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Economic Impact of Climate Change on Potato Production in the Samacá Valley - Boyacá, Colombia

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Abstract

Climate change has generated significant alterations in temperature and precipitation, affecting the productivity and profitability of potato crops in the Samacá valley, Boyacá. Therefore, the purpose of this study is to analyze the economic effects of these climatic variations on small, medium and large producers. Regarding the methodological design, the study is framed in the quantitative approach, descriptive scope and under a comparative design, through which instruments of the same nature are administered as surveys to a group of 30 farmers. The results show that small farmers' crops are more vulnerable to climate change, which leads to the conclusion that it is necessary to propose differentiated adaptation strategies that promote the use of sustainable technologies, access to credit and planning based on climate information.

Key words: Climate change, potato, agricultural economics, productivity, adaptation.

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Introduction

Climate change has become one of the main global challenges, especially for the agricultural sector, whose dependence on stable climatic conditions makes it one of the most vulnerable activities. In this context, variations in temperature, precipitation and frequency of extreme events have significantly altered agricultural production cycles and crop profitability. According to Ríos and Martinez (2020), weather fluctuations directly affect the productivity and economic stability of agriculture, creating a scenario of growing uncertainty for producers. This situation is particularly relevant in the Samacá Valley, Boyacá, Colombia, a region with a strong economic dependence on potato crops, which are affected by phenomena such as prolonged droughts, excessive rainfall and increased pests, all linked to recent climatic transformations.

Different studies have documented the effects of climate change on agriculture, showing decreases in yields, changes in planting and harvesting calendars, as well as increased vulnerability to pests and diseases. Ramirez et al. (2012) highlight how increased temperatures and altered precipitation patterns have a negative impact on sensitive crops such as potatoes, by modifying the agroecological conditions necessary for their optimal development. Similarly, studies conducted in the Cundinamarca-Boyacá highlands have revealed that small and medium producers face greater difficulties in adapting to these changes due to the limited availability of technologies, technical assistance and climate monitoring tools (Ríos and Martínez, 2020). However, a gap persists in the literature related to the differentiated analysis of the economic effects of climate change in specific local contexts such as Samacá, where agroclimatic and socioeconomic conditions demand studies with greater depth and territorial relevance.

In Samacá, farmers have reported increasing instability in their potato harvests over the last decade, attributed to unexpected climatic variations. These conditions have resulted in higher production costs, reduced product quality, lower profit margins and a latent threat to the sustainability of the crop, especially in the case of smallholders. Although some farmers with greater resources have implemented adaptation measures such as technified irrigation or the use of more resistant varieties, most lack the necessary means for an effective response. This disparity accentuates socioeconomic gaps within the rural sector, and raises questions about the resilience of potato cultivation to the economic effects of climate change. It is therefore essential to understand how this phenomenon is differentially impacting different types of producers in the Samacá valley.

Potato cultivation is one of the economic pillars of the municipality of Samacá, not only because of its relevance as a source of income, but also because of its role in local and regional food security. Faced with the advance of climate change, it is urgent to generate empirical knowledge to understand the economic effects faced by producers at different scales, identify the capacities and limitations in their adaptation strategies, and guide the design of public policies and differentiated support programs. This research contributes to the local analysis of the impact of climate change on agriculture, and seeks to strengthen the foundations for more resilient, equitable and sustainable rural management. Its value lies in combining the analysis of agroclimatic data with the perceptions and experiences of the producers themselves, providing a comprehensive view of the current challenges and opportunities for adaptation.

The purpose of this study is to analyze the economic effects of climate change on potato cultivation in the Samacá valley, Boyacá, through a comparative approach among small, medium and large producers. The analysis will allow assessing the adaptive capacity of each group and their financial sustainability, in order to understand the differentiated dynamics faced by the sector and contribute to the formulation of more effective and contextualized adaptation strategies.

Literature Review

Climate change represents one of the main challenges for agriculture worldwide, due to its adverse effects on productivity, profitability and food security. Alterations in weather patterns have generated significant impacts on the agricultural sector, especially on sensitive crops such as potato. This section addresses the fundamental concepts of climate change, its impact on agriculture and specifically on the potato crop, as well as adaptation and mitigation strategies.

Climate Change and Agriculture

Climate change, largely caused by greenhouse gas emissions (IPCC, 2022), has generated negative impacts on global agriculture, affecting water availability, phenological cycles, and increasing the incidence of pests (FAO, 2009). In Colombia, regions such as Boyacá face extreme phenomena that affect strategic crops such as potatoes (ECLAC, 2022). Peasant agriculture is especially vulnerable due to its limited technical and financial capacity.

In response, policies such as the National Climate Change Adaptation Plan (PNACC) promote integrated actions, risk management and productive sustainability (DNP, 2017). The articulation between institutions and communities has promoted adaptive practices such as agroecology, crop diversification and conservation of native seeds (Roa and Morales, 2019).

Agricultural Productivity

Agricultural productivity, understood as the ratio of production to resources used (USDA, 2020), is key to food security and rural development. Increasing it through technology, technical education and financing makes it possible to improve income and reduce poverty (Narváez Arapa, 2022; Bonilla Bolaños and Singaña Tapia, 2019). In addition, the use of tools such as sensors, artificial intelligence and drones is transforming the efficient management of crops (Universidad Miguel Hernández, 2022).

However, it is cautioned that an exclusively productivist approach may compromise sustainability. Therefore, a balanced model that integrates social justice, efficiency and environmental conservation is promoted (Maldonado and Acosta-Medina, 2022).

Potato cultivation in the Samacá Valley

The Samacá Valley in Boyacá is a strategic area for potato cultivation, an activity that sustains thousands of families (ICA, 2022). This crop has high economic, social and cultural relevance, and is vital for regional food security (Gobernación de Boyacá, 2020). However, it faces climatic challenges such as variations in rainfall and an increase in pests (Triviño and Useche, 2022).

In response, sustainable practices such as agroecology, the use of resistant varieties and the improvement of rural infrastructure are being promoted. Technical training and assistance to producers are essential to ensure resilient and sustainable production (ICA, 2022).

Potato and Climate Change

Potato is a crop sensitive to changes in temperature and humidity. High temperatures reduce tuber size and quality, while water variability favors diseases such as gout (INTAGRI, 2017). Climate change has also increased pests such as the guatemalan moth.

Adaptive strategies such as crop rotation, use of irrigation technologies, and adoption of agroecological systems are required.

Changes in Precipitation

Phenomena such as El Niño and La Niña significantly alter the distribution of rainfall in Colombia, generating droughts or excess humidity (Pérez, Montenegro and Vargas, 2022). At the national level, precipitation is projected to decrease in some areas and increase in others, which calls for differentiated agroclimatic management.

Materials and Methods

This study adopts a quantitative approach, since it is based on the collection and analysis of numerical data related to climatic variables (rainfall and temperature) and economic variables (potato sales price), with the purpose of establishing patterns, comparisons and relationships between these variables according to the type of producer (small, medium and large). This approach allows observing reality objectively and measuring phenomena accurately, which is essential for the systematic analysis of historical and current data in the agricultural context. According to Gilbert (2019), the quantitative approach "uses data collection to test hypotheses, based on numerical measurement and statistical analysis, in order to establish patterns of behavior and test theories.

The scope of the study is descriptive, since it is aimed at characterizing and analyzing the selected variables without intervening on them, limiting itself to observing and detailing their behavior over time and according to the different types of producers. According to Aggarwal and Ranganathan, (2019), descriptive studies seek to specify properties, characteristics and important features of any phenomenon being analyzed. In this case, the study does not seek to explain root causes or establish causal relationships, but rather to provide a detailed view of the behavior of variables over a given period (2012-2022).

