Doi: https://doi.org/10.19053/uptc.24223719.20115

Assessing climate change vulnerability of horticultural farmers in central Boyaca, Colombia: a participatory approach

Evaluación de la vulnerabilidad al cambio climático de los agricultores hortícolas en la zona centro de Boyacá, Colombia: un enfoque participativo

GERMÁN EDUARDO CELY-REYES[1]
PABLO ANTONIO SERRANO-CELY[1]
INGRID YANETH WALTEROS-TORRES[2, 3]

Bulb onion harvest in Samacá, Colombia.

Photo: Walteros-Torres, I.Y.

ABSTRACT

Climate change poses significant challenges to horticultural production systems, particularly in regions with high environmental and socio-economic vulnerability. This study analyzed the vulnerability of horticultural farmers in the central zone of Boyaca, Colombia, to the impacts of climate change, using a participatory approach that integrated local knowledge and scientific assessment. Data were collected through structured surveys and field visits in the municipalities of Motavita, Samaca, Siachoque, Soraca, Toca, Tunja, and Ventaquemada. The methodology combined socio-economic and biophysical indicators to assess farmers' exposure, sensitivity, and adaptive capacity. Results revealed that vulnerability levels varied across municipalities, with higher susceptibility observed in areas with limited access to technical assistance, low diversification of production, and high dependence on climate-sensitive crops such as potato and other vegetables. Farmers identified irregular rainfall, temperature fluctuations, and the increased incidence of pests and diseases as the most critical climate-related threats. Strengthening adaptive capacity through technical training, diversification strategies, and improved access to climate information was identified as essential to reduce vulnerability. The findings provide valuable insights for designing targeted adaptation strategies to enhance the resilience of horticultural systems in the Andean highlands.

Additional key words: Andean highlands; smallholder farmers; adaptive capacity; climate risk assessment; socio-economic vulnerability.

[1] Universidad Pedagógica y Tecnológica de Colombia – ROR, Facultad de Ciencias Agropecuarias, Grupo de investigación GIPSO, Tunja (Colombia)
[2] Investigador Independiente, Tunja (Colombia)
[3] Corresponding author. pablo.serrano@uptc.edu.co

RESUMEN

El cambio climático plantea desafíos significativos para los sistemas de producción hortícola, especialmente en regiones con alta vulnerabilidad ambiental y socioeconómica. Este estudio analizó la vulnerabilidad de los agricultores hortícolas de la zona centro de Boyacá, Colombia, frente a los impactos del cambio climático, mediante un enfoque participativo que integró el conocimiento local y la evaluación científica. La información se obtuvo a través de encuestas estructuradas y visitas de campo en los municipios de Motavita, Samacá, Siachoque, Soracá, Toca, Tunja y Ventaquemada. La metodología combinó indicadores socioeconómicos y biofísicos para evaluar la exposición, sensibilidad y capacidad adaptativa de los agricultores. Los resultados evidenciaron que los niveles de vulnerabilidad variaron entre municipios, con mayor susceptibilidad en zonas con acceso limitado a asistencia técnica, baja diversificación productiva y alta dependencia de cultivos sensibles al clima como la papa y otras hortalizas. Los agricultores identificaron la irregularidad en las lluvias, las fluctuaciones de temperatura y el aumento de plagas y enfermedades como las amenazas más críticas asociadas al clima. Se concluye que fortalecer la capacidad adaptativa mediante capacitación técnica, estrategias de diversificación y mejor acceso a información climática es esencial para reducir la vulnerabilidad. Los hallazgos aportan insumos clave para el diseño de estrategias de adaptación orientadas a mejorar la resiliencia de los sistemas hortícolas en los Andes colombianos.

Palabras clave adicionales: altiplano andino; agricultura campesina; capacidad adaptativa; evaluación del riesgo climático; vulnerabilidad socioeconómica.

Received: 26-05-2025 **Accepted:** 10-06-2025 **Published:** 29-07-2025

INTRODUCTION

Climate change poses a serious threat to the sustainability of various sectors, including agriculture, biodiversity, human health, and tourism. This challenge demands a global commitment to the pursuit of sustainable solutions (Abbass *et al*., 2022). In recent years, the sensitivity of agricultural systems has increased, requiring greater attention to the impacts of heat and water stress on crop performance (Parker *et al*., 2019). Evidence suggests that the Andes are particularly affected by intra-seasonal climate changes (Ponce, 2020).

Climate change and variability endanger agricultural production, food security, and, consequently, the socio-economic development of nations (Forero and González, 2020). These changes affect not only the availability of food but also its quality and affordability (Teklewold *et al*., 2019).

Andean water bodies and glaciers are shrinking due to shifts in temperature and precipitation patterns. This trend threatens rural communities that rely on agriculture and ecosystem services, as they face declining productivity, lack of alternative income sources, and shortages of fuel (Berrouet *et al*., 2020).

Climate change further exacerbates the already precarious living conditions of many smallholder farmers (Phuong *et al*., 2018). In Latin America and the Caribbean, the region's vast geographical, social, economic, and environmental diversity makes it particularly vulnerable to climate change, unsustainable agriculture and extensive livestock farming prevail in the region (Beltrán-Tolosa *et al*., 2022), often replacing traditional practices such as crop diversification, crop-livestock integration, intercropping, and the limited use of external inputs (Ponce, 2020).

In some areas of the Andes, reduced agricultural productivity caused by climate change has triggered increased migration, particularly among younger family members seeking better opportunities. While such migration may meet the short-term consumption needs of families, it reduces the availability of local labor. This can negatively affect both the quantity and diversity of future harvests, ultimately impacting food availability for household consumption (Blackmore *et al*., 2021).

In Colombia, the agricultural sector is highly sensitive to climate change, particularly during the el Niño–Southern Oscillation (ENSO) phenomenon

(Arteaga and Burbano, 2018; Valbuena Gaona *et al*., 2025). This climate pattern intensifies droughts and heavy rainfall, leading to natural disasters such as floods, landslides, wildfires, and environmental degradation. it also worsens the spread of diseases, damages infrastructure (housing, roads, bridges), places pressure on ecosystem services, and generates environmental conflicts over access to resources such as water, fertile land, and strategic ecosystems. These factors result in significant economic and social impacts, affecting productivity, inflation, rural employment, food security, and land fragmentation (Banco de la República, n.d.).

Colombia's agricultural vocation has positioned the country as an exporter of raw materials (commodities). The national economy and food security rely heavily on smallholder family farmers, who produce up to 83.5% of the country's food supply and serve as the backbone of rural employment.

