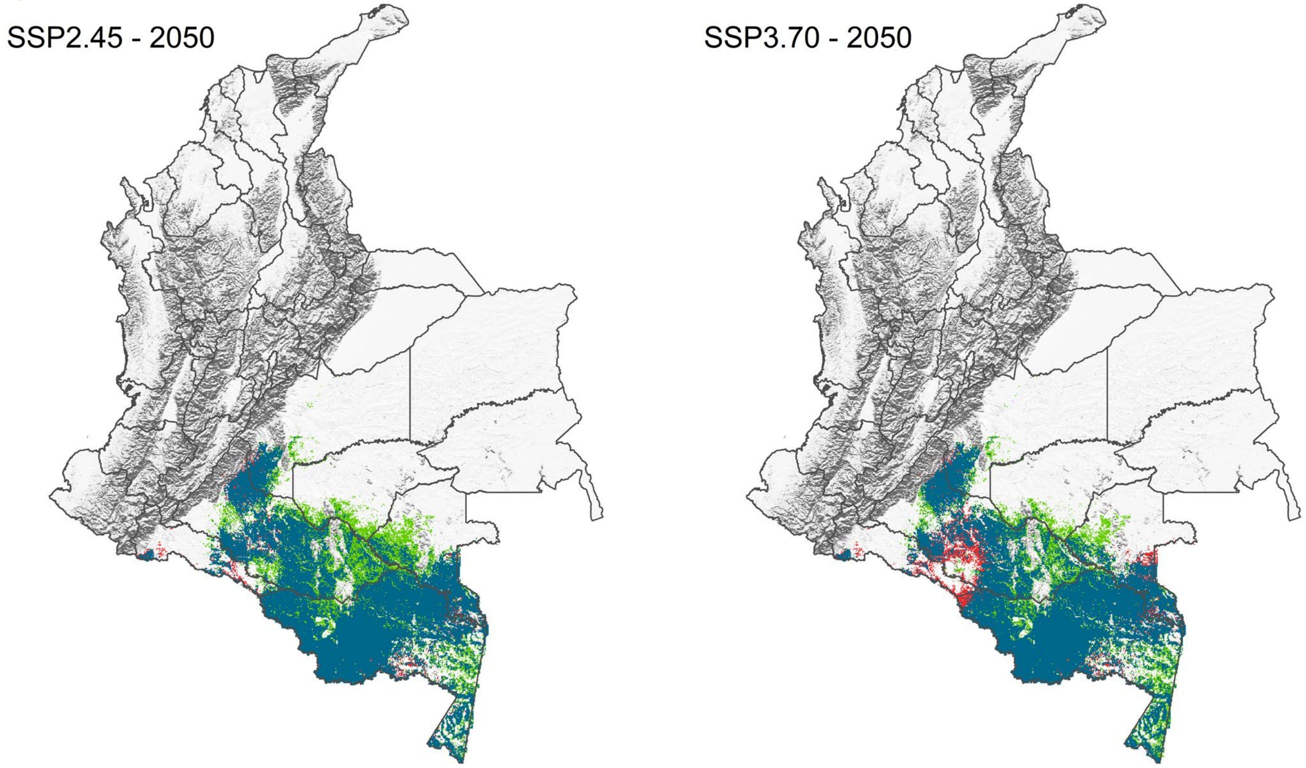


Fig. 3 Future predicted distribution of suitable habitat for cultivated cacao (panel **a**) and wild cacao (panel **b**) in Colombia in the 2050s, under the shared socioeconomic pathways (SSPs) SSP2-4.5 and SSP3-7.0. Currently suitable areas are estimated as areas where at least four out of six ensemble models agree on suitability according to the majority-vote criterion. Future predictions of the ensemble models for both cultivated and wild cacao were made where at least for three out of five general circulation models (GCMs) predict suitability, also using a majority-vote criterion. The shown borders are the department borders

(contraction area divided by current suitable area) are Vichada, Sucre, and Vaupés. The departments with the least relative contraction are Risaralda, Norte de Santander, and Boyacá, while the departments with the largest area that remains suitable in absolute terms are Antioquia, Meta, and Caquetá.

