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# Climatic suitability variations for climbing bean cultivation under climate change scenarios in Cundinamarca, Colombia

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## RESUMEN

Se prevé que el cambio climático modifique las actuales zonas aptas para el cultivo de frijol debido a variaciones regionales en la temperatura y la precipitación. A pesar de la importancia de esta especie para la economía y la seguridad alimentaria en Colombia, hay un gran desconocimiento sobre cómo el cambio climático actual y futuro podría modificar la aptitud agroclimática de las zonas productivas de frijol en el país. Este estudio tuvo como objetivo evaluar los potenciales cambios futuros en las zonas aptas para el cultivo de frijol trepador (*Phaseolus vulgaris* L.) en el departamento de Cundinamarca bajo escenarios de cambio climático. Las áreas adecuadas para el establecimiento del cultivo de frijol fueron categorizadas como A1 (mejores condiciones), A2 (restricciones moderadas), A3 (restricciones fuertes) y N1 (no apto). Esta clasificación derivó de un árbol de decisión con intervalos definidos de altitud, temperatura y precipitación. Se utilizaron el periodo 1981-2010 como clima presente y los periodos futuros 2011-2040, 2041-2070 y 2071-2100 bajo los escenarios de cambio climático RCP 4.5 y RCP 8.5. La información del Modelo Climático Global CCSM4, del Centro Nacional de Investigación Atmosférica, se empleó para identificar nuevas áreas potenciales y cambios en las zonas óptimas en escenarios futuros. Los resultados indican que en el escenario RCP 4.5, la superficie total apta disminuye ligeramente en un 3.8 %, mientras que las zonas de aptitud A1 se expanden en las regiones montañosas del altiplano. En un futuro con altas emisiones (RCP 8.5), la superficie total apta disminuye en un 14.8 % entre 2071 y 2100, mientras que las zonas no aptas aumentan en un 6.5 %. La expansión de hasta 13 % de las zonas de aptitud A3 a principios y mediados del siglo 21 refleja la degradación de las áreas actualmente óptimas o moderadas a áreas de baja aptitud debido al aumento de las temperaturas, especialmente en las subregiones de los Llanos Orientales y en las laderas del Magdalena.

## ABSTRACT

Climate change is expected to modify the current suitable areas for bean cultivation, driven by regional shifts in temperature and precipitation. Despite the economic and food security importance of beans in Colombia, there is a lack of knowledge about how ongoing and future climate change may reshape their agroclimatic suitability across the country. This study aimed to assess the potential future shifts in suitable areas for climbing bean (*Phaseolus vulgaris* L.) cultivation in the department of Cundinamarca under projected climate change scenarios. Suitable areas were categorized into A1 (best conditions), A2 (moderate constraints), A3 (strong restrictions), and N1 (not suitable), based on a decision tree with defined altitude, temperature, and precipitation intervals. The period 1981-2010 was utilized as the present climate, and the future periods 2011-2040, 2041-2070, and 2071-2100 were considered under the climate change scenarios RCP 4.5 and

RCP 8.5. Information from the Global Climate Model CCSM4 from the National Center for Atmospheric Research was used to identify new potential areas and changes in optimal zones under future scenarios. The forecast for Cundinamarca indicates that under the RCP 4.5 scenario, the total suitable area decreases slightly by 3.8%, while the A1 zone expands, especially in cooler highland regions. In a high-emission future (the RCP 8.5 scenario), the total suitable area declines more sharply (by 14.8% between 2071 and 2100), while the unsuitable area increases by 6.5%. The expansion of A3 zones by up to 13.3% in the early and mid-21st century reflects the downgrading of currently optimal or moderate areas to low suitability due to rising temperatures, particularly in the Llanos foothills and the Magdalena slopes subregions.

**Keywords:** climatic factors, global warming, agroclimatic areas, *Phaseolus vulgaris* L.

## 1. Introduction

Common beans (*Phaseolus vulgaris* L.) represent the most significant legume utilized for direct human consumption and constitute a substantial global reservoir of biodiversity within the legume family. Beans are cultivated in over 10 major market classes worldwide and have been identified by national and international agencies as a mandatory crop for food security programs due to their high protein and low-cost mineral content (Uebersax et al., 2022). Two primary regions have been identified as the sites of domestication: the Andes and Central America (Hernández-López et al., 2013). In the Andean region of Colombia, beans represent a significant source of income and employment in rural areas (Gallego et al., 2010; Barrios-Pérez and Álvarez-Toro, 2016; Arcos and Rojas, 2019). In 2023, small and medium-sized family farmers cultivated 5884 ha of beans in Cundinamarca, making it one of the region's primary agricultural commodities (Agronet, 2025). However, it is expected that climate change will particularly affect the production of this legume in Colombia. Some traditional varieties of common beans cultivated in Colombia are highly vulnerable to extreme temperatures and reduced rainfall. Furthermore, traditional varieties are expected to have a reduced capacity to be cultivated in low-elevation areas due to an increased prevalence of biotic and abiotic stresses, along with a worsened ENSO (zRamírez-Villegas et al., 2012; Feola et al., 2015; Acevedo and Martínez, 2016; Eitzinger et al., 2018; Güiza-Villa et al., 2020).

Potential climatic suitability refers to the degree to which climatic conditions meet the needs for crop growth, without consideration of other limiting factors (Zhao, et al., 2016). In fact, the assessment of a specific crop's climatic suitability in a particular region is a fundamental criterion in the decision-making process regarding its cultivation in a specific area (Duan and Zhou, 2013; He and Zhou, 2016; Feng et al., 2021; Zhao et al., 2021). However, climatic suitability is not a static feature. Ongoing climate change may result in shifts in the zones currently suitable for cultivating various crops, directly affecting the economies of peasants and the food security of rural communities (Araya et al., 2011; Benke and Pelizaro, 2010; Holzkämper et al., 2013). A comprehensive assessment of the climatic suitability of food crops in the context of climate change, in conjunction with the development of efficient crop cultivation frameworks, is of paramount importance (Yin and Wei, 2023). In its Fifth Assessment Report, the Intergovernmental Panel on Climate Change (IPCC) employed a set of four scenarios, or Representative Concentration Pathways (RCPs), to estimate future climatic suitability for crops. The scenarios include one mitigation scenario leading to very low forcing (RCP 2.6), two stabilization scenarios (RCP 4.5 and RCP 6.0), and one with very high greenhouse gas emissions (RCP 8.5) (IPCC, 2013). For Colombia, the scenarios indicate that the annual average temperature will gradually increase, reaching a peak of 2 ºC by the end of the 21st century. Nevertheless, increases in temperature and precipitation patterns will vary across regions, indicating that measures to address these changes must differ for each region of the national territory (Ideam, 2015). In this regard, it is expected to have a significant impact on the agroclimatic suitability of bean cultivation across different regions. However, although bean cultivation could experience adverse effects on productivity during this century (CIAT, 2014; Beebe et al., 2017), there are no studies assessing the suitability changes in beans related to ongoing climate change in Colombia.

Available studies have been conducted in countries such as Mexico and Brazil to analyze the impact of climate change on potential bean cultivation areas, revealing reductions in productive areas in each country (Delgado-Assad et al., 2016; Medina-García et al., 2016).