In terms of design, a comparative design is adopted, to the extent that a differential analysis of the behavior of the variables is carried out according to the size of the producer (small, medium and large). This comparison makes it possible to establish significant differences in the climatic and economic conditions faced by the different strata of producers in the municipality of Samacá, which is fundamental for generating useful information for decision-making in the agricultural sector. According to Zhang et al. (2022), comparative studies make it possible to establish relationships of similarity or difference between two or more groups according to certain variables.

Research Scenario

The present research was developed in the municipality of Samacá located in the Centro province of the department of Boyacá, Colombia, as shown in Figure 1. This territory is located approximately 30 kilometers southwest of Tunja, the departmental capital, and is georeferenced at coordinates 5° 29' 31'' north latitude and 73° 29' 12'' west longitude, according to the reference system of the Instituto Geográfico Agustín Codazzi Instituto Geográfico Agustín Codazzi [IGAC]. (2018). The field work was concentrated in the Centro, Pataguy and Tibaquirá villages, selected for their representativeness in terms of agricultural production and agroclimatic conditions.

Figure 1
Municipality of Samacá

Note: Image taken from the Mayor's Office of Samacá. 2023.

Samacá is bordered to the north by the municipalities of Sáchica and Sora; to the south by Gachetá (department of Cundinamarca) and Ventaquemada; to the east by Tunja, Cucaita and Puente de Boyacá; and to the west by Ráquira. This strategic location within the Cundinamarca highlands gives it an important relevance in terms of regional connectivity and agricultural development (Alcaldía Municipal de Samacá, 2022).

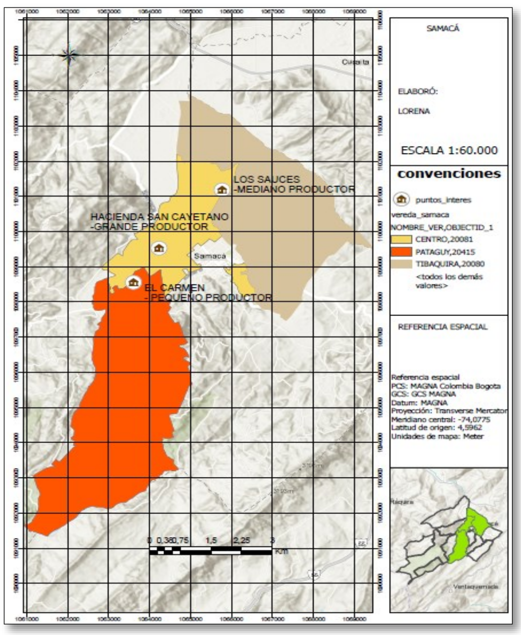
Samacá is a municipality of about 160 Km2 of extension that belongs to the Province of the Center of the department of Boyacá. It is 32 kilometers from Tunja and 159 km from Bogotá. Geographically it is located at 5 ° 29' North Latitude and 73

° 30' West Longitude of the Greenwich meridian (Alcaldía Municipal de Samacá, 2022).

Territorial division: In addition to the urban area or center, the municipality is divided into the following villages: Tibaquirá, Guantoque, Páramo Centro, Gacal, Quite, Pataguy, Salamanca, Chorrera, Loma Redonda, Ruchical and Churuvita. The vereda is a rural division where families live and work on their farms or haciendas. Generally, the veredas are sectored by neighborhood groups. Examples are: El Valle, El Venado, La Fábrica, El Abejón, El Llanito, La Cumbre, La Cabuya, Rincon Santo, El Cerrito, El Mamonal, etc. As for the physiography, the population dwells at the foot of a branch of the Eastern Cordillera and a beautiful valley that measures about 15 kilometers. Three villages in the municipality of Samacá were considered for this research: Centro, Pataguy and Tibaquirá, which are delimited in Figure 2.

Figura 1

Mapa Ubicación área de estudio municipio de Samacá



Note: Selected properties in the research The research will focus specifically on the Centro, Pataguy and Tibaquira villages of the municipality.

Subjects

The target population of this study consisted of potato growers in the municipality of Samacá, located in the department of Boyacá, Colombia. According to local records and official sources, the total population amounts to 140 active producers dedicated to this agricultural activity.

For the development of the research, a representative sample of 30 farmers was selected, considering the need to collect reliable and generalizable quantitative data within acceptable statistical confidence margins. The sampling process was carried out by means of stratified probability sampling, given that the population has a structure differentiated into three strata according to the size of the production unit: small, medium and large producers.

The strata were defined based on cultivated area and annual production capacity, in accordance with the technical criteria established by the Ministry of Agriculture and Rural Development. The distribution of the sample was as follows:

- 10 small producers (less than 1 hectare cultivated).

- 10 medium producers (7 cultivated hectares)

- 10 large producers (10 cultivated hectares)

This stratified approach made it possible to guarantee the representativeness of each type of producer in the analysis, thus ensuring a comparative and balanced view of the phenomena studied. The selection within each stratum was carried out in a simple random manner, using lists provided by the Municipal Agricultural Development Secretariat.

Study variables

In this research, three main variables were analyzed (see Table 1) with the objective of understanding the relationship between climatic conditions and the economic behavior of potato production in the Samacá valley, Boyacá, during the period 2012-2022. These variables were approached considering their behavior in three types of productive units: small, medium and large producers, in order to identify differentiated impacts according to the productive scale.

Table 1
Operationalization of Variables

Variable	Type of variable	Unit of measure	Source of data	Period of analysis
Precipitation	Continuous quantitative	Millimeters (mm)	Weather stations - IDEAM	2012 – 2022
Temperature	Continuous quantitative	Degrees Celsius (°C)	Weather stations - IDEAM	2012 – 2022
Potato selling price	Continuous quantitative	Colombian pesos (COP/kg)	Corabastos	2012 – 2022

Note: The table shows the details of the variables estimated in the study.

- **Precipitation:** The total amount of rainfall recorded annually and during the key months of the crop cycle was analyzed. This variable makes it possible to evaluate the availability of water and its relationship with crop yield, especially in areas with little access to technified irrigation.

- **Temperature:** Variations in mean annual temperature and thermal anomalies during the critical phases of the crop (planting, vegetative development, flowering and harvest) were considered. Thermal fluctuation was associated with the occurrence of diseases and impairments in the physiological development of the crop.

- **Potato sales price:** This economic variable was studied in terms of supply, demand and the influence of extreme weather events on marketing. Price trends and moments of high volatility were identified that impact profitability, especially for small producers.

Phases of the research process

The present study was structured in four consecutive phases that allowed to advance from the characterization of quantitative variables to the generation of strategic proposals. Each phase was developed in a systematic and complementary manner, responding to the specific objectives set out in the research. Through this phased approach, we sought to understand the impact of climate variability on the profitability of potato crops in the municipality of Samacá, Boyacá, as well as to establish guidelines to strengthen the resilience of the agricultural sector to the effects of climate change.

First phase: Collection and systematization of data.

The first phase was oriented to the collection, classification and systematization of data corresponding to the variables established in the study: precipitation, temperature and potato sales price for the period between 2012 and 2022. This phase included obtaining climatological information from the Instituto de Hidrología, Meteorología y Estudios Ambientales (IDEAM) and economic data from the Sistema de Información de Precios y Abastecimiento del Sector Agropecuario (SIPSA - DANE), as well as surveys applied to a representative sample of growers. The organization of the data made it possible to build a solid base for the subsequent comparative analysis.

Second phase: Causality analysis of economic losses

In this phase, the study focused on identifying the possible causes of the economic losses reported by producers, exploring the relationship between climate variability and the decrease in profit margins. A statistical analysis was carried out to detect patterns between the periods of greatest climatic affectation (drought or excess rainfall events) and falls in the price or productivity of the crop. This stage was fundamental to establish a relationship between climate change and the economic impact on agricultural activity.