Compared to cultivated cacao, projections for wild cacao were more optimistic, although predicted contraction under the more pessimistic SSP3-7.0 scenario was considerably larger (8%) than under the more optimistic SSP2-4.5 scenario (3%) (Table 1). Additionally, our models predict an expansion between 27% (SSP3-7.0) and 20% (SSP2-4.5) (Table 1), mostly concentrated in the Caquetá and Vaupés departments (Fig. 3b), resulting in a predicted net change in suitable area of 12% (SSP3-7.0) to 24% (SSP2-4.5) despite localized losses.

Present and future ecogeographical zones

Seven ecogeographical zones largely aligning with Colombia's biogeographical regions (González-Orozco 2021) are shown in Fig. 4. In the Andean region, three zones were distinguished. The first one, termed 'Interandean and Caribbean lowlands', consists of lowlands below ca. 300 masl, covering the valleys of the Cauca, Magdalena, Sinú, and San Jorge Rivers. The second zone ('Andean foothills') spans elevations between ca. 300 and 1000 masl, extending along the inner slopes of the mountain ranges. The third ('Andean midlands') is a narrower stretch at elevations from ca. 1100 to 1800 m. Outside the Andean region, the fourth identified zone ('Pacific') covers the Pacific region, including the Chocó, Cauca, and Nariño rainforests. The fifth zone ('Orinoco plains') corresponds to the Orinoco region and its transition to the Amazonian forests, covering much of the northeastern plains of the country. The remaining two zones are located in the Amazon region, with one covering the southeast of Colombia ('Eastern Amazonia') and the other situated closer to the easternmost Andean mountain range ('Western Amazonia').

The identified ecogeographic zones are expected to shift under future climatic conditions (Fig. 4), illustrating that also areas remaining suitable will experience changes in growing conditions. The most notable predicted changes are in the Andean region, where the lowland zone ('Interandean and Caribbean lowlands') is expected to expand, while the 'Andean foothills' and the 'Andean midlands' zones are predicted to shift to higher elevations.

Looking further into the predicted climatic changes within each ecogeographical zone, Table S2 shows the average shifts in mean annual precipitation and temperature projected for the 2050s. Predicted temperature increases by 2050 averaged over the five considered GCMs (see the "Future projections under climate change" section), as compared to the historical WorldClim baseline (1970–2000), range from 1.5 ('Pacific') to 1.8 °C ('Orinoquía plains' and 'Eastern Amazonia') under SSP2-4.5. Predictions from individual GCMs indicate temperature increases between 1.1 and 2.8 °C. Under SSP3-7.0, average increases in mean annual temperature range from 1.7 (Pacific) to 2 °C (Eastern Amazonia), with individual GCM predictions varying between 1.2 and 3 °C. Projected changes in mean annual precipitation are more heterogeneous across ecogeographical zones, with rainfall expected to increase across all zones (on average) except in Eastern Amazonia under SSP2-4.5, and across all zones except the Orinoquía plains and Eastern Amazonia under SSP3-7.0. However, under both scenarios, at least one GCM predicts a decrease in rainfall in each of the ecogeographical zones, indicating uncertainty in future precipitation trends. Exception to this is the Pacific zone, where all GCMs consistently project an increase in rainfall.

Outlier analysis for genotypes with potential tolerance to climate change

Based on the results of our outlier analysis (Table 2), we identified sites that could potentially harbour populations and/or genotypes with tolerance to average (Fig. 5a) and extreme (Fig. 5b) climatic conditions at the margins of cacao's environmental niche. Overall, both types of outliers show a similar pattern, suggesting consistent geographic structuring of climatic tolerance. High-temperature outliers were found mainly in the north, including the César, Magdalena, Sucre, and Bolívar departments, as well as in the lowlands of the Magdalena valley near Huila, and some locations in the lowlands of the Caquetá, Meta, and Casanare

Table 1 Predicted changes in area of suitable habitat for cultivated and wild cacao by the 2050s, under the shared socioeconomic pathways (SSPs) SSP2-4.5 and SSP3-7.0. Cultivated cacao shows negative net area changes, while wild cacao positive net area changes

