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Coffee, land, and regulation: climate resilience strategies for geographical indications

Café, terra e regulação: estratégias de resiliência climática para indicações geográficas

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ABSTRACT

This article examines the effects of climate change on the environmental and legal foundations of Geographical Indications (GIs), with particular emphasis on appellations of origin within the coffee sector. The study is grounded in the recognition that contemporary climate variability poses increasing challenges to the edaphoclimatic criteria that sustain the link between product and territory. Using the Mantiqueira de Minas Coffee as a case study, the analysis explores how variations in temperature and precipitation patterns influence production dynamics, sensory attributes, and the incidence of pests and diseases. The findings indicate that environmental transformations may simultaneously affect productive stability and the legal legitimacy of appellations of origin. The study highlights the importance of flexible regulatory mechanisms capable of incorporating scientific evidence and adaptive strategies. It concludes that the resilience of GIs will depend on the integration of climate adaptation, institutional governance, and the preservation of territorial identity.

Keywords: Geographical Indications; Coffee Production; Terroir; Climate Adaptation.

RESUMO

Este artigo examina os efeitos das mudanças climáticas sobre os fundamentos ambientais e jurídicos das Indicações Geográficas (IGs), com ênfase particular nas denominações de origem no setor cafeeiro. O estudo parte do reconhecimento de que a variabilidade climática contemporânea impõe desafios crescentes aos critérios edafoclimáticos que sustentam a relação entre produto e território. Utilizando o Café da Mantiqueira de Minas como estudo de

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caso, a análise explora como as variações nos padrões de temperatura e precipitação influenciam a dinâmica produtiva, os atributos sensoriais e a incidência de pragas e doenças. Os resultados indicam que as transformações ambientais podem afetar simultaneamente a estabilidade produtiva e a legitimidade jurídica das denominações de origem. O estudo destaca a importância de mecanismos regulatórios flexíveis, capazes de incorporar evidências científicas e estratégias adaptativas. Conclui-se que a resiliência das IGs dependerá da integração entre adaptação climática, governança institucional e preservação da identidade territorial.

Palavras-chave: Indicações Geográficas; Produção de café; Terroir; Adaptação climática.

INTRODUCTION

Geographical indications (GIs) constitute an important instrument for enhancing the value of local agricultural production by protecting products whose quality, reputation, or specific characteristics are essentially linked to their geographical origin (WIPO, 2021).

As established by the World Intellectual Property Organization (WIPO, 2021) and the Brazilian Industrial Property Law (Brazil, 1996), this territorial connection constitutes one of the fundamental pillars of the Designation of Origin, a category that requires the direct influence of both natural and human factors on the product's distinctive qualities.

However, extreme climate change has progressively altered key environmental variables including temperature, precipitation patterns, and humidity regimes that sustain the relationship between products and their territories of origin, a phenomenon widely recognized in both the scientific literature and institutional reports (IPCC, 2022).

In the coffee sector, these transformations are particularly significant because coffee cultivation is highly dependent on climatic conditions. According to CENICAFÉ (n.d.), climate plays a decisive role in the physiological development of coffee plantations, directly influencing productivity, pest incidence, and disease occurrence. Changes in temperature and rainfall patterns may disrupt the biological equilibrium of coffee production systems by favoring pathogens and insect pests while simultaneously affecting bean quality.

Beyond their agronomic consequences, environmental changes also generate significant socioeconomic impacts. Coffee production plays a strategic role in numerous producing regions, serving as an essential source of income, employment, and regional development (Costa, 2024). In this regard, the Federación Nacional de Cafeteros (2021) emphasizes that coffee production dynamics are closely associated with environmental conditions and the adaptive strategies adopted by producers, highlighting the interdependence between climatic factors and the economic sustainability of the sector.

In the specific case of Mantiqueira de Minas coffee, the Geographical Indication has become an important instrument for market differentiation, legal recognition, and territorial valorization (WIPO, 2021; Brazil, 1996). Nevertheless, climate change has increasingly modified the environmental conditions historically associated with the region's *terroir*, including temperature patterns, precipitation regimes, and altitudinal gradients (IPCC, 2022).

This scenario requires producers to adopt adaptive strategies, including varietal replacement, adjustments in agronomic management practices, and, in some cases, the relocation of production áreas a phenomenon widely observed in agricultural systems that depend on specific climatic conditions (CENICAFÉ, n.d.; Federación Nacional de Cafeteros, 2021).

This reality reveals a structural tension between preserving the territorial link required under the geographical indication regime and ensuring the productive viability of coffee cultivation in an increasingly changing environment. As argued by CENICAFÉ (n.d.), climatic variability can substantially alter the phytosanitary behavior of coffee plantations, directly affecting the dynamics of pests and diseases. Similarly, institutional studies on climate change have demonstrated that environmental changes directly affect agricultural systems whose productivity depends on specific climatic conditions (Ghini et al., 2007).