Third phase: Correlation between climatic variability and profitability

The third phase was aimed at analyzing the correlations between climatic variables (precipitation and temperature) and changes in potato crop profitability. Using descriptive and correlational statistical tools, significant trends were identified that show how climate variability affects the productive efficiency and economic sustainability of producers according to their scale (small, medium and large). This analysis allowed us to deepen our understanding of the risks associated with extreme weather conditions.

Fourth phase: Formulation of resilience strategies

The last phase of the research process focused on the formulation of proposals aimed at promoting the resilience of farmers to the effects of climate change. Based on the findings of the previous phases, technical, organizational and training strategies were designed to strengthen the adaptive capacity of the potato sector in Samacá. These recommendations include improvements in climate risk management, the use of agroclimatic monitoring technologies, income diversification and coordination with local and national public policies.

Results

The results of this study are oriented to the fulfillment of the specific objectives that guided the research process, as well as the development of each of the phases proposed in the methodological design.

- **Results First phase: data collection and systematization**

The results of the first phase of the study are in line with the theoretical references addressed in the literature review. In this sense, it was possible to establish that climate influences soil formation, with precipitation and temperature being the most important factors. Precipitation variation affects irrigation, plant physiology and planting (Boyacá Adapts to Climate Change, 2021), precipitation, more variable than other factors, impacts agricultural yields and is key to the hydrological cycle and water management (MeteoSite, 2021).

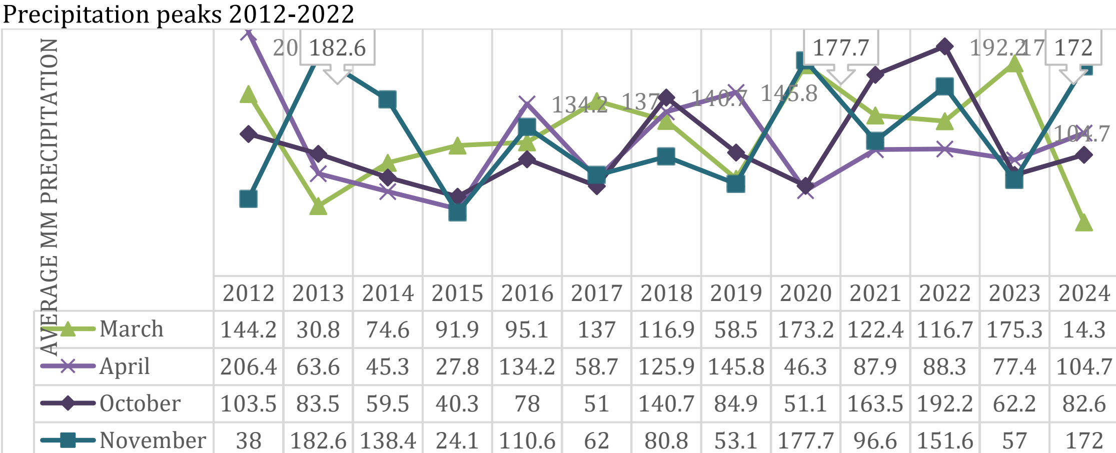
It has also been determined that temperature, as another element of climate, has a significant influence on ecological processes and agricultural production, as well as being a determining factor in the distribution of species and ecosystems. Although its interannual variability is smaller compared to precipitation, sunshine and other climatic factors, its long-term trend is key to understanding the effects of climate change. Temperature plays a fundamental role in the planet's energy balance, affecting evapotranspiration, cloud formation and atmospheric dynamics, which directly relates it to global thermal regulation and climate studies (World Meteorological Organization, WMO, 2022).

For this study, information provided by the Institute of Hydrology, Meteorology and Environmental Studies of Colombia (IDEAM) was taken from the main climate station Villa Carmen, located in the municipality of Samacá at coordinates 5° 29' 31'' North and 73° 29' 12'' West, average altitude of 2600 masl, which includes multiannual information, average precipitation (mm) and average temperature (°C) in a period between 2012 and 2022.

Figure 3 shows the average monthly rainfall in March, April, October and November, with the highest peaks between 2012 and 2022. Large interannual variability is observed, reflecting the irregularity of rainfall in key months for agriculture. For example, in April 2012 there was 206.4 mm, but in 2013 it dropped to 63.6 mm, showing this instability that affects agricultural planning (IDEAM, 2020). Between 2020 and 2022 rainfall increased, especially in October and November, exceeding 160 mm. October 2022 reached 192.2 mm and November 2020 had 177.7 mm. However, in March 2022 there was an abrupt drop to 14.3 mm, which could harm planting and yields (Pabón-Caicedo et al., 2019).

In general, the variability in monthly rainfall in these four months evidences an important challenge for small farmers, who depend directly on the rainfall regime for their crop cycles. The climatic instability observed in the graph compromises the predictability of water available for agriculture, affecting both the quality and quantity of harvests. These data reinforce the need to implement climate change adaptation strategies, such as water harvesting, the use of efficient irrigation technologies and the diversification of more resilient crops (FAO, 2021).

Figure 3
Precipitation peaks 2012-2022

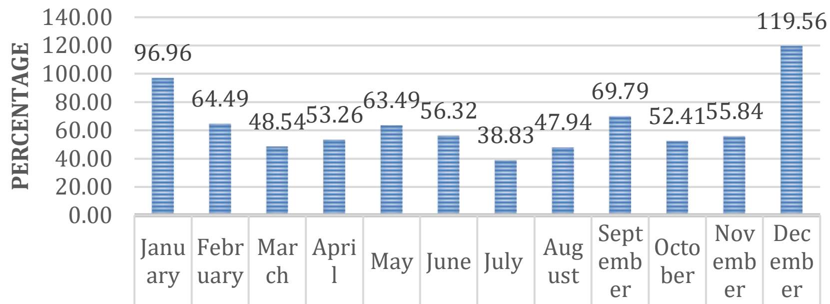


	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
March	144.2	30.8	74.6	91.9	95.1	137	116.9	58.5	173.2	122.4	116.7	175.3	14.3
April	206.4	63.6	45.3	27.8	134.2	58.7	125.9	145.8	46.3	87.9	88.3	77.4	104.7
October	103.5	83.5	59.5	40.3	78	51	140.7	84.9	51.1	163.5	192.2	62.2	82.6
November	38	182.6	138.4	24.1	110.6	62	80.8	53.1	177.7	96.6	151.6	57	172

Note. The months with the highest precipitation peaks were taken from the period (2012-2022).

An analysis showing the high annual climatic variability is presented below. The coefficients of variation of precipitation and temperature as shown in Figures 4 and 5 indicate significant monthly fluctuations. Although there are differences between both variables, the analysis considers all data, including atypical climatic events of the period studied.

Figure 4
Coefficient of variation of precipitation (2012-2022)



	January	February	March	April	May	June	July	August	September	October	November	December
CV	96.9	64.4	48.5	53.2	63.4	56.3	38.8	47.9	69.7	52.4	55.8	119.

Note: The figure shows the precipitation behavior data (2012-2022) for the Samacá-Boyacá valley.

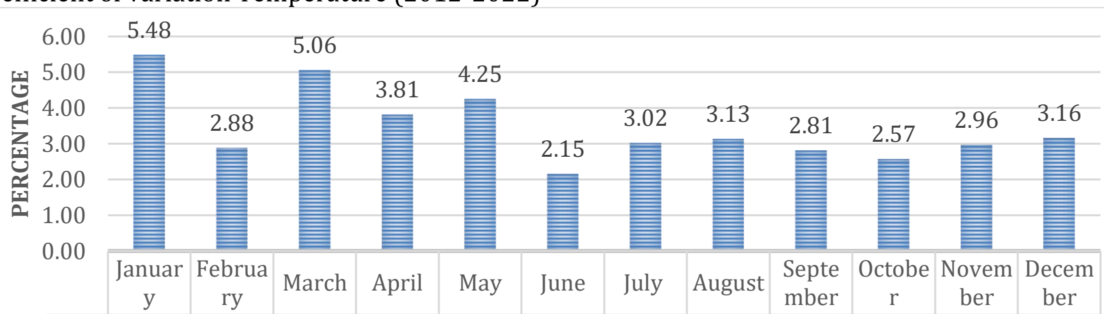
Figure 4 shows the monthly variation coefficients for precipitation in the municipality of Samacá between 2012 and 2022. Note the high dispersion of the values for each of the months, which, in all cases, exceeds the value of 30%. According to: Douglas C. Montgomery (2020) such value indicates a high heterogeneity of the values with respect to their average and consequently a high dispersion of the data.