Therefore, we assessed changes in areas suitable for climbing bean cultivation in Cundinamarca for the periods 2011-2040, 2041-2070, and 2071-2100. This was done by considering two representative concentration pathway scenarios, RCP 4.5 and RCP 8.5, using a general circulation model (GCM) to simulate Colombia's climate. This study aimed to assess how potential future climate changes, such as rising temperatures and altered precipitation patterns, could change the current climatic suitability of climbing bean areas in Cundinamarca. The output of this assessment is a biophysical potential that is exclusively conditioned by climate. These findings could aid policymakers in crafting effective adaptation plans and offer benchmarks for promoting the sustainable advancement of agriculture.

## 2. Data and methods

### *2.1 Study area*

The department of Cundinamarca is in the center of Colombia, between 3º 40' 14" and 5º 50' 11" N, and 73º 03' 08" and 74º 53' 35" W. It borders the departments of Boyacá to the north, Boyacá and Meta to the east, Meta, Huila, and Tolima to the south, and Tolima and Caldas to the west. The department lies within the Eastern Ranges and features both flat and mountainous terrain, with elevations ranging from 300 to 4000 masl, but altitudes of 2000 to 3000 masl predominate. The department encompasses natural subregions (Fig. 1): the Cundiboyacense high plateau, the Magdalena slope, and the Llanos foothills.

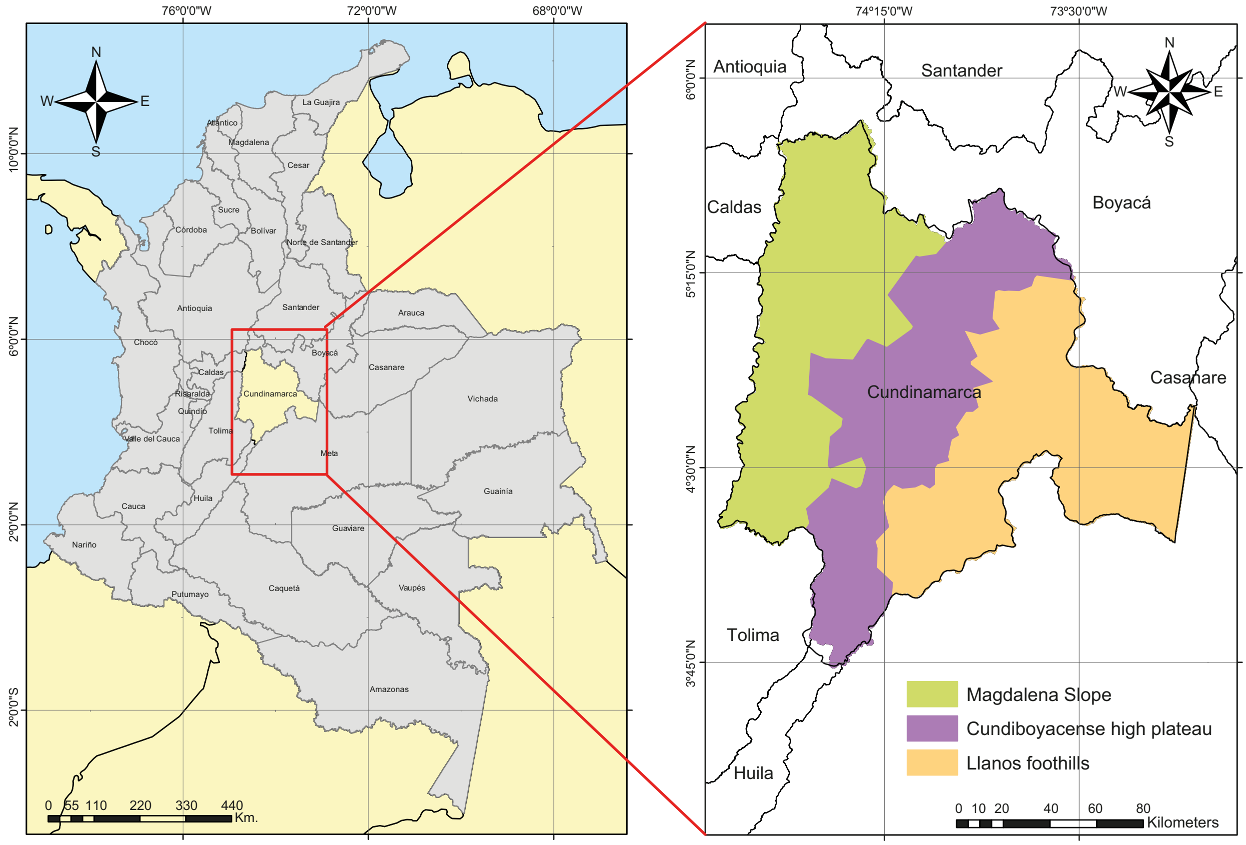


Fig. 1. Map of the study area: Cundiboyacense high plateau (violet), Magdalena slope (green), and Llanos foothills (orange).

The annual total precipitation varies spatially between 500 and 7000 mm. The highest records occur in the eastern zone along the border with Meta (5000 to 7000 mm), while the lowest are found in the high plateau (500 to 1000 mm). In the northwest area, rainfall ranges from 1500 to 3000 mm. The average annual temperature ranges from 8 to 30 ºC. Higher temperatures are observed on the Magdalena slope (20 to 28 ºC) and the Llanos foothills (24 to 28 ºC), while in the Cundiboyacense high plateau, average temperatures range from 12 to 16 ºC (Ideam, 2017).

### *2.2 Data*

In this study, a total of 306 precipitation climatic series and 60 average daily temperature series were used for the period 1981-2010 (present climate). These data were collected from the hydroclimatic network of the Institute of Hydrology, Meteorology, and Environmental Studies of Colombia (Ideam). The quality control process for the climatic series involved the following steps:

1. Statistical and physical data coherence: Data coherence in terms of statistics and physical characteristics was assessed using the methodology outlined by Guijarro (2018).
2. Homogeneity testing: Homogeneity tests, following the methods established by Alexandersson (1986), were conducted to ensure the consistency of the data.
3. Quality validation: The quality processes were validated using the McCuen test (McCuen, 2016). Only datasets with a maximum of 20% missing data for precipitation and 30% for temperature were retained for further analysis.

On the other hand, simulated climate series of precipitation and temperature were obtained from the Community Climate System Model v. 4 (CCSM4) developed by the National Center for Atmospheric Research (NCAR). These simulations covered the 1981-2010 period as well as the future periods 2011-2040, 2041-2070, and 2071-2100 under the RCP 4.5 and RCP 8.5 scenarios. These scenarios are consistent with the ones used in the Third National Communication on Climate Change (CNCC) in Colombia (Ideam, 2015). Additionally, a digital elevation model (DEM) derived from the NASA Shuttle Radar Topography Mission (SRTM) was used, with a 250 × 250 m grid.

### *2.3 Generation of observed climatic surfaces*

Daily climatic surfaces were generated from station records using inverse distance weighting (IDW) (Shepard, 1968). This method was employed for both precipitation and temperature. In the case of temperature, the DEM was also included to capture spatial variability associated with altitude. Using these daily surfaces and map algebra, annual total precipitation and average annual temperature were calculated at a spatial level. IDW estimates values at unmeasured locations based on the values of neighboring measured points, with greater weight given to closer points and less to distant ones. Incorporating the DEM enabled capturing the influence of elevation on temperature patterns, which is particularly relevant in areas with significant altitude variations, such as the study area. This process enabled the creation of distributed climatic surfaces that represent the climatic conditions observed in the study area. These surfaces were then utilized to analyze climate data and their potential implications for climbing bean cultivation under different climate change scenarios.