SSP	Period	Cultivated cacao			Wild cacao		
		Contraction area (%)	Expansion area (%)	Net area change (%)	Contraction area (%)	Expansion area (%)	Net area change (%)
SSP2-4.5	2050s	−19	+3	−16	−3	+27	+24
SSP3-7.0	2050s	−20	+3	−17	−8	+20	+12

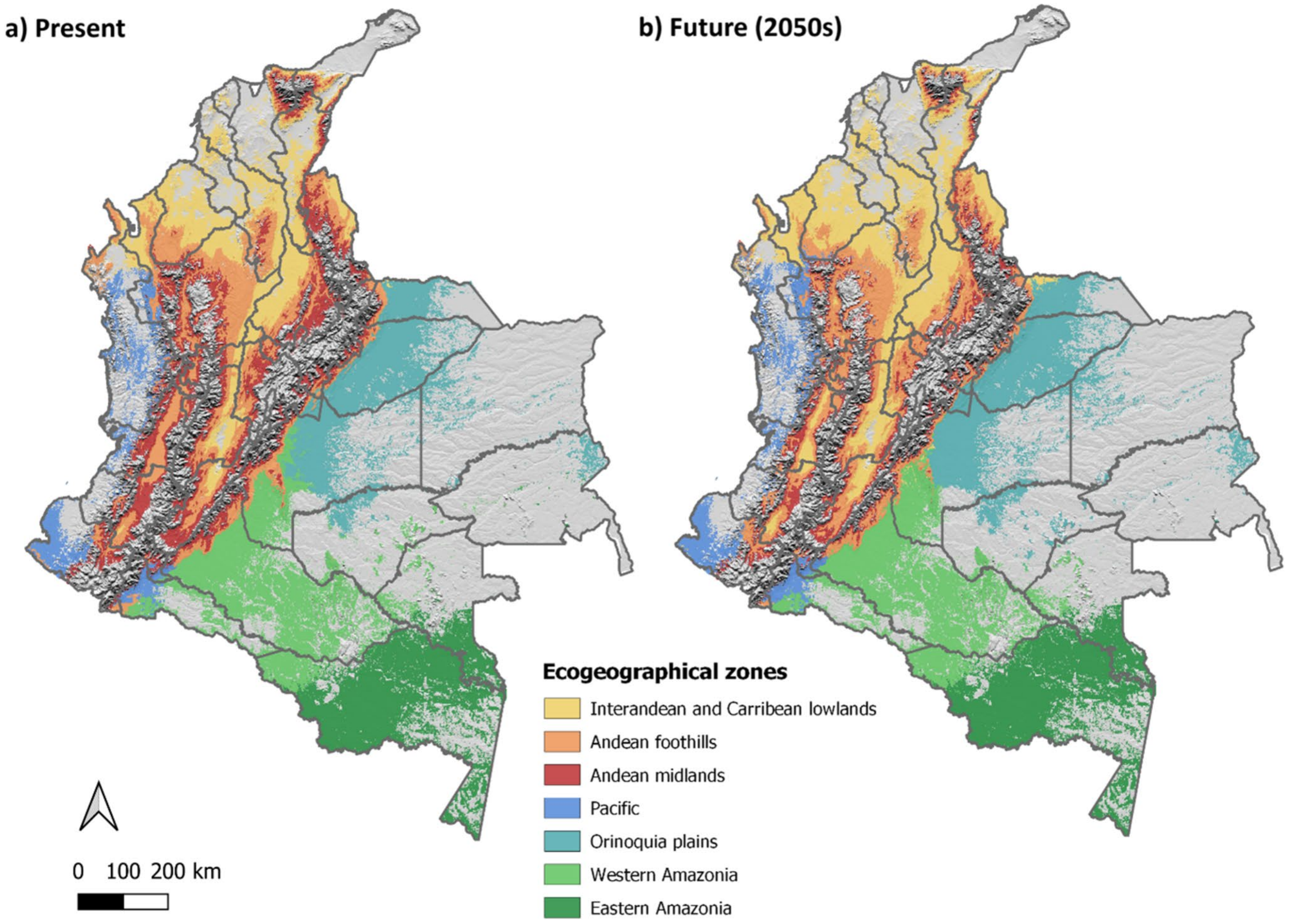


Fig. 4 Ecogeographical zones within the current distribution range of cultivated and wild cacao in Colombia, for present (panel **a**) and future (panel **b**) conditions. Predicted shifts under future conditions mainly consist of expansions of the 'Interandean and Caribbean lowlands' zone, as well as upwards shifts of the 'Andean foothills' and 'Andean midlands' zones. The future conditions (panel **b**) are those predicted under the SSP3-7.0 emission scenario by the ACCESS-CM2 general circulation model (GCM). We also projected the zones to SSP2-4.5 and other GCMs (see Figure S1 and Figure S2 in Supplementary Material 1). The shown borders are the department borders