This heterogeneity in the data reveals a high uncertainty in rainfall conditions. This represents a significant challenge for the planning of agricultural activities and the efficient management of water resources. Although the months of March and April present, on average, higher levels of precipitation, they also exhibit high coefficients of variation that make it impossible to establish with certainty a reliable schedule for agricultural activities such as potato planting. This problem will be discussed in greater depth in later sections.

As shown in Figure 5, the coefficients of variation of temperature in all cases present values lower than 30 %, which indicates a low dispersion of the data with respect to their mean.

Figure 5

Coefficient of variation Temperature (2012-2022)

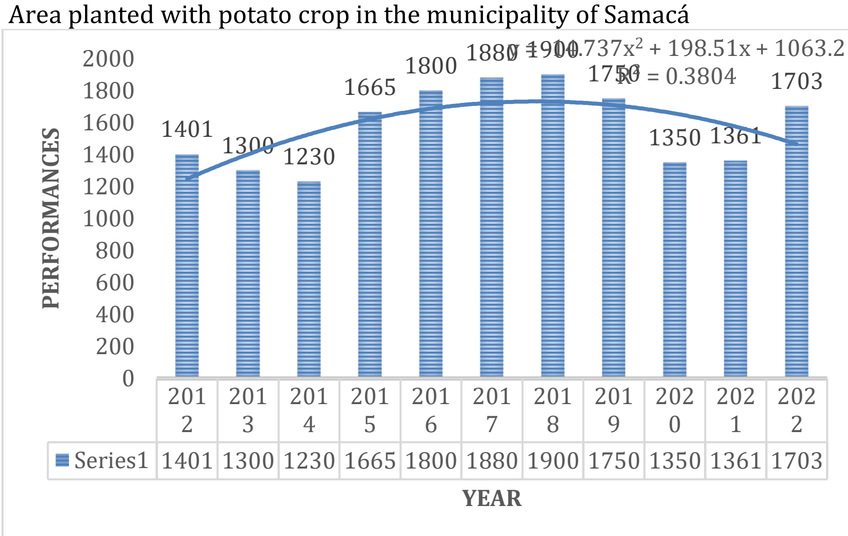


	January	February	March	April	May	June	July	August	September	October	November	December
CV	5.48	2.88	5.06	3.81	4.25	2.15	3.02	3.13	2.81	2.57	2.96	3.16

Note: The figure shows the temperature behavior data (2012-2022) for the Samacá-Boyacá valley.

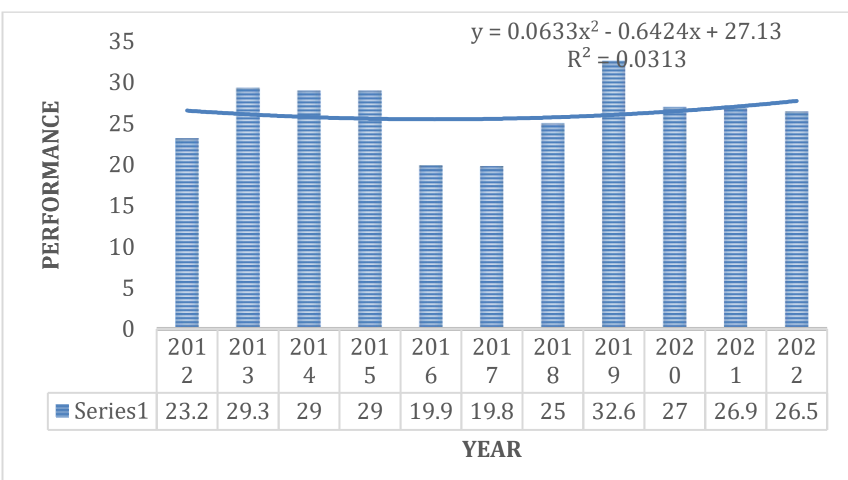
With the above, the effects of climate change result in a high dispersion of the rainfall variable that explains in part the high irregularity in the behavior of plantings as shown in Figure 6 and yield Figure 7 of the potato crop in the municipality of Samacá. Note that although the trend line that most closely approximates the area and yield is the polynomial type, the coefficient of determination (R2) (less than 50%) does not allow explaining an adjustment to the model.

Figure 6
Area planted with potato crop in the municipality of Samacá



Note: The figure shows the behavior of the area planted with potato crops in the municipality of Samacá-Boyacá.

Figure 7
Yield of potato crop in the municipality of Samacá



Note: The figure shows the yield data of the potato crop in the municipality of Samacá-Boyacá.

Díaz and Salazar (2018) analyzed how precipitation influences potato crop yield, highlighting that the increase in greenhouse gases is altering the climate and requires the agricultural sector to adopt adaptation strategies. For his part, Ramírez (2016) identified an inverse relationship between potato production and its price, evidenced in the present research by a negative correlation of -0.23 between both variables.

Results Second phase: Analysis of causality and economic loss

This research focused on potato producers in the Samacá Valley. Based on a 2022 agricultural database provided by the Municipal Mayor's Office, the information was purified and small, medium and large producers of different scales were selected according to the number of cultivated hectares, following the criteria of the Ministry of Agriculture and Rural Development (Alcaldía Municipal de Samacá, 2022).

The farms selected for each of the producers are located in representative villages of each group in the municipality of Samacá, namely, Centro, Pataguy and Tibaquira.

Potato qualities

The researcher considers it pertinent to examine aspects related to the quality of the tuber, which is discussed below:

According to FAO. (2015), potato quality is classified into three main categories, each with characteristics that affect its value in the market, as shown in Table 5. High quality corresponds to potatoes of uniform size, with no visible defects, smooth skin and no damage, standing out for their high nutritional content and flavor, which makes them the most demanded. Medium quality includes potatoes with slight imperfections, such as small spots or irregularities, but which still maintain a good overall quality, being suitable for consumption and with a significant commercial value. Finally, low quality includes potatoes with visible damage, blemishes, deformities or inconsistent size, which reduces their quality and commercial value, and are mainly destined for markets with lower demand or for the production of processed products.

Table 5
Different potato qualities

Potato quality	Description
High	Uniform potato size, no visible defects, smooth and undamaged skin. High nutritional content and flavor.
Medium	Potato with slight imperfections (such as small spots or irregularities), but of good overall quality.
Low	Potatoes with visible damage, blemishes, deformities or inconsistent size. Lower quality and commercial value.

Note: The table describes the different potato qualities (High, Medium and Low).

The classification of potato qualities established in Table 5 is fundamental for the analysis of the economic loss caused by climate change in the Samacá Valley. The quality of the tuber not only determines its market price, but also indirectly reflects the impact of adverse climatic variables on the crop, such as frost, drought or atypical rainfall. These conditions directly affect physiological aspects of the plant, resulting in tubers with deformities, stains, fungal damage or other conditions that reduce their commercial value.

From this perspective, smaller scale producers (small and medium) showed a higher proportion of production classified as medium and low quality, which has significant implications for their net income. These results suggest that the effects of climate change do not impact all producers homogeneously, and that those with less access to mitigation technologies (such as irrigation systems, cover crops or agroecological practices) are more vulnerable to quality losses.