The departments of Boyaca, Antioquia, Cundinamarca, and Nariño are the leading producers of horticultural commodities in Colombia, accounting for 70% of total national production. In 2021, Boyaca ranked as the second-largest producer (with a 19% share), supplying a wide range of crops including chard, squash, chili pepper, garlic, basil, arracacha, green peas, broccoli, zucchini, pumpkin, bulb onion, scallion, cauliflower, spinach, green beans, lettuce, slicing cucumber, pickling cucumber, bell pepper, beet, cabbage, tomato, greenhouse tomato, and carrot—both in terms of cultivated area and production volume (Minagricultura, 2025; Acero-Acero and García-Cáceres, 2024). The department benefits from fertile soils and a favorable climate characterized by moderate temperatures and year-round rainfall, which ensures high yields and quality of horticultural products. The annual production reaches 2.2 million tons, with main crops including bulb onion, carrot, tomato, and scallion (La República, 2024).

Boyaca's strategic location facilitates access to national and international markets, distributing horticultural goods—including fruits, tubers, roots, plantains, vegetables, and leafy greens—to 20 of Colombia's 32 departments. The region also plays an important role in the export of specialty crops such as blueberry, dragon fruit (pitahaya), purple passion fruit (gulupa), and cape gooseberry (uchuva) (ICA, 2023).

While institutional plans and policies have been developed to promote climate adaptation, mitigation, and resilience (Arteaga and Burbano, 2018), there remains a pressing need to identify and prioritize the most vulnerable areas and communities at the subnational level (Parker *et al*., 2019), successful strategies must address not only climatic conditions but also the underlying socio-economic and political inequalities that hinder resilience (Córdoba Vargas *et al*., 2020). Moreover, smallholder farmers are already adapting to climate change using available resources—often without the support of public institutions or the private sector (Ballesteros and Isaza, 2023). As Cortés-Cataño *et al*. (2024) point out, Colombia must manage its agricultural production zones more strategically and implement agro-industrial technologies to mitigate the impacts of climate change on agriculture.

Currently, the department of Boyaca is predominantly composed of small family farms, rooted in the region's colonial landholding legacy. These lands, historically inhabited by indigenous communities, were managed for centuries by resident laborers—some of whom received wages, while others worked in exchange for food, shelter, and basic survival means. During the 20th century, many of these families became small landowners, establishing subsistence-oriented farming systems centered on annual crops, especially Andean tubers, with the sale of surplus production (Pradilla Rueda, 2017).

Despite its cultural uniqueness and agricultural and environmental importance, local studies on climate change and variability in Boyaca remain limited (Pérez *et al*., 2020; Cortés-Cataño *et al*., 2024). Ariza Vargas (2023) reported evidence of climate impacts on peach production in the municipality of Combita (Boyaca), including frequent frosts, intense rainfall, rising temperatures, and water scarcity. The el Niño–Southern Oscillation phenomenon has caused losses in fruit quality and production due to reduced flowering and increased incidence of pests and diseases, disproportionately affecting small-scale producers who face higher input costs. Duarte Durán (2023) modeled IPCC-based climate change scenarios to forecast yields of potato and maize in eight municipalities of the mid-Chicamocha river basin (Beteitiva, Busbanza, Corrales, Floresta, Gameza, Mongua, Mongui, and Topaga). The study found that potato—a staple in local diets—is the most negatively affected crop under climate change scenarios.

In this context, assessing vulnerability is a critical first step in addressing climate-related challenges and planning adaptation efforts (Parker *et al*., 2019; Cortés-Cataño *et al*., 2024). The IPCC defines vulnerability as the degree to which a system is susceptible to, or unable to cope with, the adverse effects of climate change, including climate variability and extreme events (FAO, 2019). Understanding the extent of vulnerability in a human population or ecosystem enables proactive measures to be taken—facilitating both the mitigation of negative impacts and the optimization of potential opportunities (Otega and Paz, 2014; Parker *et al*., 2019).

Accordingly, the objective of this study was to assess the vulnerability of farmers to climate variability and change through a participatory approach in the central region of Boyaca, Colombia.

METHODOLOGY

This study was conducted in seven municipalities of the Central Province of Boyaca, Colombia: Motavita, Samaca, Siachoque, Soraca, Toca, Tunja, and Ventaquemada (Fig. 1). The main agricultural activity in the region focuses on horticultural crops such as potato, bulb onion, carrot, and green pea.

Following the methodology proposed by Ortega and Paz (2014), vulnerability was assessed by analyzing three components—exposure, sensitivity, and adaptive capacity—through a participatory approach involving local farmers. Data collection was carried out using the GeoFarmer tool, which facilitates the establishment of demographic baselines (https://home.geofarmer.org/) (Eitzinger *et al*., 2019). This tool supports the collection of information on social, environmental, and productive aspects of the cultivation systems of potato, bulb onion, carrot, and green pea.

A total of 599 rural farming households were interviewed by professionals in the fields of Social and Agricultural Sciences, after obtaining prior informed consent from each participant. Selection criteria for respondents included: being involved in at least one of the four target crop systems, being over 18 years old (or having parental consent if underage), and