departments in the east. Most low-rainfall outliers, which may indicate potential adaptation to drought, are situated in northern Colombia, particularly along the foothills of the Sierra Nevada de Santa Marta, as well as in the Norte de Santander and César departments. Most high-rainfall outliers, which may indicate greater tolerance to flooding, are situated along the Pacific, in Antioquia, and some localities along the eastern foothills of the eastern Cordillera.

Table 2 Thresholds used to identify outliers, i.e. cacao locations at the extremes of its realized niche in Colombia. Outlier thresholds correspond to the 99th or 1st percentiles of the variables shown in the table extracted at all cacao locations (cultivated and wild combined) after filtering these locations to a resolution of 30 arcsec (ca. 0.9 km at the equator), resulting in a total of 10,944 locations. Climate averages are calculated from WorldClim data (Fick and Hijmans 2017), the climate extremes from a custom dataset containing climate extremes over a 30-year period (Alzate-Velásquez 2017)

Type of outlier		Variable	Median	Outlier threshold	Predicted tolerance
Climate averages	Highest temperature	Mean max. temperature of warmest month	30.3 °C	> 34.8 °C	Heat
	Lowest precipitation	Mean annual precipitation	2330 mm	< 1369 mm	Drought
	Highest precipitation	Mean annual precipitation	2330 mm	> 3919 mm	Floods
Climate extremes	Highest temperature	Max. temperature of warmest month	31 °C	> 34 °C	Heat
	Lowest precipitation	Min annual precipitation	1997 mm	< 794 mm	Drought
	Highest precipitation	Maximum annual precipitation	3080 mm	> 5760 mm	Floods
Other outliers	Highest elevation	Elevation	602 masl	> 1598 masl	Chilling risk