In addition, it became evident that economic losses are generated not only by the reduction in production volume, but also by the degradation of product quality. A ton of high quality potatoes can double or even triple its value compared to a ton of low quality potatoes. Therefore, the decrease in the proportion of high quality potatoes has a direct impact on the producer's profit margins, which reinforces the need to adopt specific climate change adaptation strategies to conserve or improve the quality of the tuber.

Finally, this analysis highlights that potato quality should be considered as a key indicator in economic impact studies associated with climate change. Beyond yield per hectare, it is necessary to incorporate the qualitative component of the product in order to have a more comprehensive view of the economic losses faced by farmers in vulnerable regions such as Samacá.

Results Third Phase: Correlation between Climate Variability and Profitability

Smallholder

Table 6 presents the main attributes of the small producer, including aspects related to land tenure, farm location, cultivated area, product marketing location, potato variety grown and land use.

Table 6
Attributes of the small producer

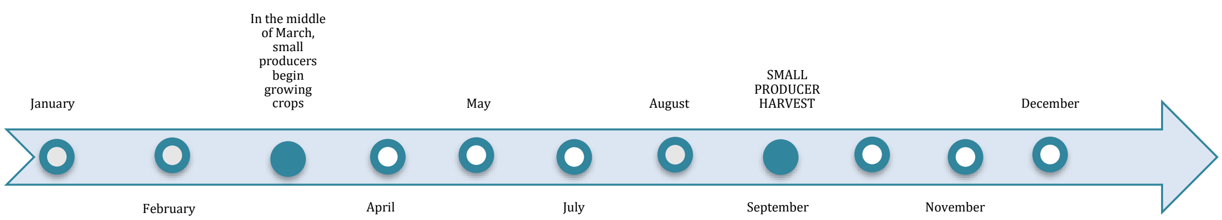
ITEM	CHARACTERISTICS
Land Tenure	Own
Farm Location	El Carmen
Cultivation Area	1 hectare
Place of sale of the Product	Same Property El Comerciante Arrives
Potato Variety	R-12
Land Use	Rotation Peas, Onions, Pastures
Village	Pataguy

Note: The table presents the characteristics taken into account in this study for the small producer.

Periodos de siembra y cosecha pequeño productor/a

Figure 8 shows the start and harvest times of small farmers considered in this study, which makes it possible to visualize the period of crop establishment and harvesting, facilitating the analysis of agricultural planning and management.

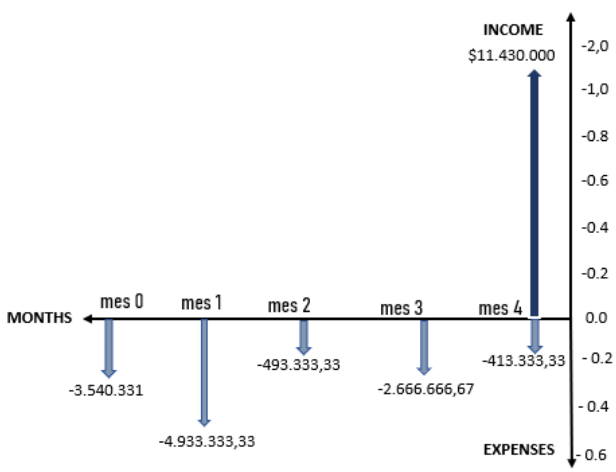
Figure 8
Planting and harvesting periods for small-scale potato growers



Note: The figure shows the planting and harvesting periods of small farmers in the Samacá-Boyacá valley.

Accordingly, harvesting takes place in the second half of the year, a period in which, due to the increase in tuber supply, prices tend to decrease significantly, which reduces income for this type of farmer, as shown in the following figure.

Figure 9
Economic diagram for the small producer of Samacá



Note: The economic diagram shows the income and expenses of the small producer.

Figure 9 shows the economic diagram with the small producer's income and expenses. Through a clear and detailed representation, the investment phases and income generation periods are identified, which facilitates the financial analysis and the evaluation of the profitability of agricultural activities.

The small potato producer has yields of 13.25 tons per hectare for the Diacol capiro variety, which is below the national average (Guerrero Guio, J, 2019). Added to the above, the Internal Rate of Return (IRR) which is below the selected Opportunity Rate (OER) and the negative Net Present Value (NPV), indicate the non-financial feasibility of the system for this small producer as evidenced in Table 8.

Financial evaluation makes it possible to determine the economic viability of a production system by analyzing income and expenses over time. In this context, cash flow is key to identify the profitability of the project and the producer's capacity to maintain its activity. Table 7 presents the cash flow as part of the economic sustainability analysis.

Table 7
Cash flow for the small producer 1 ha

ITEM	OPERATION	MONTH 0	MONTH 1	MONTH 2	MONTH 3	MONTH 4
INCOME	Sum					$ 11.430.000,00
EGRESS	Subtract	$ 3.540.331,40	$ 4.933.333,33	$ 493.333,33	$ 2.666.666,67	$ 413.333,33
NET INCOME	Difference	-$ 3.540.331,40	-$ 4.933.333,33	-$ 493.333,33	-$ 2.666.666,67	$ 11.016.666,67
CASH FLOW	Cash Flow	-$ 3.540.331,40	-$ 4.933.333,33	-$ 493.333,33	-$ 2.666.666,67	$ 11.016.666,67

Note: The table presents the Cash Flow Result of the small producer.

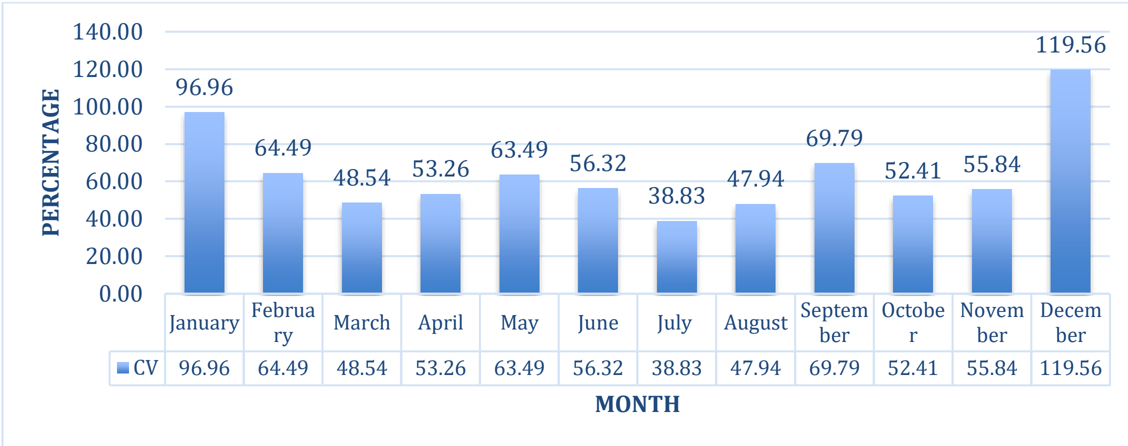
Table 8
Financial profitability indicators

9.2 NPV AND IRR		
NPV (0,8458%)	$ -$ 864.147,23	Not financially feasible
IRR	-2%	Not financially feasible
TIO	-0,8458%M	Opportunity interest rate (maximum CDT rate s 2022)

Note: The table presents the calculation of financial indicators such as NPV, IRR, OER.

The results show that small farmers face economic losses that compromise their quality of life and the sustainability of their systems. This vulnerability is accentuated by the high dependence on rainfall and the absence of irrigation systems. In the case analyzed, planting occurs in March, coinciding with the onset of the rains; however, climate variability limits planning. Despite adaptation efforts, the instability of rainfall generates uncertainty, especially during the tuberization stage (June-July), when the crop operates at the threshold of its water needs (400-700 mm) without sufficient supply (Guerrero Guio, 2019).