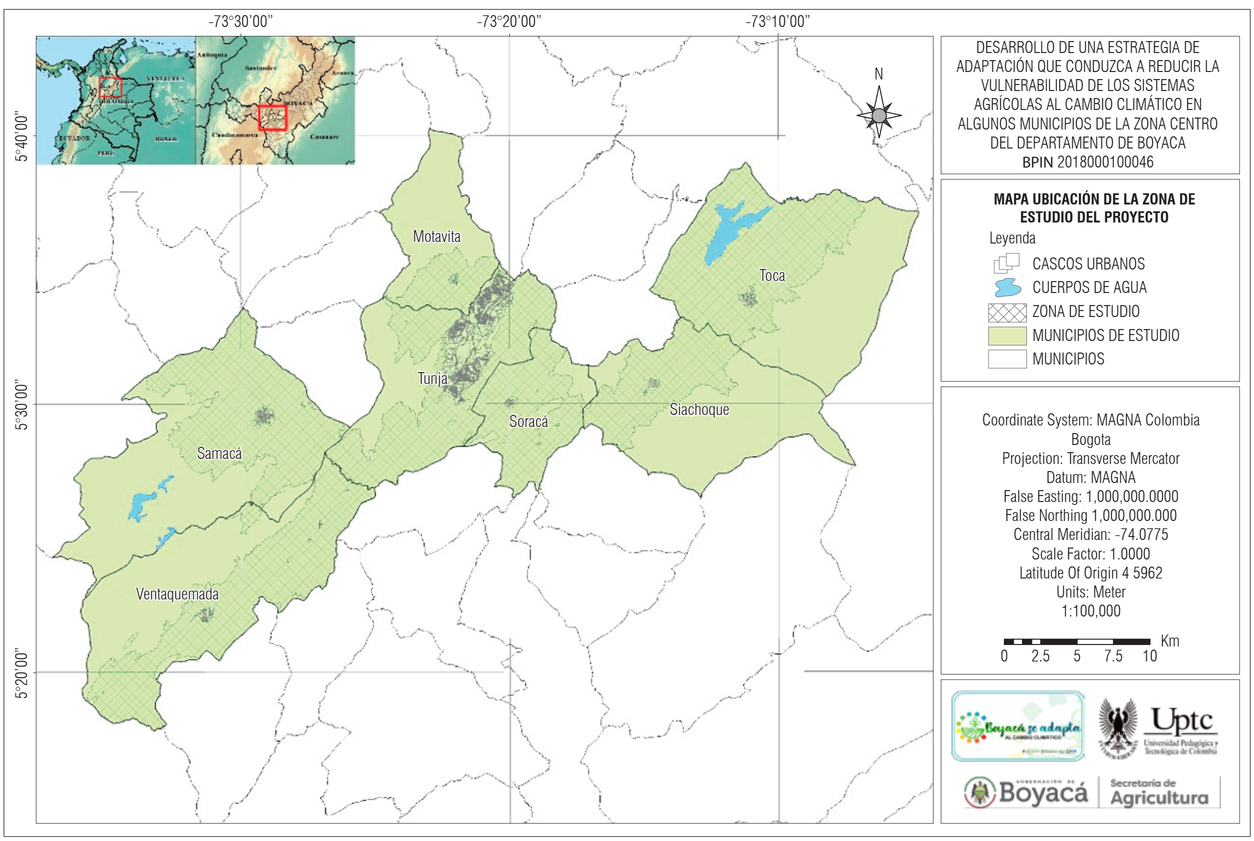

Figure 1. Location of the study area.

availability to complete the interview. The collected data were analyzed using univariate descriptive statistics in RStudio v4.0.5.

Assessment of exposure, sensitivity, adaptive capacity, and vulnerability

Out of the 103 GeoFarmer survey questions designed to capture farmers' perceptions of vulnerability to climate change and extreme weather events, 14 key questions were selected for analysis:

1. Did you receive personal income from agricultural activities?
2. Were you able to save money from your agricultural income?
3. How many people live in your household (including yourself)?
4. What is the terrain type of the largest cultivated area on your farm?
5. What are the sources of irrigation water?
6. Has your household been affected by any situation that reduced production and/or agricultural income?
7. Did you have access to daily or weekly weather forecasts?
8. How many young household members (12–18 years old) participate in farming activities?
9. What is your highest level of education?
10. Do you own the land you use for farming activities?
11. How many household members participate in on-farm agricultural work?
12. Do you have an irrigation system?
13. Do you use weather forecasts to make farming decisions?
14. Do you practice crop rotation?

Exposure was assessed based on the farmers' perception of climate-related events or shocks caused by climate variability or change, which negatively affect one or more of the three evaluated components: social, environmental, or productive. Respondents were asked which climate-related events had affected their income and/or agricultural production. A three-point scale was applied to classify the level of exposure: 1 indicating low exposure, 2 medium exposure, and 3 high exposure.

Sensitivity, understood as the degree to which a system or population is affected—either negatively or positively—by climate variability or change, was evaluated using a weighted scale. This scale was applied to the social, environmental, and productive components to determine their respective sensitivity levels, with 1 indicating low sensitivity, 2 medium sensitivity, and 3 high sensitivity (Tab. 1).

Adaptive capacity was assessed with the objective of identifying how systems, institutions, human groups, and agricultural producers adjust to climate variability and extreme weather events. This evaluation aimed to recognize both the potential to harness positive impacts and the ability to mitigate the negative effects of climate change.

To this end, an inventory of adaptation practices implemented on-farm was compiled, focusing on

Table 1. Sensitivity assessment.

Component	Variable	¿How it reflects sensitivity?
Social	Participation of youth in agricultural activities	Low youth participation may indicate reduced future resilience and increased reliance on older adults
	Use of savings	Lack of savings increases sensitivity to climate-related crises
	Household size	Larger households with limited income may face higher sensitivity
Environmental	Access to climate information	Limited access increases sensitivity due to lack of preparedness
	Terrain type	Sloped or eroded terrain is more sensitive to heavy rainfall
	Sources of irrigation water	Dependence on unreliable water sources increases sensitivity to drought
Productive	Income from agricultural activities	Sole reliance on agricultural income heightens economic sensitivity to climate events
	Impact on agricultural production from extreme climate events	A history of climate-related losses indicates high sensitivity

actions designed to reduce the adverse impacts of various meteorological phenomena. The evaluation was carried out using the following weighted scale: High (3) – the farmer implements adaptation practices that significantly reduce the negative effects of extreme climatic events; Medium (2) – adaptation practices are implemented, but they are insufficient to fully mitigate the negative impacts; and Low (1) – no adaptation practices are implemented in response to extreme weather events.

Table 2 presents the components and variables used for the assessment of adaptive capacity. To obtain a global indicator per farm, a composite score was calculated based on the responses to each evaluated variable.

Lastly, vulnerability was determined by summing the variables within the components of exposure and sensitivity, and then subtracting the adaptive capacity (Formula 1), in accordance with the Illustrative Guide for Territorial Vulnerability Analysis to Climate Change (Corporación Autónoma Regional de Cundinamarca and Universidad Nacional de Colombia, 2018).

$$\text{Vulnerability} = (\text{Exposure} + \text{Sensitivity}) - \text{Adaptive capacity} \quad (1)$$

The resulting score indicates the level of vulnerability on a scale from 1 to 5, where 1 represents very low vulnerability and 5 represents very high vulnerability, as illustrated in figure 2.

Level of vulnerability	Very low	Low	Medium	High	Very high
Scale of vulnerability	1	2	3	4	5

Figure 2. Vulnerability levels and scales.

The described procedure was applied to 86 farmers from the municipalities of Motavita, Siachoque, Toca, and Ventaquemada, and to 85 farmers from Soracá, Samacá, and Tunja, totaling 599 participating farmers. Based on the collected data, Random Forest Spatial Interpolation (RFSI) and RStudio were employed to interpolate the information and generate a spatially continuous representation of climate change vulnerability for the entire study area.

This method differs from standard Random Forest models by incorporating spatial correlation. RFSI includes the nearest observations and their distances to the prediction location as covariates (Sekulić *et al*., 2020). Interpolations were conducted in RStudio following the methodology of Sekulić *et al*. (2020). The parameters used were: 600 trees (parameter ntree), and the random selection of features (mtry) was set by default at one-third of the total covariates for RFSI modeling.