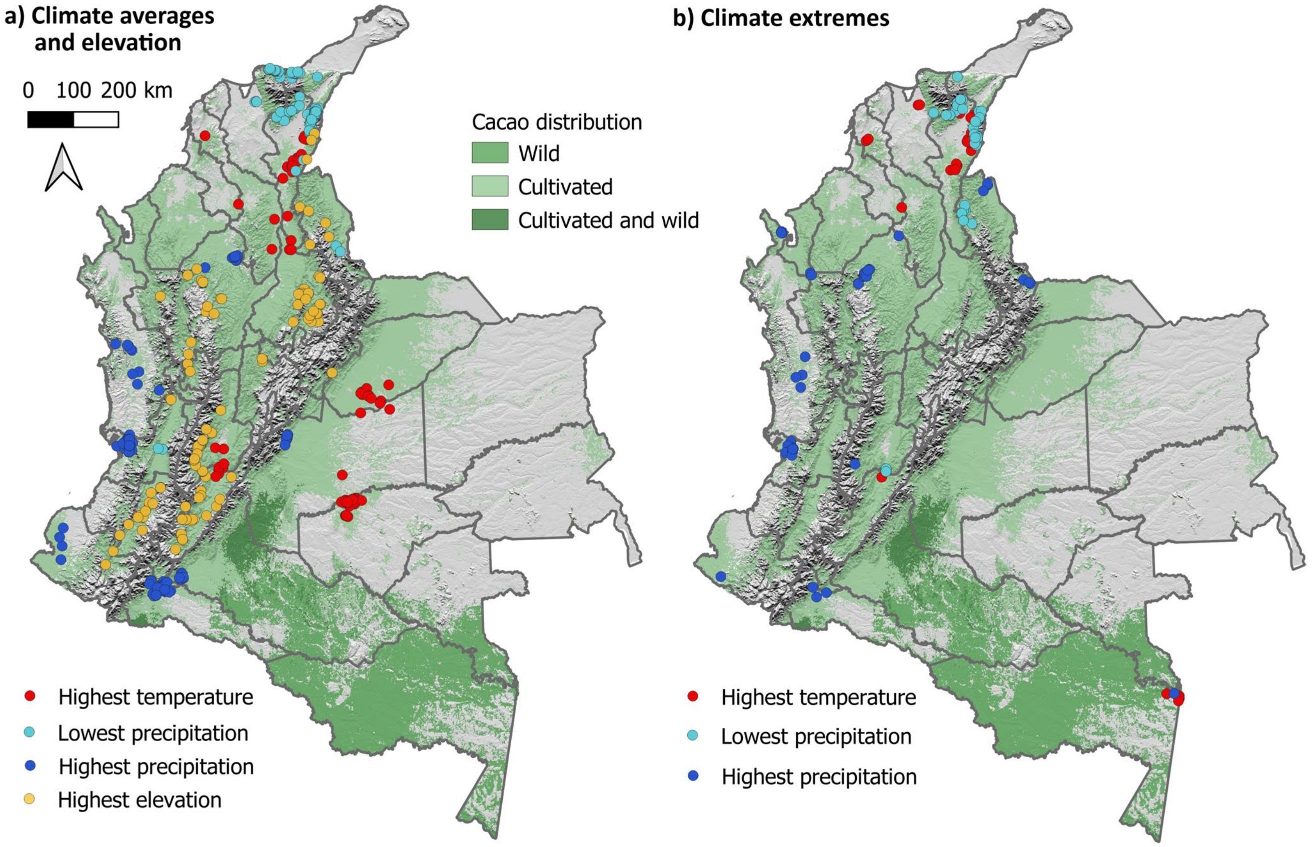


Fig. 5 Results of the outlier analysis showing localities where cacao is growing under extreme environmental conditions (i.e. conditions at the margin of its environmental niche, see the "Outlier analysis for potential climate change–tolerant genotypes" section for methodological details and for the thresholds used to identify outliers), according to monthly climate averages and elevation (panel **a**) and climate extremes (panel **b**). These locations correspond to areas where climate change–tolerant genotypes of cacao resistant to heat (highest temperature), drought (lowest precipitation), floods (highest precipitation) and chilling risk (highest elevation) may be potentially present

High-elevation outliers (exceeding 1598 masl) were spread out throughout the Andean region, with most situated in the departments of Cauca, Huila, Tolima, Antioquia, Santander, and Norte de Santander (Fig. 5a).

Discussion

Current and future distribution of suitable areas for cultivated and wild cacao

In this study, we estimated the spatial distribution of suitable environments for cultivated and wild cacao in Colombia using a combination of different ensemble models (i.e. ensemble-of-ensemble models), following Ceccarelli et al. (2024). Our findings confirm that cultivated and wild cacao have markedly different distributions in Colombia. The models also predict distinct impacts of climate change, predicting a net contraction for cultivated cacao and a net expansion for wild cacao. Most predicted contraction areas for cultivated cacao are situated in the lowlands of northern and eastern Colombia. However, the cacao-growing regions along the Andean foothills, which are currently most important for commercial cacao cultivation, are predicted to remain largely suitable, at least until the 2050s. In this regard, Colombia's emerging position in the fine-flavour cacao market does not seem to be at great risk of being negatively impacted by climate change in the coming decades.

Previous suitability modelling studies have similarly forecasted a net contraction in suitable area for cultivated cacao in other parts of Latin America. In Central America, for example, de Sousa et al. (2019) obtained very similar results, predicting that 83–87% of current cacao-growing areas will remain suitable, with only limited expansion opportunities to higher elevations (2%). Our results are also similar to previous studies in Peru (Ceccarelli et al. 2021) and Ecuador (Ceccarelli et al. 2024), although results in Ecuador were strongly region-specific, with net expansion along the coast and net contraction in the lowlands in the east of the country. In West Africa, Schroth et al. (2016) have predicted a marked decrease in high-suitability areas, with a decrease of 57% in Côte d'Ivoire and 41% in Ghana. Compared to West

Africa, cacao in Colombia is typically cultivated at higher elevations, which may explain the lower predicted vulnerability to climate change. However, a more recent study in West Africa by Ariza-Salamanca et al. (2023) yielded much more optimistic results, with a predicted net expansion of up to 6%.