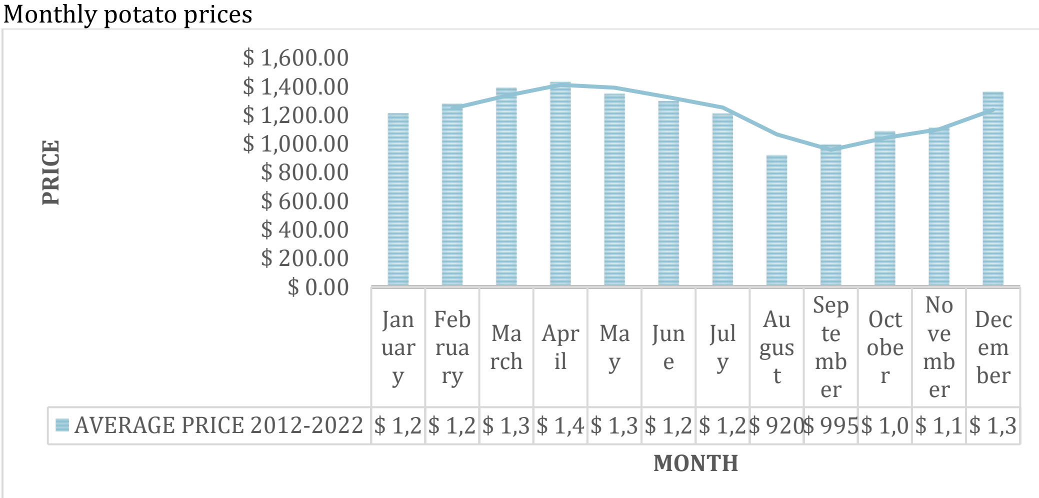
Figure 10
Average precipitation (2012-2022)



Note: The graph presents the historical average rainfall from January to December (2012-2022).

Similarly, as shown in Figure 11, an analysis was carried out using information from Corabastos (2022), which shows the average price of potatoes expressed in pesos per kilogram ($/kg), taking as a reference the period between 2012 and 2022. This analysis allows us to observe the evolution of prices in the wholesale market and their possible relationship with climatic and supply factors.

Figure 11
Monthly potato prices



Note: The figure illustrates the average potato price in $/K taking as reference the period 2012-2022. Modified from Corabastos (2022).

Guerrero Guio (2019) points out that potato, being a transitory and rainfed crop, is favored by increased rainfall at the beginning of the year, particularly in contexts associated with the La Niña phenomenon, which leads to an increase in planting and, consequently, a greater supply during the second half of the year. However, small producers face structural limitations, such as the lack of irrigation and drainage infrastructure and the limited use of certified seed, which increases their vulnerability to climate variability and reduces their competitiveness.

However, their resilience is based on the multifunctionality of the farm, self-consumption and sociocultural aspects that allow them to diversify their productive activities to mitigate economic losses. In this context, Table 9 presents the distribution of potato production by quality (one, two and three), allowing the economic contribution of each category to be measured and underlining the need to adopt agronomic and commercial practices that improve the quality of the final product.

Table 9
Production by quality for the small potato producer 1 ha

QUALITY	UNIT OF MEASURE	QUANTITY	UNIT VALUE		TOTAL VALUE	
QUALITY 1 (COARSE)	BULTO	213	$	50.000,00	$	10.650.000,00
QUALITY 2 (THIRD)	BULTO	26	$	20.000,00	$	520.000,00
QUALITY 3 (RICHE)	BULTO	26	$	10.000,00	$	260.000,00
TOTAL VALUE					**$**	**11.430.000,00**

Note: The table shows production by quality for small producers in the Samacá Valley.

Although a good volume of potatoes was produced, the financial analysis shows losses for the small producer. Sales income of $11,430,000 does not cover the costs of inputs, labor and other expenses, preventing profitability. This reflects the economic vulnerability caused by low prices, poor bargaining power and variable product quality.

Medium producer

Table 10 shows the key attributes of the medium producer, including land tenure, location, cultivated area, marketing, potato variety and land use.

Table 10
Attributes Medium Producer

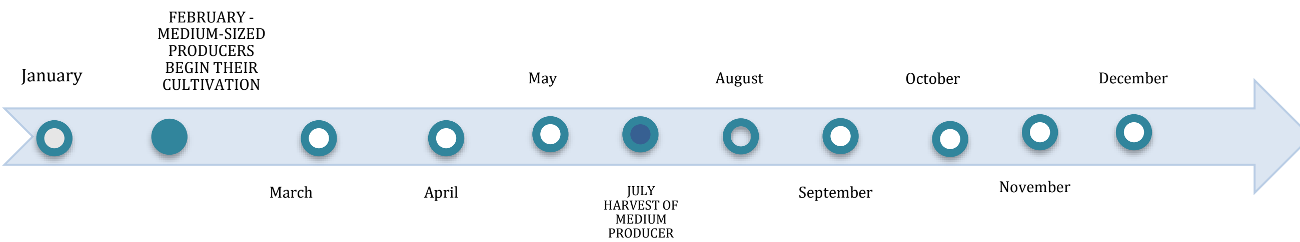
ITEM	CHARACTERISTICS
Land tenure	Own
Location of the farm	Los Sauces
Cultivation area	7 ha
Place of sale of the product	Bogotá - Directly Papas Margaritas
Potato variety	R-12
Land use	Onion, Corn, Barley Rotation
Village	Pataguy

Nota: La tabla presenta las Características tenidas en cuenta en este estudio para el mediano productor

Planting and harvesting periods for medium-scale farmers

Figure 12 shows the start and harvest times of the medium-sized producer considered in this study, which allows visualizing the crop establishment and harvesting period, facilitating the analysis of agricultural planning and management.

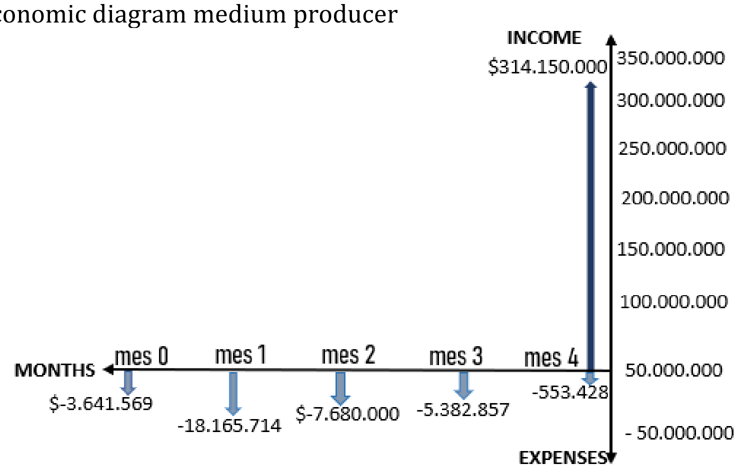
Figure 12
Economic diagram of the medium-sized producer



Note: The figure shows the estimated harvest of the medium-sized producer in the Samacá Valley.

Harvesting takes place in July, coinciding with the dry season, which facilitates harvesting by reducing the risk of rainfall. In addition, the lower agricultural supply in this period can increase prices, improving the farmer's profitability.

Figure 13
Economic diagram medium producer



Note: The figure represents the income and expenses of the medium-sized producer.

Table 11 and Figure 13 show that the medium producer in Samacá obtains a yield of 32.64 t/ha, 146.33% higher than the small producer. In addition, the high IRR and a NPV of $268,752,381.56 confirm the financial viability of the system.