### *2.4 Generation of simulated climatic surfaces*

The process of generating simulated climatic surfaces involved a two-step approach to scale down the model outputs, originally in grid format, to the locations of the weather stations. This scaling process was achieved using the bias correction and statistical downscaling (BCSD) method. This technique was initially developed for seasonal-to-interannual prediction applications (Wood et al., 2002) and has been extensively used in climate change studies at monthly scales (Payne et al., 2004; Vicuna et al., 2007). The goal of BCSD is to minimize the difference between observed and simulated values by applying an adjustment factor to the model's raw data. The BCSD method is executed in two steps:

1. Spatial scaling from the model's grid to the location of the weather station. This involves mapping the model pixel to the station's coordinates and extracting the simulated climatic variable data series.

2. Statistical bias correction of the model's variable simulations at the station's point location (Eq. [1]).

$$X_i^* = \alpha_j \bullet X_i^{mod} \tag{1}$$

where $X_i^*$ is the adjusted value of the variable $X$ (precipitation or temperature) for day $i$, $X_i^{mod}$ is the model's value of the variable for day $i$, and $\alpha_j$ is defined in Eq. (2).

$$\alpha_j = \frac{\overline{X_j}^{bs}}{\overline{X_j^{mod}}} \tag{2}$$

where $\overline{X_j^{obs}}$ is the multi-year average for month $j$ of observed values and $\overline{X_j^{mod}}$ is the multi-year average for month $j$ of simulated values.

After the scaling-down process, daily surfaces of the simulated variables were generated for the present climate period and future periods under both RCP 4.5 and RCP 8.5 scenarios, using the same methodology as employed for observed surfaces. Annual total precipitation and average annual temperature were then calculated for the periods 1981-2010, 2011-2040, 2041-2070, and 2071-2100 based on these simulated surfaces.

### 2.5 Classification of optimal crop areas

Suitable areas for the climbing bean crop were determined using a decision tree (Fig. 2) that correlates the spatial distribution of climatic variables with altitude. Within the classification structure, the following categories are distinguished: A1 (High) represents the best cultivation conditions; A2 (Moderate) involves moderate restrictions; A3 (Low) includes strong restrictions and marginal suitability; and N1 (Not Suitable) denotes areas unsuitable for cultivation.

The ranges of the variables were defined as follows:

1. *Altitude:* Altitudes below 1200 masl and above 3200 masl are limiting for cultivation. The ideal elevation for planting is between 1700 and 2800 masl, and yields decrease as one moves away from this elevation range while the vegetative cycle extends (Ligarreto-Moreno et al., 2017). Therefore, it was considered that between 1700 and 2800 masl the cultivating area has suitability A1; between 1500-1700 and 2800-3000 masl, it has suitability A2; between 1200-1500 and 3000-3200 masl, it has suitability A3; and values below 1200 and above 3200 masl are classified as N1.
2. *Precipitation:* Values below 800 mm year$^{-1}$ and above 2000 mm year$^{-1}$ are considered limiting for cultivation (Ligarreto-Moreno et al., 2017). Therefore, records within this range are classified suitability A3. Between 800-1000 and 1500-2000 mm year$^{-1}$, they are categorized as A2, and between 1000-1500 mm year$^{-1}$ as A1.

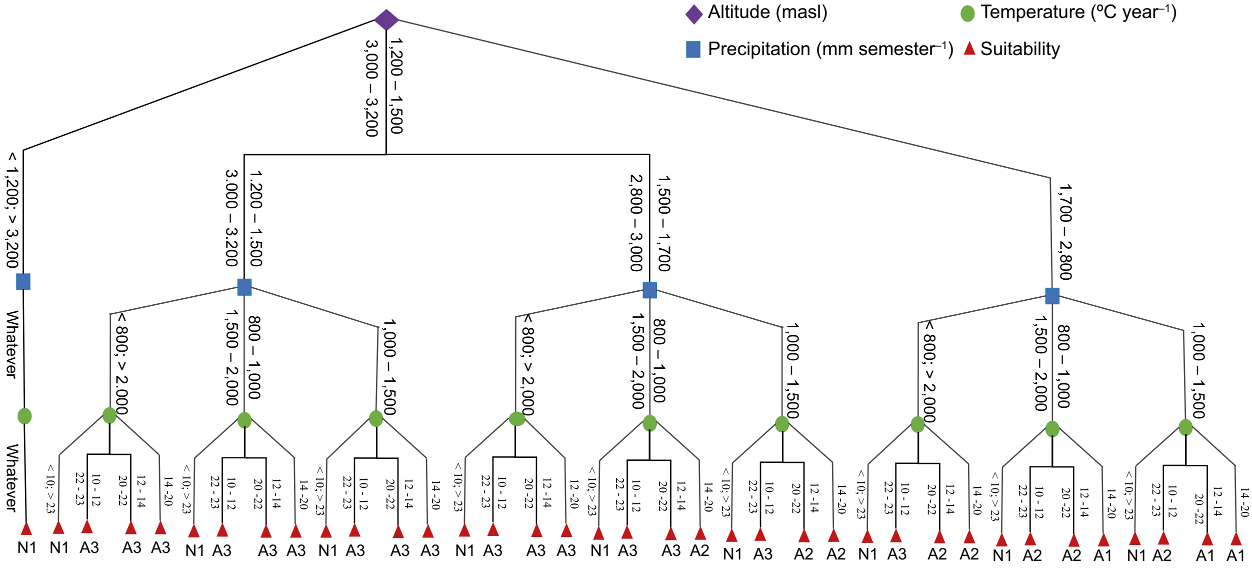


Fig. 2. Decision tree for climatic conditions

3. *Temperature:* The minimum limiting temperature for climbing bean cultivation is 10 ºC, and the maximum value is 23 ºC. Records below or above these values are considered unsuitable, classified as N1. Temperatures between 14-20 ºC are estimated as A1, between 12-14 and 20-22 ºC as A2, and between 22-23 and 10-12 ºC as A3.

Climbing beans are a short-cycle crop (~ 90-120 days), and annual precipitation may not be adequately reflected. However, for the aim of this study, annual precipitation was adopted as a proxy indicator of agroecological/bioclimatic water availability because it is consistently available across historical and projected climate scenarios from GCMs.

The classification was carried out spatially using RStudio v. 2023.03.0 and QGIS v. 3.16.16. The determination of suitable zones was done for the present climate (1981-2010) using observed and simulated data, as well as for future periods 2011-2040, 2041-2070, and 2071-2100 under the representative concentration pathways RCP 4.5 and RCP 8.5. Suitability areas were determined, and areas outside the agricultural boundary defined by UPRA (2018) were subtracted.

To assess the sensitivity of suitable areas, a spatial analysis was performed based on classification results using RStudio. The analysis was conducted in two dimensions: across different scenarios (RCPs) and future periods. The N1 class was excluded from the analysis to avoid distortion of statistical estimates. To account for uncertainty, a Monte Carlo simulation approach was applied. For each analysis, 100 simulations were generated by adding controlled random noise (normally distributed with a standard deviation of 0.3) to the original suitability values. After generating simulations, a mean suitability map was computed for each analysis and then stacked to evaluate temporal sensitivity through pixel-wise statistics: range and standard deviation. To facilitate interpretation, the range values were reclassified into three sensitivity levels: (1) Low (range ≤ 0.5), (2) Medium (0.5 < range ≤ 1.5), (3) High (range > 1.5).