The RFSI algorithm operates as follows: each point of the target variable is geolocated, and then overlaid with the raster layers of the covariates. For each observation, the distance to the N nearest neighbors is

Table 2. Components and variables used to assess adaptive capacity.

Components	Variable	How it contributes to adaptive capacity?
Social	Educational level	Higher educational attainment facilitates understanding of technical and climate information, improves decision-making, and supports the adoption of adaptation technologies
	Land tenure	Land ownership or secure access encourages long-term investments in adaptation practices (e.g., irrigation, soil conservation, diversification)
	Number of household members involved in on-farm agricultural activities	Greater family participation ensures labor availability, continuity of the farming system, and intergenerational adaptation
Environmental	Use of agroclimatic information	Using forecasts or early warnings allows anticipation of adverse climate events (e.g., early planting or harvesting, crop protection), reducing associated risks
	Availability of irrigation systems	Access to irrigation helps cope with dry periods or irregular rainfall distribution, thereby reducing vulnerability to drought
Productive	Crop rotation	Crop rotation improves soil health, reduces pests and diseases, and diversifies risk under adverse climate conditions

calculated. This spatial information is incorporated into the model calibration and prediction process, with these raster-based distances converted into an additional covariate. Using this input, interpolations are performed to generate a final raster layer that displays the spatial distribution and trends in vulnerability across the study area.

RESULTS AND DISCUSSION

The agricultural sector is particularly vulnerable to current and future climate risks due to the low adaptive capacity of farming communities. This is characterized by a lack of technical skills, poverty, and inadequate infrastructure to recover from or transition to alternative livelihoods (Beltrán-Tolosa *et al*., 2022).

Lozano-Povis *et al*. (2021) report an increase in migratory flows from rural Andean areas due to the lack of economic opportunities. The demographic baseline revealed that households consisted of an average of four members, with ages ranging from 18 to 68 years for both men and women. Household sizes varied from a minimum of one person (single-parent family) to a maximum of seven (extended biparental family), with a mean of 3.50 persons. Regarding agricultural involvement, the average number of individuals engaged in productive activities per household was 2.09, indicating that approximately half of the household members participated in internal activities within the production systems (Tab. 3). In some cases, participation reached up to six individuals.

Beltrán-Tolosa *et al*. (2022) emphasize the importance of income diversification among household members—both on- and off-farm—as a strong indicator of resilience to vulnerability. Similarly, Pérez *et al*. (2020) highlight the relevance of the proportion of household members involved in productive decision-making, as well as the gender of the household head. In all the studied municipalities, male-headed households dominated, with a participation rate of 75.45%, compared to 24.55% for female-headed households (Fig. 3). This trend aligns with the findings of Pradilla Rueda (2017), who noted the persistence of a cultural legacy in the gendered division of labor: men are typically responsible for cultivation activities, while women manage domestic tasks. Such patterns may contribute to increased vulnerability.

Table 3. Demographic parameters of horticultural producers in Boyaca.

Variables	Min	Max	Median	Average	Q (25%)	Q (75%)
Age	18	68	41.21	40.45	33.39	47.96
Household size	1	7	3.57	3.50	3	5.14
Participation in agricultural activities	1	6	1.86	2.09	1.29	2.29

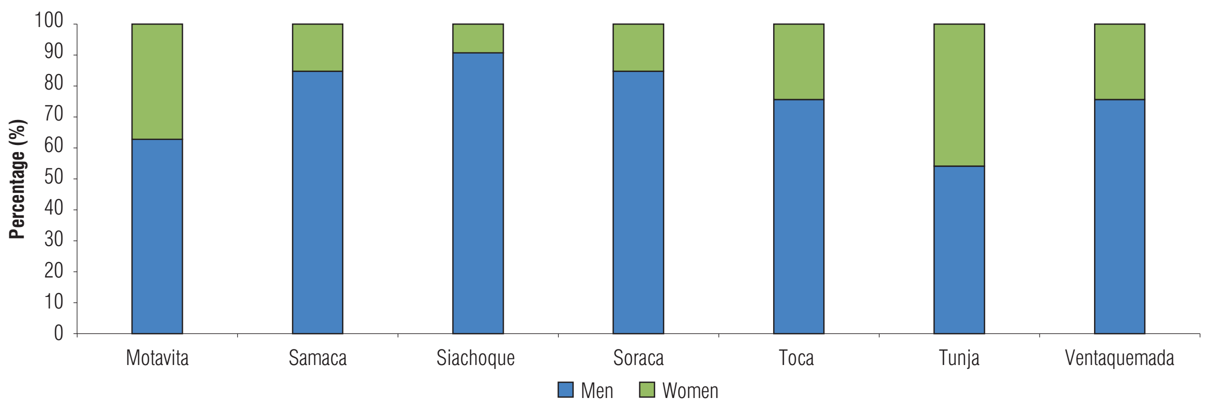

Figure 3. Gender of household head and involvement in productive decision-making among horticultural producers in Boyaca.

Regarding productive decisions and the gender of the household head, in all the municipalities studied, men had greater representation (Fig. 3). In Tunja, a slight balance was observed between men and women, with 54.12 and 45.88%, respectively. Siachoque was the municipality with the lowest representation of women, with only 9.30% (Fig. 3).

Exposure

Exposure to extreme events affected the income and agricultural production of 94.5% of respondents (Fig. 4). Most farmers (49.91%) experienced climate shocks related to both frosts and droughts in equal proportion, 30.38% experienced only frosts, and 13.85% only droughts. The absence of events was reported less frequently (5.50%), as was hail (0.33%). The municipality of Soracá reported the greatest impact from both frosts and droughts, followed by Motavita and Siachoque. In Toca, Tunja, and Ventaquemada, drought was identified as the most significant event affecting crops.

Rodríguez *et al*. (2021) state that farmers consider the repeated occurrence of prolonged droughts, associated with the *El Niño* phenomenon, to be responsible for soil fertility loss and erosion. In contrast, the *La Niña* phenomenon is linked to fertility loss due to topsoil leaching, landslides from torrential rains, and flooding in flat areas.

The study area did not report events such as landslides, fires, mudslides, or flooding that directly or indirectly affected agricultural activities, infrastructure, health, economy, or the environment—issues identified by Beltrán-Tolosa *et al*. (2022) for the Global Humid Forest Ecoregion of the Napo in the Colombian-Ecuadorian Amazon. Conversely, farmers in the Colombian Andean highlands can perceive a highly variable climate, along with changes in the timing of rainy and dry seasons, as well as variations in the intensity and frequency of nighttime frosts, droughts, and precipitation (Ballesteros and Isaza, 2023; Fischer *et al*., 2024). Lozano-Povis *et al*. (2021) explain that a higher warming rate of the lower troposphere (the layer in contact with the earth's surface) particularly affects high-altitude regions. This is especially evident in the high mountains of South America, where the resolution of climate models is insufficient to capture hydrologically significant gradients in temperature and precipitation. This situation is exacerbated by the scarcity of field-obtained meteorological data and the complex topography, factors that hinder the proper identification of farmers' vulnerability.