Table 11
Cash Flow Medium Producer

ITEM	OPERATION	PERIOD ($ IN PESOS)				
		MOTH 0	MOTH 1	MOTH 2	MOTH 3	MOTH 4
INCOME	Sum					$ 314.150.000

EGRESS	Subtract	$ 3.641.569	$ 18.165.714	$ 7.680.000	$ 5.382.858	$ 553.429
NET INCOME	Difference	-$ 3.641.569	-$ 18.165.714	-$ 7.680.000	-$ 5.382.858	$ 313.596.571
CASH FLOW	CASH FLOW	-$ 3.641.569	-$ 18.165.714	-$ 7.680.000	-$ 5.382.857,7	$ 313.596.571

Note: Cash flow from medium producer analysis.

Table 12 presents the results of the financial profitability analysis of the medium-sized producer, including indicators such as Net Present Value (NPV), Internal Rate of Return (IRR) and Internal Opportunity Rate (IOR).

Table 12
Medium producer financial profitability indicator

NPV AND IRR		
NAV (0.84%)	$ 272.393.949	Financially Feasible
IRR	117%	Financially Feasible
TIO	0,8458%	0,8458% M Opportunity interest rate (maximum CDT rate s 2022)

Note: Results of financial indicators Medium producer, Samacá Valley.

Production by quality median producer

Table 13
Production by quality of medium producer 7 ha

PERFORMANCE	UNIT OF MEASURE	QUANTITY	MARKET PRICE PER PACKAGE	TOTAL VALUE
QUALITY 1 (COARSE)	BULTO	3300	$ 80.000,00	$ 264.000.000,00
QUALITY 2 (THIRD)	BULTO	920	$ 45.000,00	$ 41.400.000,00
QUALITY 3 (RICHE)	BULTO	350	$ 25.000,00	$ 8.750.000,00
	TOTAL VALUE			$ 314.150.000,00

Note: The table shows the results of the quantity of production by quality of the medium producer of the Samacá Valley.

The results indicate a favorable outlook for the medium-sized producer, who can plant early and harvest in June and July, when prices are more competitive. Unlike the small producer, the medium producer does not depend only on rainfall, since he uses irrigation, drainage and certified seed, which reduces risks due to climate variability and improves quality and yield (ASOCUCH, 2020).

The medium-sized grower markets directly with Margarita (PepsiCo), growing specific varieties (R-12) that meet rigorous standards for size, sugar content, and dry matter, guaranteeing an optimal product for potato chips. In addition, the company follows strict agronomic practices, controls pests and diseases, and carefully selects and stores them to ensure quality prior to processing.

Gran productor

Table 14 presents the main attributes of the large producer, including aspects related to land tenure, farm location, area under cultivation, product marketing location, potato variety grown and land use.

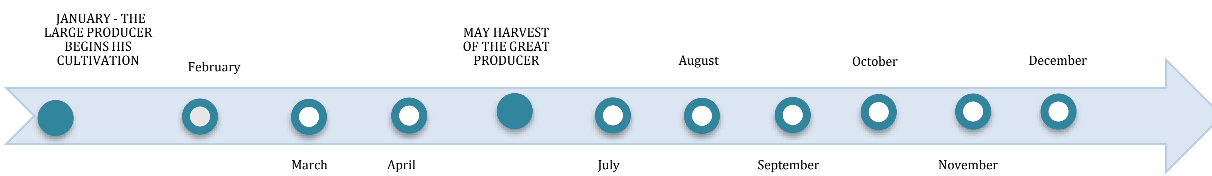
Table 14
Attributes Large Producer

ITEM	CHARACTERISTICS
Land tenure	Working 50/50 for 10 Ha
Location of the farm	San Cayetano Farm
Cultivation area	10 ha
Place of sale of the product	The trader arrives at the property
Potato variety	R-12
Land use	Rotation peas, onion, corn, onion
Owner's Name	Center

Note: The table shows the characteristics of the large producer.

Planting and harvesting period of the large potato producer in the Samacá Valley.

Figure 14
Planting and harvesting period for large potato producers in the Samacá valley.

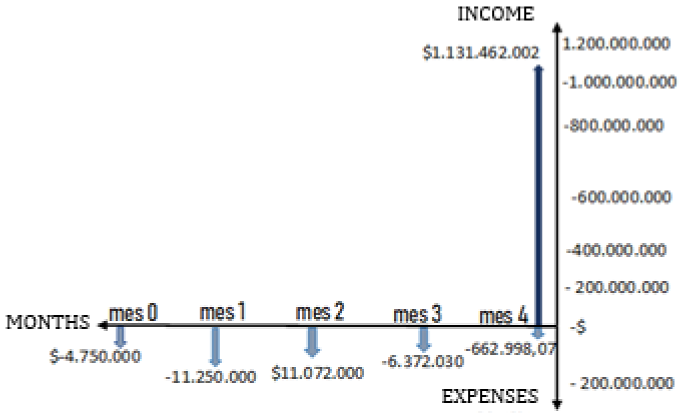


Note: The figure shows the harvest date of the large producer in the Samacá Valley.

Figure 14 shows that large producers plant earlier, optimizing land use and increasing production. In addition, by choosing land that is less prone to frost, using irrigation and new technologies, he is more competitive with other farmers.

Figure 15

Economic diagram of large producer valley Samacá- Boyacá



Note: The figure shows the behavior of the outflows and incomes of the large producer for the Samacá valley.

Figure 15 presents the economic diagram of the large producer, showing income, expenses, investment phases and income generation to facilitate financial analysis. Table 15 shows its cash flow and Table 16 the profitability indicators. With a yield of 53.36 tons/ha, its production exceeds the small producer by more than 300% and the medium producer by 63.48%. In addition, an IRR of 254 % and a NPV of more than $1,000,000,000 demonstrate the financial viability of the system.

Table 15
Cash flow large producer

ITEM	OPERATION	PERIOD				
		MONTH 0	MONTH 1	MONTH 2	MONTH 3	MONTH 4
REVENUE	SUM					$ 1.132.125.000,00
EXPENDITURE	SUBTRACT	$ 4.750.000,00	$ 11.250.000,00	$ 11.072.000,00	$ 6.372.030,00	$ 662.998,07
NET INCOME	DIFFERENCE	-$ 4.750.000,00	-$ 11.250.000,00	-$ 11.072.000,00	-$ 6.372.030,00	$ 1.131.462.001,93
CASH FLOW		-$ 4.750.000,00	-$ 11.250.000,00	-$11.072.000,00	-$ 6.372.030,00	$ 1.131.462.002,00

Note: The table shows the cash flow for large producers.

Table 16
Large producer profitability indicator

9.2 NPV AND IRR		
NAV (0.84%)	$ 1.065.722.565,57	Financially Feasible
IRR	232%	Financially Feasible
TIO	0,8458%	0,8458% M Opportunity interest rate (maximum rate CDT s 2022)

Note: Result of large producer financial indicator.

The Net Present Value (NPV), with a monthly discount rate of 0.8458 %, indicates a significant financial surplus after covering costs, evidencing the economic viability of the project and the efficiency in the use of technologies and good practices. The Internal Rate of Return (IRR) of 232% reflects a profitability much higher than that of small and medium producers, far exceeding the opportunity rate and demonstrating high profitability and capacity to absorb financial risks.

In summary, the financial analysis confirms that the project is economically viable, with a favorable return and benefits that exceed costs. The large producer, who uses certified seed and irrigation and drainage systems, can plant in lots that are less exposed to frost, optimizing yields. By planting between December and January, they can access better prices between April and May, reducing the uncertainty caused by climatic variability, especially in rainfall.

Table 17

Production by quality large producer 10 ha

PERFORMANCE	**UNIT OF MEASURE**	**QUANTITY**	**MARKET PRICE PER PACKAGE**		**TOTAL VALUE**	
QUALITY 1 (COARSE)	BULTO	8091	$	125.000,00	$	1.011.375.000,00
QUALITY 2 (THIRD)	BULTO	1277	$	75.000,00	$	95.775.000,00
QUALITY 3 (RICHE)	BULTO	555	$	45.000,00	$	24.975.000,00
CACHIRRE	BULTO	750	$	35.000,00	$	26.250.000,00
	TOTAL VALUE				**$**	**1.132.125.000,00**

Note: The table shows the quality production of the large producer in the Samacá Valley.