### *2.6. Comparison of simulated and observed data for the baseline period*

To compare the observed data with the CCSM4 simulations for the base period (1981-2010), root mean square error (RMSE) and mean absolute error (MAE) were calculated. The results (Table I) show that for precipitation, the RMSE and MAE values were 16.3 and 10.2 mm, while for average temperature, the values were 7.3 and 7.0 ºC, respectively.

Table I. Model validation metrics (RMSE and MAE) for precipitation and average temperature, simulated and observed, for the baseline period (1981-2010).

| Variable | RMSE | MAE |
|---|---|---|
| Precipitation (mm) | 16.3 ± 3.00 | 10.2 ± 1.78 |
| Average temperature (ºC) | 7.3 ± 4.60 | 7.0 ± 4.78 |

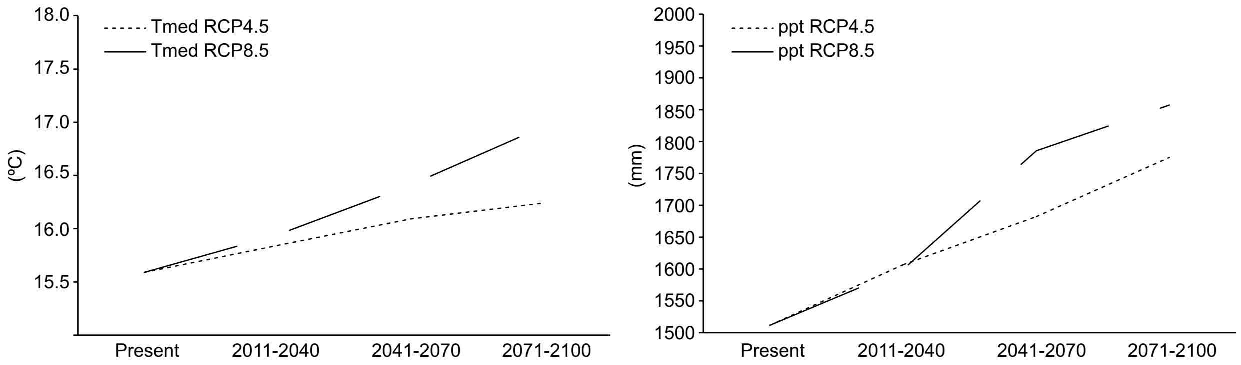
It should be noted that the RMSE and MAE values obtained, especially for average temperature, are primarily explained by the size of each pixel (latitude ~ 0.94º, longitude ~ 1.25º), which fails to accurately represent the terrain, necessitating an adjustment for the altitudinal gradient. Likewise, climate change scenarios are convincing descriptions of a future state of the climate and, as such, constitute alternative images that enable the generation of projections with some degree of uncertainty (Ideam, 2015).

## 3. Results and discussion

### *3.1 Spatial changes in precipitation and temperature*

Compared to the current value of 15.6 ºC, an increase in the multi-year average temperature was observed mainly in the central and northwest regions of Cundinamarca for all three future periods under both RCP scenarios. The expected temperature increases are 0.3 ºC (RCP 4.5) and 0.4 ºC (RCP 8.5) from 2011 to 2040; 0.5 ºC (RCP 4.5) and 0.8 ºC (RCP 8.5) from 2041 to 2070; and 0.6 ºC (RCP 4.5) and 1.4 ºC (RCP 8.5) from 2071 to 2100. On the other hand, precipitation could increase by 6.3% (RCP 4.5) and 5.8% (RCP 8.5) in the period 2011-2040, 11.3% (RCP 4.5) and 18.1% (RCP 8.5) in 2041-2070, and 17.4% (RCP 4.5) and 22.9% (RCP 8.5) in 2071-2100 (Fig. 3).

For any altitude and precipitation range, temperatures below 10 ºC and above 23 ºC are classified as unsuitable for bean cultivation. The increase in areas with temperatures above 23 ºC indicates a decrease in



| | | | |
|---|---|---|---|
| **Δ (°C) RCP 4.5** | 0.3 | 0.5 | 0.6 |
| **Δ (°C) RCP 8.5** | 0.4 | 0.8 | 1.4 |

| | | | |
|---|---|---|---|
| **Δ (%) RCP 4.5** | 6.3 | 11.3 | 17.4 |
| **Δ (%) RCP 8.5** | 5.8 | 18.1 | 22.9 |

Fig. 3. Changes in mean temperature and multi-year precipitation for the periods 2011-2040, 2041-2070, and 2071-2100 under the RCP 4.5 and RCP 8.5 scenarios.

suitability for climbing bean cultivation. This trend is evident across all three future periods, especially on the eastern side of the Llanos foothills and in the western region of the Magdalena slope. However, in the Cundiboyacense high plateau region, the temperature increase ranges from 12-14 to 14-16 ºC, indicating a transition from A2 to A1 (Fig. 4).

Regarding precipitation, changes would be most evident in the Cundiboyacense high plateau. A higher percentage of areas would fall within the 1000-1500 mm year$^{-1}$ range, leading to an increase in suitable A1 areas (Fig. 5).

By the middle and end of the century, increases in mean annual temperature (0.2 to 1.4 ºC) will result in significant changes in thermal suitability, especially in areas close to the A1/A3 and A3/N1 boundaries. The emergence and growth of N1 heat stress areas at lower elevations will cause the main production losses. The emergence of heat-limiting conditions (> 23 ºC) will reduce the suitability of low-elevation zones in the eastern Llanos foothills and western Magdalena slope. Additionally, new A3/N1 zones will emerge in those warm, humid lowlands.

On the other hand, climate warming will increase the suitable A1 areas for growing climbing beans in the currently cold-limited areas of the Cundiboyacense high plateau. This will gradually shift the optimal thermal range for growing climbing beans upslope by 100-200 m. This warming will shorten the growing cycle, which could be beneficial given the new conditions of earlier ripening and harvest, as well as a lower risk of frost. In the same region, projected increases in annual precipitation (6-23%) will push significant portions into the 1000-1500 mm yr$^{-1}$ range (A1), which will improve water availability for rainfed systems. However, this benefit may be offset in some zones by increased evapotranspiration and an increased risk of diseases such as angular leaf spot, anthracnose, powdery mildew, rust, and other leaf pathogens. Under this scenario, improved drainage and disease control can capitalize on these gains. In heat-prone lowlands, adaptation will require heat-tolerant varieties, shading, and irrigation management. On overly humid slopes, drainage and resistant cultivars will be critical to maintaining crop viability.

### *3.2 Suitable areas for climbing beans cultivation*

An estimated potential area for climbing beans was 1 043 919 ha under the present climate scenario, accounting for 43.3% of Cundinamarca's land area. This includes 23.4% in A2, followed by 18.0% in A1, and 1.9% in A3. N1, which also includes excluded areas beyond the agricultural boundary, is 1 369 431 ha, equivalent to 56.7% of the Cundinamarca department (Table II).

At the RCP 4.5 scenario, the optimal area for climbing beans could decrease by 3.8% compared to the area calculated under present climate conditions.