Sensitivity

Overall, 95% of farmers exhibited medium sensitivity to climate change, followed by high sensitivity (4.67%) and low sensitivity (0.33%). Farmers in the municipality of Ventaquemada identified the main causes as limited access to climate information, low youth participation in agriculture, and scarce sources of irrigation water. Tunja had the highest percentage of high sensitivity (15.12%), attributed to low access to climate information, dependence on agricultural income, lack of savings, and limited youth involvement in farming activities (Fig. 5).

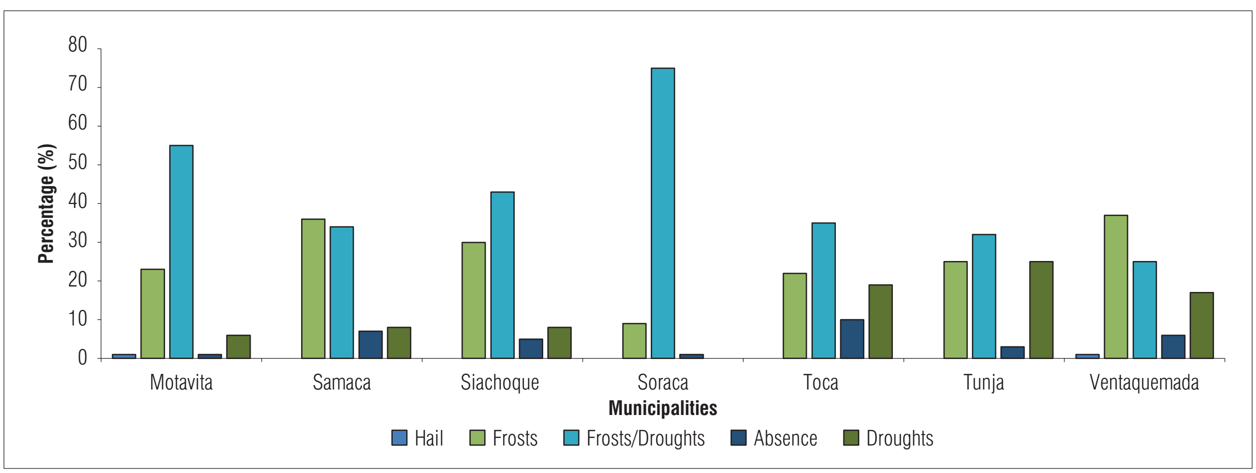

Figure 4. Perception of extreme events or climate shocks among horticultural producers in Boyaca.

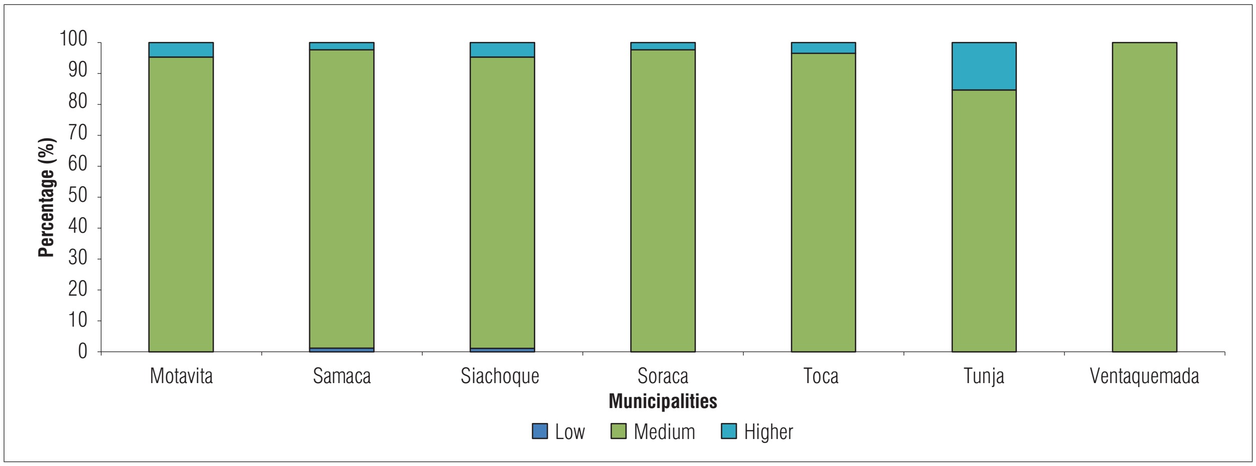

Figure 5. Level of sensitivity of farmers to climate variability and change among horticultural producers in Boyacá.

These results indicate that most farmers consider that "the current climate impact is equal to or slightly greater than in normal years." In this context, climate perceptions are consistent in the farmers' memory, as they recognize the environmental importance of forest cover within their production systems.

Beltrán-Tolosa *et al*. (2022) also highlight the importance of forests, water access, and fertile land as indicators of sensitivity. They identify additional factors such as income, land tenure, access to infrastructure, public services, healthcare, education, and food, as well as the impact of armed conflict, which affects agricultural activity.

Córdoba Vargas *et al*. (2020) report that deforestation and pollution are perceived by Colombian farmers as the main causes of climate variability, in addition to the intensity of solar radiation leading to crop and biodiversity loss. However, as described by Parker *et al*. (2019), some farmers did not perceive changes in the climatic suitability of their region for prioritized vegetable crops, which reflects the variability in perceptions regarding climate impacts.