Although the models suggest a limited impact of climate change on Colombia's main cacao-growing regions, it is worth highlighting that our models exclusively assess the effects on cacao suitability; further studies should also examine effects not considered here, including effects on yields, bean quality, and pest and disease pressure. Another limitation of our models is that they do not consider adaptation measures such as irrigation or agroforestry, which may help to mitigate the losses in suitability (see next section), nor do they consider the impacts of increased CO_2 concentrations, which may counteract some of the negative effects of climate change on cacao suitability and productivity by increasing photosynthetic rates and decreasing stomatal conductance, thereby increasing water use efficiency (Lahive et al. 2019; Black et al. 2020). Because correlative habitat suitability models cannot account for these effects, our predictions must be interpreted with appropriate caution and complemented with mechanistic (process-based) models that allow better understanding of climate change impacts on cacao plants' physiology. In a recent study focusing on West Africa, Asante et al. (2025) used such a physiological crop model to investigate the effects of climate change on cacao yields. They found that increases in CO_2 may effectively compensate for the predicted temperature increase and lead to increases in cacao yields in large parts of West Africa, especially under wetter climate change scenarios. Similar methods should be applied in Colombia and elsewhere in Latin America to complement the correlative models used in this study.

The national planning strategy for commercial cacao cultivation adopted by the Colombian government (UPRA 2018) uses an alternative method for producing crop suitability predictions, based on a multicriteria analysis consisting of a weighted overlay of spatial layers expressing physical, socioecological, and socioeconomic aspects relevant for cacao production. By including socioecological (e.g. land use, ecological integrity) and socioeconomic (e.g. land price, market access) factors (Flórez et al. 2018), this method addresses another limitation of our models, which rely exclusively on biophysical variables. Both maps coincide in predicting suitability along the Andean foothills, where most commercial cacao cultivation is currently concentrated. However, the comparison between our ensemble models and the UPRA map also reveals that the latter is much more conservative in many parts of Colombia, as almost half (44%) of the grid cells with cacao farms ($n = 4805$) were located outside the area classified as suitable by UPRA, although these locations were the same as those used to train our models, hindering an independent comparison of both maps.

On the other hand, the national planning strategy also identifies some areas not predicted to be suitable by our models, particularly in the Meta and Vichada departments of eastern Colombia, which are regions where cacao has only recently started expanding. As a result, we were only able to compile a limited number of cacao coordinates from these departments, which may have resulted in an underestimation of the suitability for cacao cultivation, despite the measures taken to reduce the effects of spatial bias. This is an advantage of the approach used by UPRA, as it is not influenced by the spatial bias of cacao farm locations. However, our results suggest that many of these expansion areas in the lowlands of eastern Colombia are predicted to lose suitability for cacao cultivation due to climate change, which is an aspect not considered in the UPRA map. Therefore, any expansion into these areas should be approached with caution and possibly accompanied by the necessary adaptation measures (see further). In summary, our map and the UPRA map are complementary, and further studies should attempt to explicitly combine correlative suitability modelling with an analysis of other factors that determine land suitability for commercial cacao cultivation.

In terms of wild cacao, our models predict that populations will be able to persist or even expand under climate change, highlighting the potential contribution of their genetic resources to the adaptation of cultivated cacao, and stressing the importance of their in-situ conservation and characterization. This is particularly the case in areas that overlap with climate refugia identified by González-Orozco et al. (2021a) in the Caquetá-Putumayo Bajo Caguan river region, for the high and unique genetic diversity these regions may harbour.

Preparing for climate change threats: adaptation measures and policy recommendations

While our results suggest that most areas currently most important for commercial cacao cultivation may remain largely suitable, at least until the 2050s, temperatures will rise throughout Colombia, also in regions predicted to remain suitable. Predicted changes in precipitation are less straightforward: while the overall trend indicates an increase, individual GCMs often predict a decrease in precipitation at least in some of the ecogeographical zones (Table S2). In each of the ecogeographical zones, which represent regions with similar environmental conditions, farmers typically use cacao varieties adapted to these conditions. However, under climate change, varieties well-adapted to current conditions will not necessarily perform well under future conditions, as illustrated by the shifts in the ecogeographical zones. Overall, it is clear that cacao-producing regions will experience different climatic conditions in the future, calling for adaptation measures that consider location-specific limitations and needs.