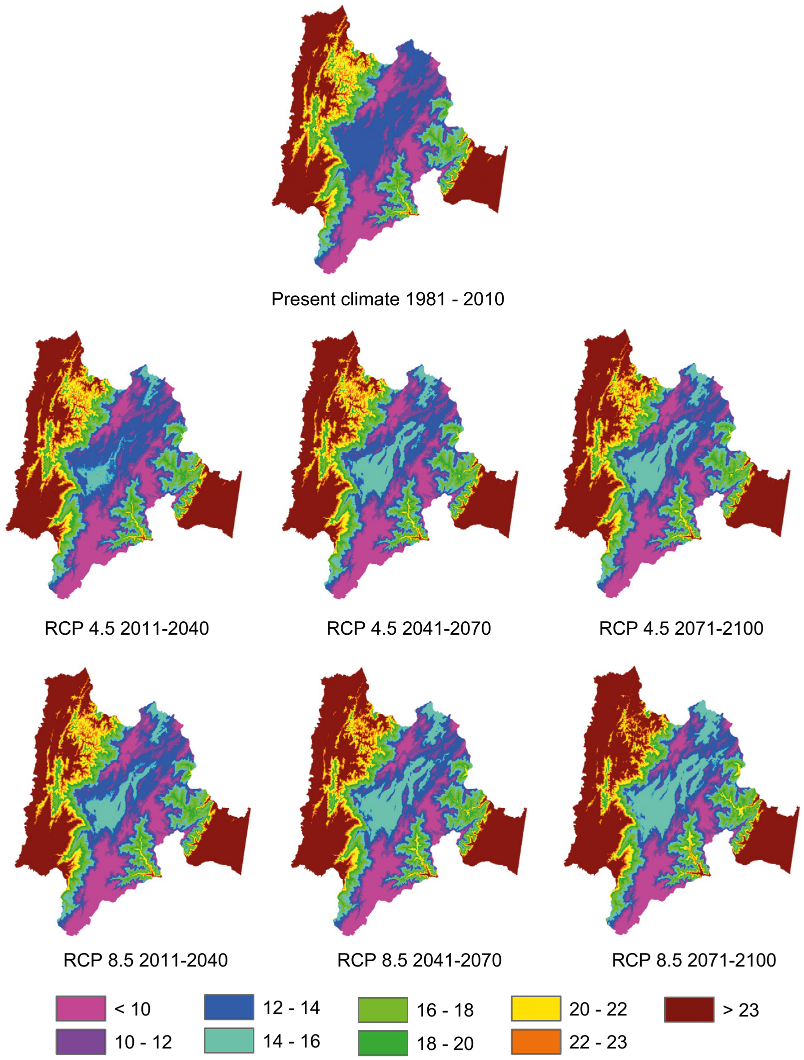
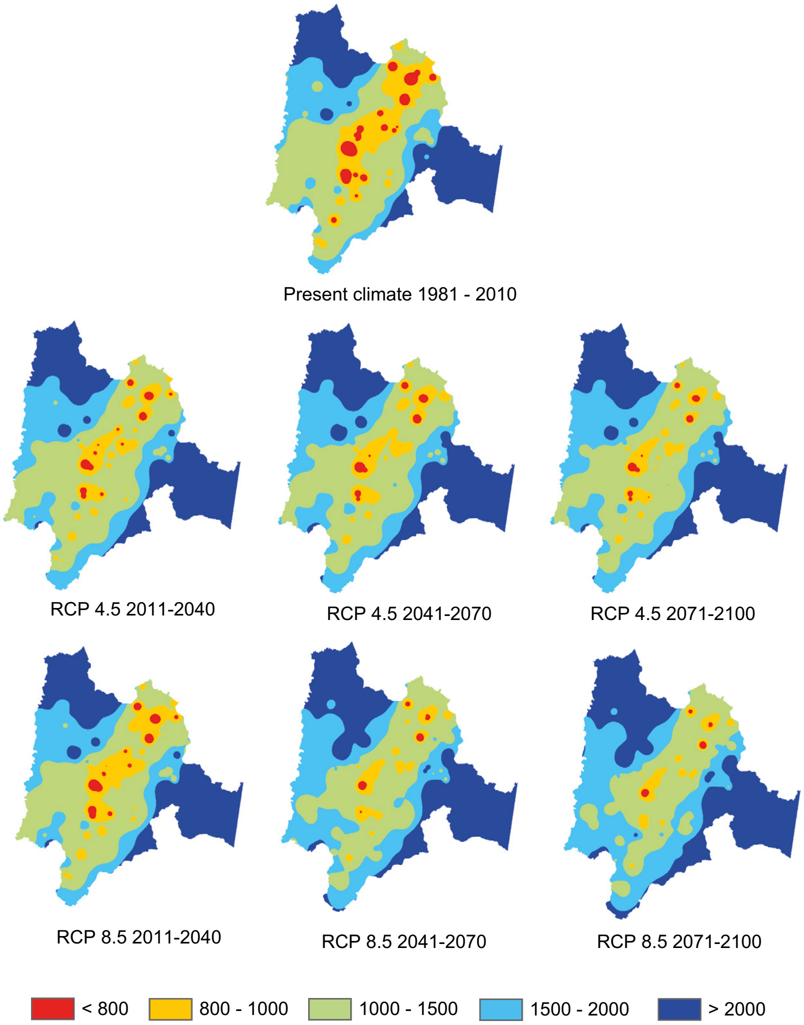


Fig. 4. Multi-year average temperature for present climate (1981-2010) and the periods 2011-2040, 2041-2070, and 2071-2100 under RCP 4.5 and RCP 8.5 scenarios.

This reduction might persist during all three future periods. This trend could be related to the stabilization characteristics of RCP 4.5, which is based on initial increases in $CO_2$eq in the atmosphere during the beginning of the century, reaching a peak around 2040, and then stabilizing. This represents a stabilization in temperature and an increase in precipitation. As a result of modeling, this may not severely impact the reduction of climbing bean areas. The A1 areas (dark green) would increase from 394 263 ha in 2011-2040 to 437 581 ha in 2071-2100. Meanwhile, A2 areas (light green) would decrease from 242 850 to 211 575 ha, and A3 areas (yellow) would transition from 316 619 to 304 575 ha. The potential reduction in A2 and A3 in favor of A1, is particularly noticeable in the Cundiboyacense high plateau. N1 areas would maintain the same extent in the future periods 2041-2070 and 2071-2100 (Fig. 6, Table II).

Similar to the RCP 4.5 scenario, the assessment of suitable areas for common bean cultivation under the RCP 8.5 scenario indicates a possible reduction in suitable areas across the three future periods. The total probable suitable area for 2011-2040 is 953 731 ha, for 2041-2070 it is 949 738 ha, and for 2071-2100


Present climate 1981 - 2010

RCP 4.5 2011-2040

RCP 4.5 2041-2070

RCP 4.5 2071-2100

RCP 8.5 2011-2040

RCP 8.5 2041-2070

RCP 8.5 2071-2100

Fig. 5. Multi-year average precipitation for present climate (1981-2010) and the periods 2011-2040, 2041-2070, and 2071-2100 under RCP 4.5 and RCP 8.5 scenarios.

it is 888 969 ha. Therefore, at the emission rate set by the RCP 8.5, the unsuitable areas would increase from 1 369 431 to 1 524 381 ha (6.5%). The three periods show dynamic percentage changes in suitability. Compared to the present climate, categories A1 and A2 (dark green and light green, respectively) would decrease, while category A3 (yellow) would increase from 1.9to 13.3% in 2011-2040, 12.7% in 2041-2070, and 9.7% in 2071-2100. Therefore, areas with high and moderate suitability could transition to low-suitability areas or, in some cases, become unsuitable (N1) (Fig. 6, Table II).