Adaptive capacity

Adaptive capacity was mostly medium (61.93%) and low (38.07%) regarding the effects of climate variability and change (Fig. 6). Among the respondents, 58.76% were illiterate or had only completed primary education (reading, writing, and basic math skills), 28.71% had finished secondary education,

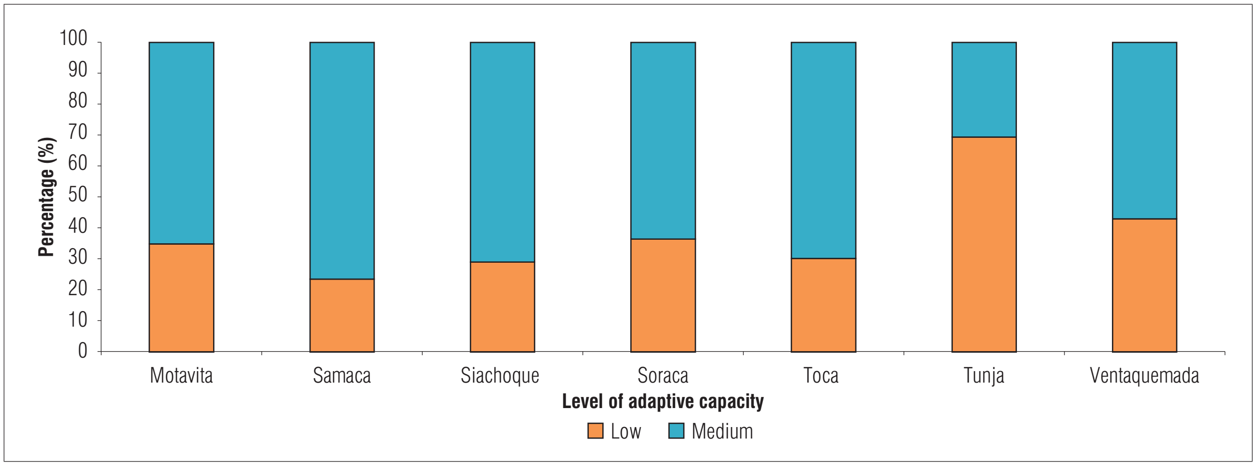

Figure 6. Level of adaptive capacity to climate variability and change among horticultural producers in Boyaca.

and 12.52% had technical or professional studies. According to Parker *et al*. (2019), the more educated a farmer is, the easier it is for them to adopt technology and innovations. When household members have a higher level of education, the farm is more likely to adopt modern production strategies and technologies. Nevertheless, Onyeneke *et al*. (2018) reported a negative influence of years of schooling on the adoption of sustainable agriculture practices, arguing that individuals with a significant level of formal education tend to seek employment in the non-agricultural economy. This apparent contradiction suggests that the effect of education may vary depending on the local socioeconomic context.

Land tenure proved to be a relevant factor in analyzing household economy and the satisfaction of basic needs, since this variable significantly influences agricultural livelihoods. About 67.44% of respondents were landowners, while 32.55% worked the land without owning it. It is worth noting that 80% of small farmers in Colombia own less than one Family Agricultural Unit (UAF), classifying them as micro-holders. Some mixed cases were found: landowners who also rent a smaller portion of land, and farmers who rent most of the land they cultivate, owning only a small fraction. Beltrán-Tolosa *et al*. (2022) state that land ownership is a key factor in adaptive capacity, as owners tend to implement more conservation measures than tenants and enjoy greater permanence security, thus avoiding migration.

Regarding irrigation, 27.37% had no access to water or irrigation systems, while 72.62% had wells, reservoirs, or some form of irrigation. Having irrigation systems or water storage mechanisms to cope with climate variability is a priority (Arteaga and Burbano, 2018). Berrouet *et al*. (2020) found relatively low vulnerability to changes in surface water supply in rural communities of the northern Colombian Andes, due to their ability to substitute water sources and adapt to new circumstances. On the other hand, most farmers knew and implemented crop rotation (58.1%), while 41.9% either did not know about it or did not practice it. Beltrán-Tolosa *et al*. (2022) identified the importance of soil conservation.

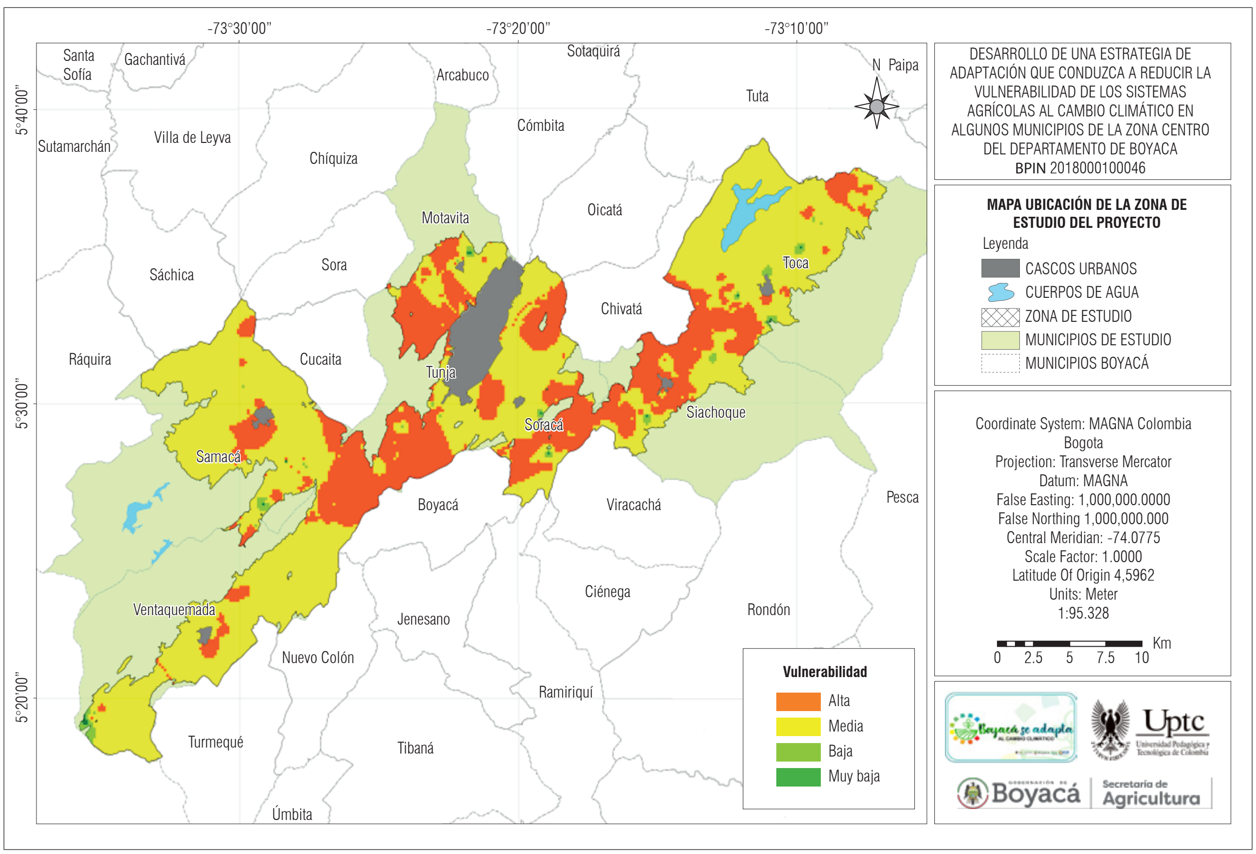

Figure 7. **Vulnerability of farmers to climate variability and change among horticultural producers in Boyaca.**

Regarding the use of climate information, 92.48% of the population had no access to or did not use this information, and only 7.51% used it to make decisions about their crops. Research has shown that the higher the level of education, the better the understanding of climate change and adaptation options (Mihiretu *et al*., 2019). Evangelista *et al*. (2013) add that literate farmers can respond to climate change by making better-informed adaptive decisions based on their experience.