Several adaptation strategies may be available to cacao farmers to respond to climate change impacts. Notably, agroforestry systems can help to reduce heat stress and drought stress, thanks to the buffering effect of the tree canopy on air temperature and vapour pressure deficit (Heming et al. 2022; Kohl et al. 2024), which may reduce temperatures in the understorey of cacao agroforestry systems by up to 6–7° C (Abdulai et al. 2018b; Heming et al. 2022). This effect will likely become critical in the future, especially in those areas where temperature extremes may exceed crop tolerance limits (Heming et al. 2022), stressing the need for increased investments and agricultural extension to promote the adoption of agroforestry systems. While temperatures between 31 and 33 °C are optimal for cacao photosynthesis (Balasimha et al. 1991; Mensah et al. 2023), values in cacao fields are already often much higher, with temperatures of 40 °C and higher measured in Ghana (Abdulai et al. 2018b). More research is needed to investigate the temperature extremes that cacao can tolerate without negatively impacting productivity and bean quality (Lahive et al. 2019).

Despite their clear impact of shade trees on microclimatic conditions, the impact of shade trees on soil moisture available to cacao is less straightforward. Shade tree agroforestry has been described as most effective in hot, dry climates (Beer et al. 1998) and cacao farmers in dry regions of Ghana opt for higher shade tree densities than in wet regions (Abdulai et al. 2018a), but the combined transpiration of cacao and shade trees may be higher in agroforestry systems than in monocultures, leading to competition for water (Abdulai et al. 2018b). In Ghana, Abdulai et al. (2018b) even found shaded cacao to be more affected by an extreme drought event than full-sun cacao, although these findings may have been influenced by the chosen sampling strategy (Norgrove 2018). In contrast, in a study in Bolivia, Niether et al. (2017) found higher levels of soil moisture in the top soil under agroforestry than in monoculture.

To maximize the potential benefits of agroforestry on drought stress mitigation, it is important to maintain the right amount of tree cover. Both low and high tree cover have been found to increase soil moisture stress in cacao production systems in Ghana, with optimal tree cover values of around 30% (Blaser et al. 2018). Also, the selection of the right tree species plays a role, as species differ in their microclimate effects (Kohl et al. 2024) and water use (Dierick et al. 2010). For example, deep-rooted trees can extract water from deeper root layers, reducing competition with relatively shallow-rooted cacao plants (Moser et al. 2010). Also, planting design plays a role: Kohl et al. (2024) found cacao growth to be more affected by distance to the shade tree than by shade tree species and recommend avoiding planting cacao trees at close distances (< 3 m) of shade trees. Additional measures for alleviating drought stress, implemented either separately or as part of agroforestry, include irrigation, organic fertilizers, mulching, cover crops, and the use of biochar (Acheampong et al. 2019; Amfo et al. 2021; Wei et al. 2023).

Identifying and utilizing cacao genotypes with tolerance to climatic stresses is a relatively underexplored yet promising avenue for climate adaptation (Lahive et al. 2019). Planting material may be sourced from targeted collection efforts in the locations highlighted as likely to host climate change–tolerant cacao types, or from existing germplasm collections or previous collection missions. It is important that only locally adapted genotypes, i.e. those that have emerged through natural evolution or pollination (either open or controlled) within farmers' fields, are selected, rather than genotypes introduced from other Latin American regions, as these are not necessarily adapted to local conditions. Candidate genotypes should undergo rigorous evaluation for climate resilience, both in controlled environments and in the field, before being integrated into breeding initiatives. A similar study in Peru (Ceccarelli et al. 2021) allowed confirming through climate chamber trials (Zavaleta et al., unpublished) that the origin of cacao provenances correlates with their performance under drought and heat stress. In efforts to identify climate change–tolerant cacao genotypes, assessments should also consider traits like light use efficiency, which is key for maintaining high productivity in shaded agroforestry systems (Lahive et al. 2019).