Within this context, the following research question emerges: How may climate change affect the environmental criteria underlying the Geographical Indication of Mantiqueira de Minas coffee, and what are the implications of these transformations for maintaining the relationship between the product and its territory, which is essential for the legal protection afforded by the Designation of Origin? Addressing this question is particularly important given the absence of clearly defined regulatory and technical instruments capable of reconciling productive adaptation to new climatic conditions with the preservation of the authenticity and territorial identity of protected products.

Accordingly, this study examines the impacts of climate change on the environmental criteria underlying the Geographical Indication of Mantiqueira de Minas coffee, considering that understanding this relationship is essential for advancing discussions on productive sustainability, the preservation of *terroir*, and the adequacy of the legal and regulatory mechanisms designed to protect geographical indications.

METHODOLOGY

This study adopts a qualitative and exploratory research approach, which is appropriate for analyzing complex phenomena involving legal, environmental, and productive dimensions. To achieve the proposed objectives, a comprehensive bibliographic review was initially conducted using both primary and secondary sources. Primary sources included legislation governing Geographical Indications (GIs), institutional regulations, regulatory documents, and technical instruments related to the Mantiqueira de Minas Designation of Origin. Secondary sources comprised scholarly books, peer-reviewed journal articles, and institutional publications addressing intellectual property, climate change, agriculture, and *terroir*, thereby providing the interdisciplinary theoretical framework supporting the present analysis.

In addition, documentary research was undertaken through the examination of the Regulations of Use and the Technical Specifications Manual governing the selected Geographical Indication, as well as technical reports and official statistical data produced by public institutions. This stage enabled the identification and assessment of the environmental, productive, and regulatory criteria underlying the recognition of the Designation of Origin, while also providing an empirical basis for discussing climate variability and its impacts on coffee production.

Furthermore, a case study strategy was employed, with the Mantiqueira de Minas Coffee Designation of Origin serving as the empirical object of investigation. This case was selected due to its economic, territorial, and environmental relevance, as well as the strong dependence of coffee production on local soil and climatic conditions. The case study approach enabled an in-depth analysis of the interactions among environmental change, production dynamics, and the legal protection afforded by Geographical Indications.

Finally, within this analytical framework, the study examined phytosanitary aspects of coffee cultivation, particularly diseases and pests associated with climatic conditions in Brazil, supported by empirical evidence derived from official data published by the Brazilian Institute of Geography and Statistics (IBGE, 2025) through the Systematic Survey of Agricultural Production, as well as technical analyses from the National Supply Company (Conab). The discussion also incorporated evidence from international experiences involving Geographical Indications and broadly recognized scientific foundations, including the concepts of climate variability and the assessment reports of the Intergovernmental Panel on Climate Change (IPCC). In addition, the environmental and geomorphological characteristics of the study area were considered through the analysis of paleoclimatic records and evidence associated with Quaternary geocryogenic processes, providing a historical perspective on the climatic sensitivity of the territory.

1-Mantiqueira de Minas Coffee as a Geographical Indication

The Mantiqueira de Minas region is one of Brazil's most renowned producers of specialty coffee and holds Geographical Indication (GI) registration No. G200704, granted by the Brazilian National Institute of Industrial Property (INPI). The registration, requested by the Mantiqueira Coffee Producers Association, covers the products *green coffee beans* and *roasted coffee beans or ground roasted coffee*. The geographical indication was initially recognized as an Indication of Source (*Indicação de Procedência*) on May 31, 2011, under the designation *Região da Serra da Mantiqueira de Minas Gerais*. Subsequently, on June 9, 2020, its legal status was upgraded to a Designation of Origin (*Denominação de Origem*). The protected geographical area comprises the twenty-five municipalities that form the Mantiqueira de Minas region on the Minas Gerais side of the Mantiqueira Mountain Range, as defined by IMA Ordinance No. 1600 of April 11, 2016.

The Mantiqueira de Minas Designation of Origin is associated with a distinctive combination of natural factors characteristic of the southern region of the state of Minas Gerais. According to the Regulations of Use and the Technical Specifications Manual, the region exhibits considerable altitudinal variation, ranging from 812 m to 2,252 m above sea level, with an average annual temperature of 17.9 °C and an average annual rainfall of approximately 1,665 mm. These climatic and geographical characteristics constitute specific edaphoclimatic conditions that directly influence the development and quality of the coffee produced within the protected geographical area (INPI, 2020).

Within this context, geographical factors particularly altitude, climate, and precipitation patterns play a decisive role in the uniqueness of Mantiqueira de Minas coffee. According to the Technical Specifications Manual, these natural characteristics, combined with the production practices adopted by local coffee growers, contribute to coffees exhibiting distinctive sensory attributes, including balanced acidity, aromatic complexity, and remarkable flavor profiles. Consequently, the reputation and identity of Mantiqueira de Minas

coffee are intrinsically linked to the region's environmental conditions, thereby justifying its recognition as a Geographical Indication under the Designation of Origin category (INPI, 2020).

As illustrated in Figure 1, the Mantiqueira de Minas Geographical Indication is located in southern Minas Gerais, on the Minas Gerais side of the Mantiqueira Mountain Range, an area of outstanding environmental importance due to the presence of strategic remnants of the Atlantic Forest and legally protected areas, including the Mantiqueira Mountain Range Environmental Protection Area (APA) (ICMBio, 2025).