Vulnerability

The RFSI methodology made it possible to define the vulnerability of the study area by identifying that 68.87% of the area presented medium vulnerability to climate change, followed by high vulnerability (30.13%), low (0.89%), and very low (0.12%). No municipalities studied were found to have very high vulnerability (Fig. 7).

The families of Colombian Andean farmers perceive that climate change is affecting their daily lives, especially in aspects related to food security due to reduced availability and quality of products, particularly during drought periods, and in family comfort due to increased daytime and nighttime heat, greater pest and disease pressure, and water scarcity during the dry season. These aspects have been little studied in climate change research, which highlights the need to prioritize work on understanding mitigation, adaptation, resilience, vulnerability, and sustainability processes of peasant families in the face of environmental change (Rodríguez *et al*., 2021).

Studies have shown that older farmers are more vulnerable than younger ones because they are less likely to participate in livelihood diversification. Aging farmers face health issues and have fewer opportunities to seek additional income. Even when they engage in agricultural diversification, their production costs are higher than those of younger farmers due to the high cost of labor. In contrast, younger farmers are more enthusiastic about learning advanced agricultural techniques for climate change adaptation (Tran *et al*., 2022).

Among farmers' strategies to mitigate climate change, water conservation has been a priority due to its vital importance for farming and household use. About 72.62% of surveyed farmers reported having access to irrigation systems, which allows for more efficient water use. They have also adopted soil conservation practices, such as crop rotation.

Acknowledgments

The authors would like to thank the Universidad Pedagógica y Tecnológica de Colombia, executing entity of the project *"Desarrollo de una estrategia de adaptación que conduzca a reducir la vulnerabilidad de los sistemas agrícolas al cambio climático en algunos municipios de la zona centro del departamento de Boyacá"*, identified BPIN: 2018000100046. Likewise, we thank the *Sistema General de Regalías* for the funding, the *Gobernación de Boyacá* and the municipal authorities. Special thanks go to the farmers of the municipalities of Motavita, Samaca, Siachoque, Soraca, Toca, Tunja, and Ventaquemada for their participation in the study.

Conflict of interest. The authors declare that there is no conflict of interest that could have influenced the results or the interpretation of this study.

Author contributions. The authors contributed equally to the preparation of this manuscript.

Data availability. The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Use of artificial intelligence. Generative AI (ChatGPT) was used solely as support for language and style revision; all interpretations, analyses, and the organization of information were verified by the authors.

BIBLIOGRAPHIC REFERENCES

Abbass, K., M. Qasim, H. Song, M. Murshed, H. Mahmood, and I. Younis. 2022. A review of the global climate change impacts, adaptation, and sustainable mitigation measures. Environ. Sci. Pollut. Res. Int. 29, 42539-42559. Doi: https://doi.org/10.1007/s11356-022-19718-6

Acero-Acero, N.Y. and R.G. García-Cáceres. 2024. Caracterización de la cadena de valor y abastecimiento de hortalizas en Colombia. Face 24(2), 13-157.

Ariza Vargas, L.A. 2023. Estrategias de adaptación basadas en la evaluación de la vulnerabilidad al cambio climático del sistema socioecologico vereda El Carmen, municipio de Cómbita (Boyacá, Colombia). MSc thesis. Universidad de Ciencias Aplicadas y Ambientales, Bogota.

Arteaga N., L.E. and J.E. J.E. Burbano N. 2018. Efectos del cambio climático: Una mirada al Campo. Rev. Cienc. Agr. 35(2), 79-91.

Ballesteros, J. and C. Isaza. 2023. Adaptation measures to climate change as perceived by smallholder farmers in the Andes. J. Ethnobiol. 41(3), 428-446. Doi: https://doi.org/10.2993/0278-0771-41.3.428

Banco de la República Colombia. n.d. Cambio climático. In: https://www.banrep.gov.co/es/contenidos/cambio-climatico?page=0; consulted: March, 2025.

Berrouet, L., C. Villegas-Palacio, and V. Botero. 2020. Vulnerability of rural communities to change in an ecosystem service provision: surface water supply. A Case Study in the Northern Andes, Colombia. Land Use Policy 97, 104737. Doi: https://doi.org/10.1016/j.landusepol.2020.104737

Beltrán-Tolosa, L., G. Cruz-Garcia, J. Ocampo, P. Pradhan, and M. Quintero. 2022. Rural livelihood diversification is associated with lower vulnerability to climate change in the Andean-Amazon foothills. PLOS Clim 1(11), e0000051. Doi: https://doi.org/10.1371/journal.pclm.0000051

Blackmore, I., C. Rivera, and W. Waters, 2021. The impact of seasonality and climate variability on livelihood security in the Ecuadorian Andes. Clim. Risk Manag. 32, 100279. Doi: https://doi.org/10.1016/j.crm.2021.100279

Córdoba Vargas, C.A., S. Hortúa Romero, and T. León-Sicard. 2020. Resilience to climate variability: the role of perceptions and traditional knowledge in the Colombian Andes. Agroecol. Sustain. Food Syst. 44(4), 419-445. Doi: https://doi.org/10.1080/21683565.2019.1649782

Cortés-Cataño, C.F., Y. Foronda-Tobón, J.A. Paez-Ricardo, J.E. Parra-Herrera, and M.J. Cañon-Ayala. 2024. The effect of environmental variations on the production of the principal agricultural products in Colombia. PLoS ONE 19(7), e0304035. Doi: https://doi.org/10.1371/journal.pone.0304035

Corporación Autónoma Regional de Cundinamarca – Universidad Nacional de Colombia. 2018. Guía ilustrativa sobre análisis de la vulnerabilidad territorial ante el cambio climático. Propuesta metodológica para los entes territoriales de la jurisdicción CAR. Grupo de Cambio climático DGOAT CAR – Grupo de investigación “Tiempo, clima y sociedad”. Universidad Nacional de Colombia, Bogota.

Duarte Durán, C.A. 2023. Adaptación al cambio climático y su relación con la seguridad alimentaria en municipios de Boyacá. MSc thesis. Universidad Distrital Francisco José de Caldas, Bogota.