The reduction in suitable areas could be related to the increase in average temperature (0.4, 0.8, and 1.4 ºC) across the three high-concentration scenarios. Similarly, a continuous increase in emissions is expected, leading to a persistent increase in average temperature in areas of the Llanos foothills and the Magdalena slope. This would result in a further reduction in suitable areas.

### *3.3 Changes in suitability areas by subregions*

The notable difference in the reduction of potential areas for establishing bean cultivation varies

Table II. Estimated suitability areas for climbing bean cultivation under present climate (1981-2010) and future periods (2011-2040, 2041-2070, and 2071-2100) under the RCP 4.5 and 8.5 scenarios.

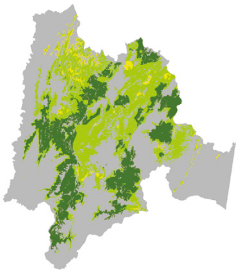
| Suitability | Present climate 1981-2010 | | RCP 4.5 | | | | | | RCP 8.5 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 2011-2040 | | 2041-2070 | | 2071-2100 | | 2011-2040 | | 2041-2070 | | 2071-2100 | |
| | (ha) | (%) | (ha) | (%) | (ha) | (%) | (ha) | (%) | (ha) | (%) | (ha) | (%) | (ha) | (%) |
| A1 | 433,738 | 18.0 | 394,26 | 16.3 | 417,73 | 17.3 | 437,58 | 18.1 | 392,31 | 16.3 | 429,60 | 17.8 | 425,11 | 17.6 |
| A2 | 564,306 | 23.4 | 242,85 | 10.1 | 220,68 | 9.1 | 211,57 | 8.8 | 240,78 | 10.0 | 212,57 | 8.8 | 229,01 | 9.5 |
| A3 | 45,875 | 1.9 | 316,61 | 13.1 | 315,30 | 13.1 | 304,57 | 12.6 | 320,63 | 13.3 | 307,55 | 12.7 | 234,83 | 9.7 |
| Total | 1,043,919 | 43.3 | 953,73 | 39.5 | 953,73 | 39.5 | 953,73 | 39.5 | 953,73 | 39.5 | 949,73 | 39.4 | 888,96 | 36,8 |
| N1 | 1,369,431 | 56.7 | 1,459,61 | 60.5 | 1,459,61 | 60.5 | 1,459,61 | 60.5 | 1,459,61 | 60.5 | 1,463,61 | 60.6 | 1,524,38 | 63,2 |

proportionally in the three subregions indicated for the department of Cundinamarca (Fig. 7). The Cundiboyacense high plateau, the sector with the highest potential, has a lower reduction during the three future periods and the two RCP scenarios. The Llanos foothills and the Magdalena slope currently have reductions of 35.1 and 34.6%, respectively. However, the losses on the Magdalena slope would be greater, decreasing by up to 17.6% for the period 2071-2100 under the RCP 8.5 scenario.

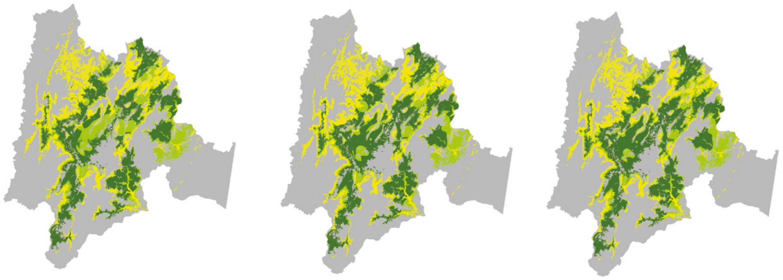
The RCP 4.5 and RCP 8.5 scenarios (Fig. 8) show that suitability A1 areas would increase in the Cundiboyacense high plateau, but a reduction is projected in the Magdalena slope and the Llanos foothills. Similarly, areas with suitability A2 would decrease in all three subregions compared to the present climate under both RCP 4.5 and RCP 8.5 scenarios, with an increase projected for the Llanos foothills for 2041-2070 and 2071-2100. In category A3, increases are observed across all subregions, with a trend toward stabilization in the RCP 4.5 scenario and a slight decrease in the RCP 8.5 scenario.

Overall, the RCP 4.5 scenario shows moderate changes and potential improvements in optimal areas, with the total suitable area decreasing slightly (3.8%). Areas rated A1 expand, especially in the colder highland regions, where moderate warming removes cold constraints for beans. The main offset is a gradual reduction in the A2 and A3 areas, suggesting that the current marginal areas could improve (A2 to A1). N1 areas remain constant beyond mid-century, indicating a low risk of abrupt production losses if emissions are reduced. The RCP 8.5 scenario shows a progressive contraction in suitability. In a high-emissions future, the total suitable area decreases more sharply (14.8% for 2071-2100), while the unsuitable area increases by 6.5%. The expansion of A3 zones in the early and mid-century (up to 13.3%) reflects a widespread degradation of currently optimal or moderate zones due to rising temperatures, especially in low-elevation and low-slope areas, such as the foothills of the Llanos and the slopes of the Magdalena River. By the end of the century, these zones experience a progressive transition to N1, further removing them from viable production.

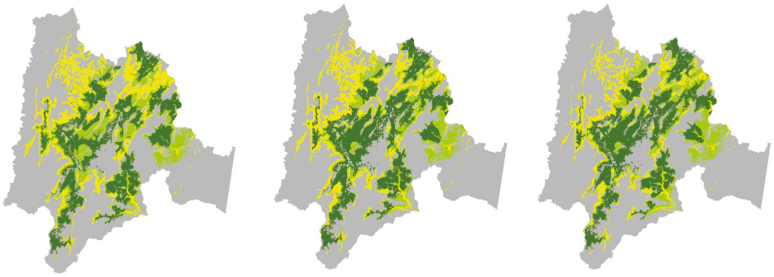
Given these scenarios, it is necessary to deploy bean genetic resources to build future climate-resilient agri-food systems. To this end, integrated conser-



Present climate 1981 - 2010



RCP 4.5 2011-2040 RCP 4.5 2041-2070 RCP 4.5 2071-2100



RCP 8.5 2011-2040 RCP 8.5 2041-2070 RCP 8.5 2071-2100

🟩 A1 🟩 A2 🟨 A3 ⬜ N1

Fig. 6. Suitable areas for bean cultivation under present climate (1981-2010) and future periods (2011-2040, 2041-2070, and 2071-2100) under RCP 4.5 and RCP 8.5 scenarios.

vation (in situ and ex situ) and genetic improvement will enable communities to create viable, sustainable agroecosystems. In-situ conservation systems strengthen the future local climate resilience by supporting the natural evolution and dynamic adaptation of current bean cultivars to new climatic conditions and facilitating community access to locally adapted genetic resources. Germplasm banks and ex situ conservation systems support genetic diversity in the event of catastrophic losses in the field (e.g., extreme droughts, new pests, etc.), provide resilient varieties that can be reintroduced into agri-food systems after future climate disasters, and act as a reservoir for crop research and genetic improvement, thus favoring the development of new, more resilient bean crops. On the other hand, the development of bean materials tolerant to extreme climatic conditions, such as heat and excess water, will minimize, mitigate, and attenuate the adverse effects of the new climatic conditions proposed in this study. Bean materials with increased expression of heat shock proteins (HSPs), efficient photosynthetic enzyme systems at high temperatures (e.g., activated Rubisco), and reduced photorespiration or C4-like metabolism will be required to cope