Table 17 shows the total yield obtained corresponds to $1,132,125,000, resulting from the marketing of different product qualities. The largest share of the total value comes from Quality 1 (Coarse), which represents an income of $1,011,375,000 thanks to the sale of 8,091 packages at a unit price of $125,000. To a lesser extent, Quality 2 (Tercera) generated $95,775,000 from the sale of 1,277 packages at $75,000 each, while Quality 3 (Riche) contributed $24,975,000 from the sale of 555 packages at $45,000 each.

Finally, the riche category generated $26,250,000 through the sale of 750 packages at a unit price of $35,000. From these data, it is evident that the highest profitability comes from Quality 1, due to its high volume and price, while the other qualities have a significantly lower contribution to the total value.

The results show that small producers operate in an agricultural system of high financial vulnerability, closely influenced by climatic conditions. The harvest takes place during the second half of the year, a period characterized by an increase in potato supply at the regional level, which generates a drop in prices and, consequently, a decrease in income. This phenomenon is reflected in a negative Net Present Value (NPV) of -$864,147.23 and an Internal Rate of Return (IRR) of -2%, both indicators that confirm the non-financial feasibility of the production model under current conditions. Despite reaching a total production of 13.25 tons per hectare, the income generated ($11,430,000) does not cover production costs, which highlights the low profitability and limited capital accumulation capacity of this type of farmer.

The cash flow analysis shows that income is concentrated in the last month of the production cycle, while expenses are distributed in a staggered manner from the beginning, forcing the producer to assume a prolonged financial risk with no guarantee of return. This situation is aggravated by the high dependence on rainfall, since the system lacks irrigation infrastructure, limiting its capacity to respond to climate variability. In particular, the tuberization stage of the crop (June-July) coincides with a critical period of water need, where rainfall is usually unstable and insufficient. Thus, the unpredictability of the weather not only compromises crop yields, but also the planning and sustainability of the production system.

Despite technical and economic limitations, small producers maintain their activity thanks to resilience strategies such as the multifunctional use of the land (rotation with peas, onions and pastures), direct marketing on the farm, self-consumption and the use of different product sizes. However, the distribution of production by quality shows that only a significant part of the crop (213 bulks) reaches high commercial standards, while medium and low grades represent marginal income. This reality reinforces the need to implement improved agronomic practices, strengthen associativity and facilitate access to differentiated markets that value quality and producer effort, with a view to improving profitability in an increasingly uncertain climatic context.

Results Fourth phase: Formulation of resilience strategies

The findings obtained in the three previous phases show that potato producers in Samacá face contrasting profitability scenarios, highly influenced by climate variability and productive capacities differentiated according to scale (small, medium and large). This fourth phase of the study is aimed at designing resilience strategies to mitigate the negative impacts of climate change on the potato crop, adapted to the particular conditions of each type of producer.

One of the key strategies proposed is the implementation of technified irrigation and water harvesting systems. Given that small and medium-sized producers are highly dependent on rainfall, the adoption of drip, sprinkler or micro-sprinkler irrigation technologies can significantly improve water use efficiency, guarantee water supply at critical crop stages such as tuberization, and reduce losses due to water deficit. In addition, the construction of water reservoirs and rainwater harvesting systems would make it possible to take better advantage of intense rainfall events, which currently occur irregularly.

Another key strategy is related to productive diversification and the use of certified seeds resistant to water and heat stress. Promoting complementary crops in rotation (such as legumes and cereals), as well as encouraging the use of improved potato varieties adapted to extreme climatic conditions, contributes to reducing economic and agronomic vulnerability. This action should be accompanied by technical assistance and farmer training programs that strengthen local capacities for agroecological management, pest and disease control, and direct or associative marketing, which can increase profitability.

Finally, it is proposed to consolidate a local climate governance model that links producers with municipal institutions, research centers and regional markets. This model should include climate early warning mechanisms, agricultural insurance against losses due to extreme events, and access to green financing. Strengthening peasant associations will also improve the bargaining power of small producers, facilitate access to inputs and machinery, and collectively manage the risks arising from climate change.

Discussion

The results of this study confirm that climate variability, especially rainfall, is a determining factor that directly affects potato crop profitability, especially among smallholders. As warned by studies such as those of Castillo and Domínguez (2021) and Guerrero Guio (2019), instability in rainfall regimes interferes with the planning of agricultural cycles and compromises the quality of the harvested tuber. In the case of the Samacá Valley, the data show that, although some months present adequate levels of precipitation, their high interannual dispersion prevents reliable programming, generating uncertainty and inefficiency in the use of soil and resources.

In economic terms, significant gaps were identified between the different types of producers. Small producers face a reality of financial non-feasibility, with a negative Net Present Value (NPV) and an Internal Rate of Return (IRR) lower than the opportunity cost, which shows their high vulnerability to climate change and their limited capacity to invest in adaptive technologies. In contrast, medium and large producers, with irrigation systems, access to certified seed and stable marketing channels, are better able to mitigate climate risks and optimize their profitability, validating what FAO (2021) stated about structural inequalities in the agricultural sector.

Product quality emerged as a key variable in determining economic losses. The degradation of potato to medium or low quality, largely attributed to climatic factors such as frost, excessive rainfall or water stress, significantly reduces its commercial value, limiting the producer's income.

This observation coincides with the contributions of UPRA (2016), who points out that oversupply and low quality increase the downward pressure on prices, especially during the second half of the year, when most of the harvest reaches the market. Thus, the focus of the analysis cannot be restricted only to yield per hectare, but must incorporate quality variables and market context (UPRA, 2016).

Finally, the formulation of resilience strategies represents an opportunity to strengthen the sustainability of the local agrifood system. The implementation of irrigation systems, adaptive agronomic practices, and the consolidation of associative and commercial processes not only mitigate the effects of climate change, but also open up new possibilities for a more equitable and efficient agriculture. However, their adoption requires political will, public investment and the active participation of producers. This study contributes to the understanding of the problem and offers valuable inputs for the construction of differentiated agroclimatic policies aimed at closing the gaps between producers and ensuring food security in rural contexts such as Samacá.

Conclusions

This study showed that climatic variability, especially in relation to rainfall, has a significant impact on potato production in the Samacá Valley, Boyacá. This instability in rainfall directly affects crop yields and limits agricultural planning, generating uncertainty during critical stages such as planting and tuberization. It was found that the impacts of climate change are not uniform for all producers, with small farmers being the most vulnerable due to the lack of irrigation infrastructure and scarce access to adaptive technologies.

A direct relationship was also identified between the size of the producer and the capacity to cope with the effects of climate change. While small producers presented negative financial indicators, such as an unfavorable Net Present Value (NPV) and an Internal Rate of Return (IRR) below the Opportunity Rate, medium and large producers demonstrated high economic viability thanks to the use of certified seed, irrigation systems, advanced planning and strong business linkages. These differences reflect structural inequalities in access to resources, technologies and markets.

Another relevant finding was the influence of product quality on profitability. Although acceptable yields can be obtained in terms of volume, the degradation in tuber quality, derived from climatic factors such as frost or heavy rains, significantly reduces the commercial value of the potato. This shows that the economic analysis should include not only the yield per hectare, but also the quality distribution and its impact on the producer's income.

In short, the research highlights the need to formulate and implement climate resilience strategies focused on local conditions. Measures such as the use of efficient irrigation technologies, water harvesting, productive diversification, technical training and the strengthening of associative and direct marketing processes are proposed. These strategies not only mitigate the risks arising from climate change, but also contribute to the economic and social sustainability of potato producers in

Samacá. It is essential that these actions be supported by public policies that promote a more equitable, resilient and climate-smart agriculture.

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