Eitzinger, A., J. Cock, K. Atmanstofer, C. Binder, P. Laderach, O. Boniñña-Findji, M. Bartling, C. Mwongera, L. Zurira, and A. Jarvis. 2019. GeoFarmer: a monitoring and feedback system for agricultural development projects. Comput. Electron. Agric. 158, 109-121. Doi: https://doi.org/10.1016/j.compag.2019.01.049

FAO. 2019. Aportes al diseño y evaluación de políticas públicas vinculadas a la vulnerabilidad de los sectores agrícolas y ganaderos al cambio climático. Quito.

Fischer, G., H.E. Balaguera-López, A. Parra-Coronado, and S. Magnitskiy. 2024. Adaptation of fruit trees to different elevations in the tropical Andes. pp. 193-208. In: Tripathi, S., R. Bhadouria, P. Srivastava, R. Singh, and R.S. Devi (eds.). Ecophysiology of tropical plants - Recent trends and future perspectives. CRC Press, Boca Raton, FL, USA.

Forero, N. and C. González. 2020. Agricultura climáticamente inteligente (ACI) en Colombia: diagnóstico y retos de política pública. Coyuntura Económica: Investigación Económica y Social 50, 211-247.

ICA, Instituto Colombiano Agropecuario. 2023. Acciones del ICA en Boyacá para garantizar calidad fitosanitaria en la producción vegetal (Newspaper). In: https://www.ica.gov.co/noticias/acciones-del-ica-en-boyaca-para-garantizar-calidad; consulted: November, 2024.

La República. 2024. Gracias a la diversidad de Boyacá contamos con más de 97 renglones productivos (Newspaper). In: https://www.larepublica.co/especiales/boyaca-destino-de-inversion/tenemos-mas-de-97-renglones-productivos-3911503; consulted: november, 2024.

Lozano-Povis, A., C.E. Alvarez-Montalván, and N. Moggiano-Aburto. 2021. El cambio climático en los andes y su impacto en la agricultura: una revisión sistemática. Sci. Agropecu. 12(1), 101-108.

MinAgricultura, Ministerio de Agricultura y Desarrollo Rural. 2025. Agronet -Reporte de área, producción y rendimiento nacional por cultivo del periodo 2012-2022. In: https://www.agronet.gov.co/estadistica/Pagin as/home.aspx?cod=1; consulted, September: 2024.

Mihiretu, A., E. Ndemo Okoyo, and T. Lemma. 2019. Determinants of adaptation choices to climate change in agro-pastoral dry lands of Northeastern Amha _ Enhanced Reader. *Cogent Environ. Sci. 5*(1). Doi: https://doi.org/https://doi.org/10.1080/23311843.2019.1636548

Onyeneke, R.U., C.O. Igberi, C.O. Uwadoka, and J.O. Aligbe. 2018. Status of climate-smart agriculture in southeast Nigeria. GeoJournal 83(2), 333-346. Doi: https://doi.org/10.1007/s10708-017-9773-z

Ortega, L.A. and L.P. Paz. 2014. Manual para la formulación de planes prediales de adaptación a la variabilidad climática. Empresa Energética ISA; Fundación Pro Cuenca Río Las Piedras; Fundación Ecohabitats, Bogota.

Parker, L., C. Bourgoin, A, Martinez-Valle, and P. Läderach. 2019. Vulnerability of the agricultural sector to climate change: The development of a pan-tropical climate risk vulnerability assessment to inform sub-national decision making. PLoS ONE 14(3), e0213641. Do: https://doi.org/10.1371/journal.pone.0213641

Pérez, L., D.A. Rios, D.C. Giraldo, J. Twyman, G. Blundo-Canto, S.D. Prager, and J. Ramirez-Villegas. 2020. Determinants of vulnerability of bean growing households to climate variability in Colombia. Clim. Dev. 12(8), 730-742. Doi: https://doi.org/10.1080/17565529.2019.1685931

Phuong, L.T.H., G.R. Biesbroek, L.T.H. Sen, and A.E.J. Wals. 2018. Understanding smallholder farmers' capacity to respond to climate change in a coastal community in Central Vietnam. Clim. Dev. 10(8), 701-716. Doi: https://doi.org/10.1080/17565529.2017.1411240

Ponce, C. 2020. Intra-seasonal climate variability and crop diversification strategies in the Peruvian Andes: A word of caution on the sustainability of adaptation to climate change. World Dev. 127, 1-22. Doi: https://doi.org/10.1016/j.worlddev.2019.104740

Pradilla Rueda, H. 2017. Cubios, rubas, ibias y papas de Boyacá: la comida de los Andes. Nuevas Lecturas de Historia No. 29. Univeridad Pedagógica y Tecnológica de Colombia, Tunja, Colombia.

Rodríguez, J.J.N., J.C.C. Rodríguez, D.M. Carrero, L.L.R. Novoa, and J.V.S. Frank. 2021. Representations of Colombian Andean farmers on climate change and mitigation and adaptation strategies. Rev. Econ. Sociol. Rural 59(2), e220439. Doi: https://doi.org/10.1590/1806-9479.2021.220439

Sekulić, A., M. Kilibarda, G.B.M. Heuvelink, M. Nikolić, and B. Bajat. 2020. Random forest spatial interpolation. Remote Sens. 12(10), 1687. Doi: http://dx.doi.org/10.3390/rs12101687.

Teklewold, H., T. Gebrehiwot, and M. Bezabih. 2019. Climate smart agricultural practices and gender differentiated nutrition outcome: An empirical evidence from Ethiopia. World Dev. 122, 38-53. Doi: https://doi.org/10.1016/J.WORLDDEV.2019.05.010

Tran, P.T., B.T. Vu, S.T. Ngo, V.D. Tran, and T.D.N. Ho. 2022. Climate change and livelihood vulnerability of the rice farmers in t North Central Region of Vietnam: A case study in Nghe An province, Vietnam. Environ. Chall. 7, 100460. Doi: https://doi.org/10.1016/j.envc.2022.100460

Valbuena Gaona, L.A., M.I. Munera López, G. Fischer, S. Magnitskiy, H.E. Balaguera López, and J.G. Ramírez Gil. 2025. Variabilidad climática en la fruticultura tropical: consideraciones para Colombia. pp. 71-94. In: Torres Lima, P.A., J.G. Cruz Castillo, L.A. Barrera Guzmán, M.E. Galindo Tovar, H. Mata Alejandro, H.T. Mojica Zárate, J. Murguía González (coord.). Producción de frutales en cambio climático - Experiencias en América Latina. Ediciones Comunicación Científica, Ciudad de México. Doi: https://doi.org/10.52501/cc.296.04