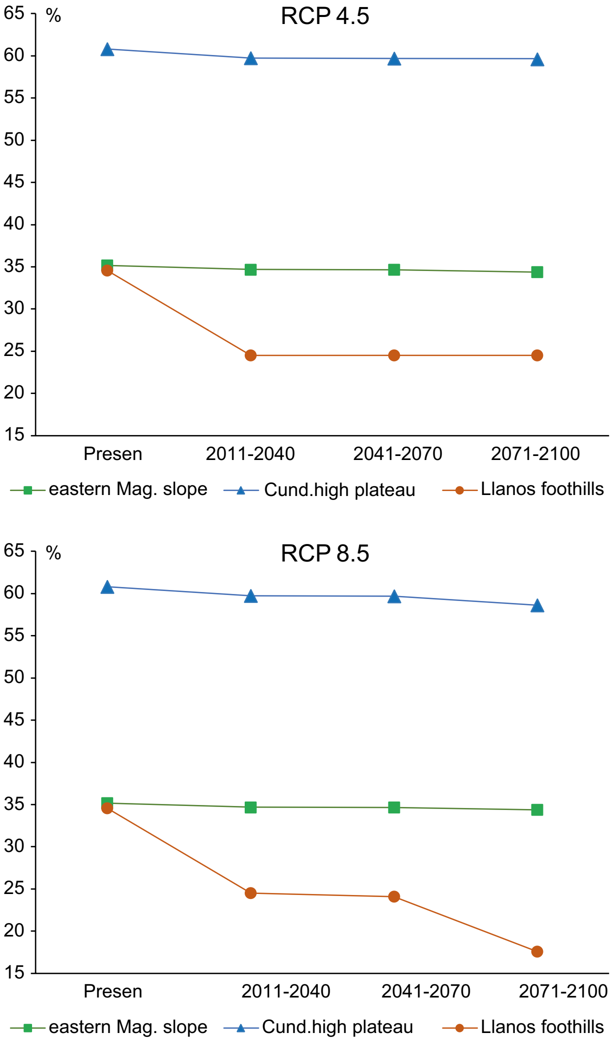


Fig. 7. Percentages of the total suitable area for common bean cultivation for present climate (1981-2010) and future periods (2011-2040, 2041-2070, and 2071-2100) by subregions.

with rising average and maximum temperatures and increased frequencies of heat waves in the Magdalena slope and the Llanos foothills. Likewise, the considerable increase in precipitation in the Cundiboyacense high plateau will require new materials with hypoxia-tolerant traits (roots with greater aerenchyma tissue), greater capacity for rapid stem elongation and post-flooding recovery, as well as genetic resistance to emerging diseases and the induction of systemic acquired resistance (SAR), among others.

### *3.4 Sensitivity analysis*

The sensitivity analysis revealed variability in suitability areas across both scenarios and future periods. Regarding the scenario dimension, over 75% of the suitable areas were classified as having medium sensitivity under both RCPs. Similarly, when analyzed by future period, medium sensitivity remained the most representative classification (Fig. 9). At the subregional level, the Cundinamarca high plateau displayed the largest extent of highly sensitive areas,

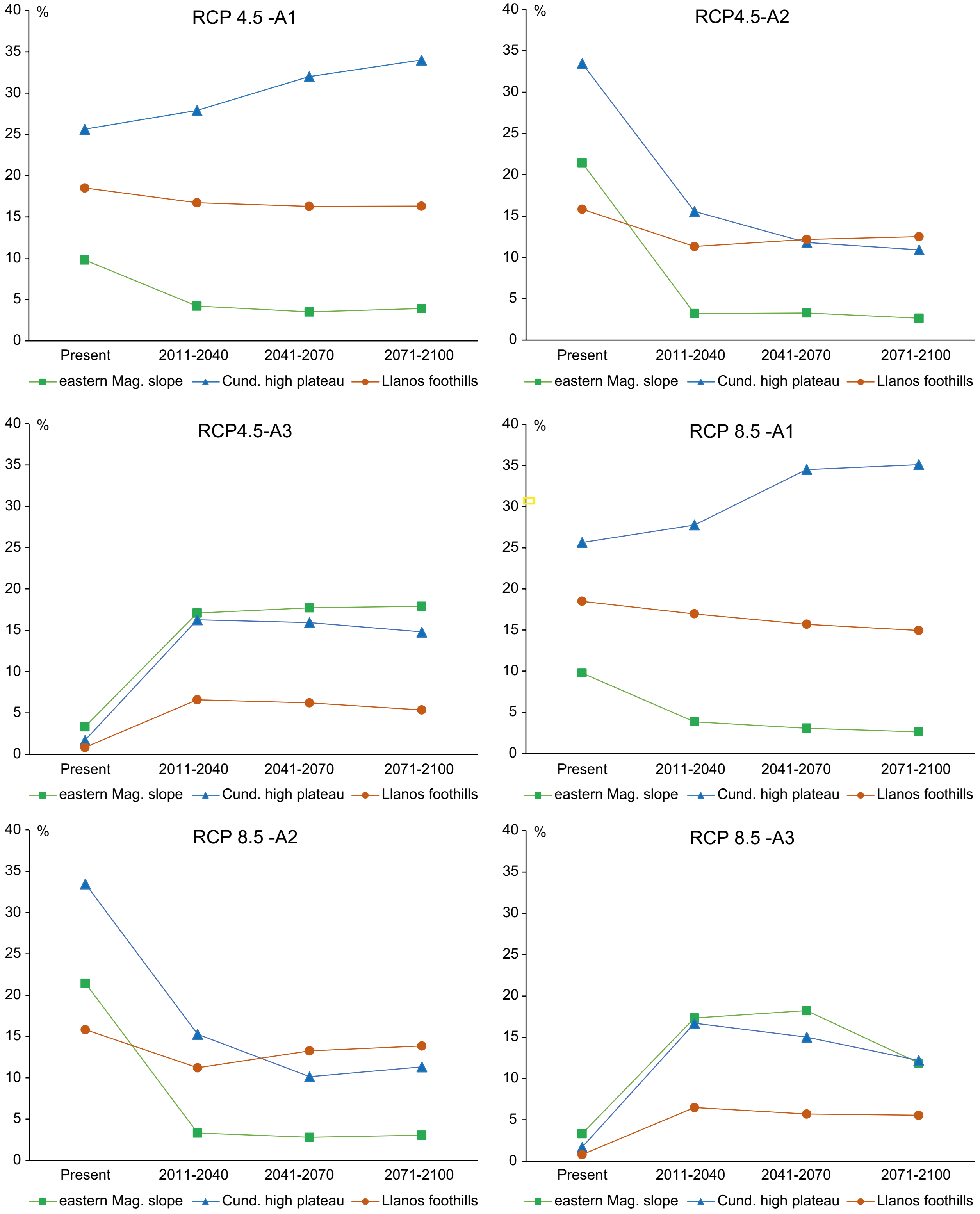


Fig. 8. Suitability percentage by category (A1, A2, and A3), period (present, 2011-2040, 2041-2070, 2071-2100), and scenario (RCP 4.5 and RCP 8.5) by subregions.