In the following, we discuss some priority adaptation measures for each of the ecogeographical zones. In the lowland zones 'Interandean and Caribbean lowlands', 'Orinoquía plains', and 'Western Amazonia', some areas are predicted to become unsuitable, especially in the lowest-elevation areas. While any expansion into areas predicted to become unsuitable should be approached with caution, we do not suggest that all farmers currently cultivating cacao in these areas should abandon cacao cultivation. Instead, we recommend widespread adoption of well-designed agroforestry systems to mitigate heat stress (Heming et al. 2022) and the use and development of varieties tolerant to high temperatures (Lahive et al. 2019). All high-temperature outliers of cultivated cacao fall within one of these lowland ecogeographical zones, making them potentially important sources of genetic resources for climate change–tolerant cacao breeding. Furthermore, the north of the 'Interandean and Caribbean lowlands' zone also contains most of the low-rainfall outliers, which could be instrumental in identifying or developing drought-tolerant cacao varieties.

In the Andean region, the ecogeographical zones show a shift towards higher elevations, suggesting that a possible adaptation strategy is to use varieties used at lower elevations. Therefore, in the 'Andean foothills' zone, we recommend testing varieties currently successfully cultivated in the adjacent lowland ecogeographical zone. Similarly, in the 'Andean midlands' zone, we propose testing varieties currently used in the 'Andean foothills'. In both zones, particularly in the 'Andean midlands', agroforestry systems may be less critical for heat stress mitigation than in the lowlands. However, they could still alleviate other stress factors typical of these Andean environments, such as soil erosion and strong winds. In the 'Andean midlands' zone, we suggest exploring cacao cultivation at elevations above the current range, provided this does not involve clearing the already highly threatened montane forests. Genotypes currently growing at high-elevation outliers, distributed along the different Andean mountain ranges, could be candidates for trials along this upward shifting elevation margin, as these may exhibit greater tolerance to cold conditions ('chilling risk').

In the 'Pacific' ecogeographical zone, where rainfall is already very high, precipitation is expected to increase even further (Table S2). Due to this high rainfall, along with the high cloud cover characteristic of this region, agroforestry systems may be less crucial than elsewhere. Genetic material adapted to extremely high rainfall could be identified locally, as most high-rainfall outliers were located within this zone, or in other high-rainfall areas of Antioquia or the eastern foothills of the Andes. Other adaptation measures to avoid flooding damage may include the use of drainage channels or planting cacao on raised beds.

In the 'Eastern Amazonia' zone, commercial cacao cultivation is currently almost non-existent, but the outlier analysis revealed a few high-temperature and high-rainfall outliers according to the climate extremes, in the very east at the border with Brazil, which may be useful for breeding climate change–tolerant varieties for regions where rainfall is expected to increase.

Conclusion

This study provides the first nationwide assessment of climate change impacts on both cultivated and wild cacao in Colombia, using a robust ensemble-of-ensemble modelling approach. The results indicate that climate change could considerably reduce environmentally suitable areas for cultivated cacao by the 2050 s, particularly in the lowland regions in the northeast and the north. On the positive side, most of the areas that are currently most important for cacao production, located mainly along the Andean foothills, are predicted to remain suitable. In contrast, wild cacao is predicted to experience a net range expansion, highlighting its potential as a valuable source of genetic diversity for climate-resilient breeding.

By delineating ecogeographical zones and identifying sites at the margins of cacao's climatic niche, our study offers a framework for guiding the selection and use of climate-adapted genotypes and zone-specific adaptation measures. In particular, the broader adoption of agroforestry systems and the use of climate change–tolerant genotypes will be key to strengthening the climate resilience of Colombia's cacao sector.

Future research should complement correlative habitat suitability modelling (as in this study) with mechanistic crop models that allow to estimate the physiological response of cacao to climate change, including its response to increased CO_2 concentrations and climate change effects on cacao yields. Moreover, candidate genotypes from potentially climate change–tolerant populations identified here should be evaluated through climate chamber and field experiments to confirm their tolerance to heat, drought, and flooding. The integration of these different approaches will be essential for the further development of science-based climate adaptation strategies for cacao production.

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Data availability The maps generated in the current study are available from the corresponding author on request.

Declarations

Competing interests The authors declare no competing interests.

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