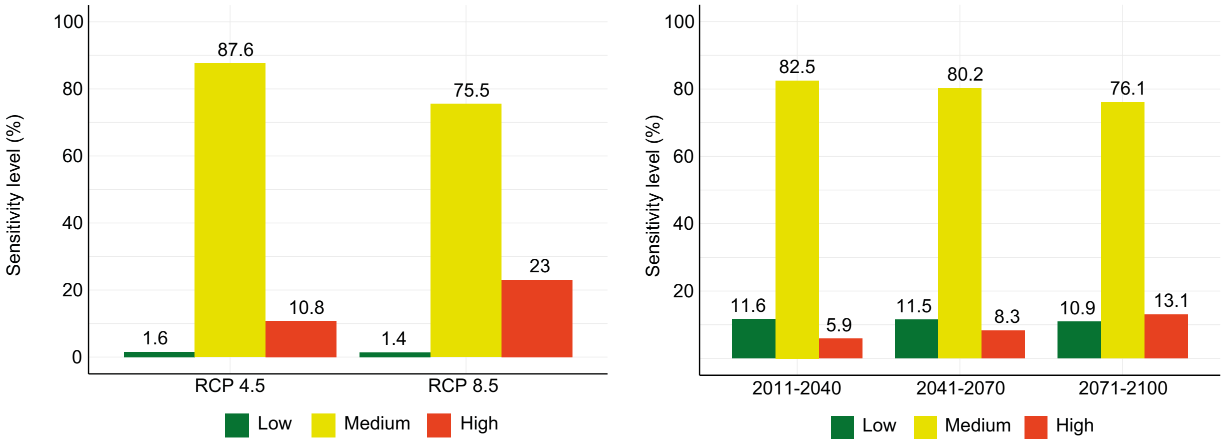


Fig. 9. Sensitivity analysis by scenario (RCP 4.5 and RCP 8.5) and future periods (2011-2040, 2041-2070, and 2071-2100).

whereas the Magdalena slope registered the least sensitivity.

When comparing scenarios, it is possible to identify that under RCP 8.5, a greater proportion of suitability areas exhibit high sensitivity levels (23%). In terms of temporal periods, the far-future horizon (2071-2100) displays a slightly higher percentage of areas with high sensitivity (13.1%). The sensitivity levels evaluated across RCP scenarios are larger than those obtained across periods. These findings suggest that as scenarios become more pessimistic and time horizons extend further into the future, uncertainty increases, reflected in a greater extent of areas classified as high sensitivity. It has been consistently reported in the literature (Lu et al., 2019; Cronin et al., 2020; Karapetsas et al., 2024).

These results underscore the importance of incorporating sensitivity analysis in suitability evaluation processes, particularly for long-term agricultural planning under dynamic environmental conditions. Identifying zones with low sensitivity levels can support more reliable land-use decisions, while areas with higher sensitivity may require targeted monitoring, adaptive management strategies, or further modeling refinement.

The findings presented in this study are a direct consequence of the performance of the CCSM4 model in Colombia. While the CCSM4 model provides a solid basis for analyzing climate impacts in the Andes, it is important to recognize potential biases in its representation of the annual cycle and spatial distribution of precipitation (Pabón-Caicedo et al., 2020). In this context, annual precipitation was adopted as a proxy for agroecological water availability. Annual precipitation datasets are consistently available for historical and projected climate scenarios from GCMs, enabling temporal comparisons across scenarios. Future studies could refine this approach by integrating monthly or decadal precipitation distributions from downscaled climate models, soil moisture indices derived from remote sensing, and local water-balance modeling calibrated for *Phaseolus vulgaris* in Cundinamarca. Given current data availability, annual precipitation remains the most robust and comparable criterion for representing bioclimatic water supply across present and future climate scenarios.

The CCSM4 is the official source for regionalized climate change scenarios in Colombia, providing an extensive and complete time series for the radiative forcings used in this study (RCP 4.5 and RCP 8.5), which is useful for historical and prospective comparative analyses. However, CCSM4 may be limited in Cundinamarca due to its low spatial resolution (approximately 100 km) and inability to represent the complex orography, microclimates, and altitudinal gradients that are critical for common beans in the Colombian Andes. This also implies that physical and biophysical processes decisive for crop growth on a small scale are simplified. Despite this, the model performs acceptably in the Colombian Andes and can be useful for climate change studies, as demonstrated by Pabón-Caicedo et al. (2020).

## 4. Conclusions

The analysis of changes for the department of Cundinamarca under the RCP 4.5 and RCP 8.5 scenarios shows, on average for the department's surface, a trend towards increasing mean temperature and precipitation throughout the 21st century. These variations represent future losses of suitable areas for common bean cultivation and changes in suitability categories in some areas. Under both RCP 4.5 and RCP 8.5 scenarios, the Magdalena slope subregion will be the most affected by the largest reductions in potential bean-suitable crop areas, mainly due to heat stress, while the Cundiboyacense high plateau and the Llanos foothills will experience smaller decreases. The Cundiboyacense high plateau will experience thermal and hydrological gains (in annual totals). Due to the thermal optimum shifting 100-200 m upslope, gains in A1 suitability will be concentrated in cooler highland regions where warming alleviates the limitations of cold temperatures. However, the realized yield will be determined by future agricultural management in the face of increased effective moisture and disease pressure.

According to the sensitivity analysis, changes in the suitability of areas for climbing bean cultivation were revealed in the evaluated scenarios and periods. This variability yields moderate sensitivity in the overall results, suggesting that in a more pessimistic scenario (e.g., RCP 8.5) and over longer periods (e.g., 2071-2100), uncertainty would increase. However, the projections are consistent with Andean Mountain climatology. Although the model reasonably captures the general precipitation pattern, the RMSE and MAE values for rainfall indicate that there are occasional months or locations where the simulated rainfall differs substantially from the observed values. This discrepancy may be due to local-scale variability that the GCM cannot resolve. While moderate and acceptable rainfall errors may be suitable for large-scale climate suitability analyses, they may not be suitable for fine-scale hydrological balance estimates. The RMSE and MAE for temperature are around 7 ºC, indicating that the model-simulated mean temperatures significantly deviate from the observed records during the reference period. These biases reflect the GCMs inaccurate representation of regional topography and microclimate, particularly in mountainous regions such as Cundinamarca. Coarse-resolution models tend to over- or underestimate average temperatures in these areas because of the smoothing of elevation.

In the RCP 4.5 and RCP 8.5 scenarios, climate change adaptation practices will need to be different. Under RCP 4.5, adaptation can focus on consolidating bean yield gains in the highlands and managing moderate losses in marginal zones. Under RCP 8.5, the progressive contraction of suitable zones and expansion of N1 will require more intensive adaptation measures (integrated conservation, heat-tolerant varieties, agroforestry) and, in some areas, crop substitution.

As with most modelling studies on the effects of climate change on crop climatic suitability, this study is subject to certain limitations. This approach disregards phenological windows and does not incorporate seasonality. Furthermore, the impact of edaphic factors on the growth of *Phaseolus vulgaris* and on water storage capacity (texture, depth, stoniness, drainage) was not considered. However, the focus of this study is purely climatic, meaning that the areas defined and the approach are based on the perspective of climatic suitability (not agroclimatic suitability). Climate suitability is the assessment of the congruence between the bioclimatic requirements of the crop (temperature, precipitation, radiation, extremes, frost, water deficit) and the site climate.

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