The region is characterized by mountainous landscapes, remarkable ecological diversity, and unique edaphoclimatic conditions that support the production of high-altitude specialty coffees while contributing significantly to environmental conservation and regional socioeconomic development (EMBRAPA, 2022). Beyond its agricultural importance, the Mantiqueira region has become a destination for multiple forms of tourism, including ecotourism, rural tourism, adventure tourism, and gastronomic tourism, reinforcing the integration of natural heritage, cultural identity, and sustainable development (SEBRAE, 2023). In this context, the Geographical Indication extends far beyond its commercial function as a quality label for coffee, establishing itself as a strategic instrument for promoting a productive territory of exceptional environmental significance and growing tourism potential (MAPA, 2024).

Figure 1. Map of the Serra da Mantiqueira Environmental Protection Area (APA).

Source: Adapted by the authors from DISPersores – DISPersORES Group Blog, published on August 25, 2021.

The sensory characteristics of Mantiqueira de Minas coffee are widely recognized for their exceptional quality. The beverage is distinguished by its floral aroma, balanced citrus acidity, pronounced sweetness, and flavor notes reminiscent of yellow and red fruits. These sensory attributes are closely associated with the region's high-altitude environment (above 1,000

meters above sea level), mineral-rich soils, and the long-standing tradition of small-scale coffee producers who employ selective harvesting and carefully controlled post-harvest processing techniques (Ferreira & Silva, 2019).

The Geographical Indication not only enhances the commercial value of the coffee but also promotes sustainable territorial development. By protecting and recognizing the region's distinctive characteristics, the Designation of Origin strengthens local identity, encourages the adoption of more sustainable agricultural practices, and creates economic opportunities for rural communities. The active involvement of local cooperatives and producer associations, particularly the Mantiqueira de Minas Coffee Producers Association (APROCAM), has played a fundamental role in the certification process and in increasing the market value of the product (Barbosa & Silva, 2019).

A recent initiative aimed at the digitalization and traceability of Brazilian coffee Geographical Indications represents a significant advancement in promoting and enhancing the value of territorially recognized coffee production, including that of Mantiqueira de Minas. In July 2024, the Digital Platform for Coffee Geographical Indications, developed by the CNA Institute in partnership with the Brazilian Agency for Industrial Development (ABDI) and SEBRAE, issued its first traceability seals for export. This system enables coffee produced in the Mantiqueira de Minas region to be marketed in international destinations such as Australia and Uruguay using QR codes that certify the product's origin, quality, and compliance with the Technical Specifications Manual (CNA Brasil, 2024).

The region was initially recognized as an Indication of Source (*Indicação de Procedência*, IP) in 2011 and was subsequently granted Designation of Origin (DO) status by the Brazilian National Institute of Industrial Property (INPI) in 2020, as published in the *Revista da Propriedade Industrial* (RPI) No. 2579. This institutional transition is illustrated in Figure 2.

The conversion from Indication of Source to Designation of Origin represents a significant institutional milestone because the DO category requires clear evidence of a direct relationship between the product's distinctive characteristics and the natural and human factors of the geographical environment, including climate, soil, altitude, and specific production practices (INPI, 2020). This transition reinforces the intrinsic connection between the product and its geographical environment, a fundamental principle underlying the legal framework governing Geographical Indications.

Figure 2. Comparison between the Indication of Source (IP) and the Designation of Origin (DO) of Mantiqueira de Minas.

Item	Indication of Source (GI)	Requested change
Geographical name	Region of the Serra da Mantiqueira of Minas Gerais	Mantiqueira de Minas
GI representation		
Delimited geographical area	22 municipalities, namely: Baependi, Brasópolis, Cachoeira de Minas, Cambuquira, Campanha, Carmo de Minas, Caxambu, Conceição das Pedras, Conceição do Rio Verde, Cristina, Dom Viçoso, Heliodora, Jesuânia, Lambari, Natércia, Olimpio Noronha, Paraisópolis, Pedralva, Pouso Alto, Santa Rita do Sapucaí, São Lourenço and Soledade de Minas.	25 municipalities, namely: Baependi, Brasópolis, Cachoeira de Minas, Cambuquira, Campanha, Carmo de Minas, Caxambu, Conceição das Pedras, Conceição do Rio Verde, Cristina, Dom Viçoso, Heliodora, Jesuânia, Lambari, Natércia, Olimpio Noronha, Paraisópolis, Pedralva, Piranguinho, Pouso Alto, Santa Rita do Sapucaí, São Lourenço, São Gonçalo do Sapucaí, São Sebastião da Bela Vista and Soledade de Minas.
Book of Technical Specifications	Coffee	Green coffee beans and industrially roasted coffee beans, whole or ground
	85% of the crops planted between 1000 and 1200 meters	Crops planted above 1040 meters of altitude have special characteristics
Type	IP	DO

Source: INPI (2021).

RESULTS AND DISCUSSION

Climate change has emerged as one of the most significant drivers of transformation in contemporary agricultural systems, producing impacts that extend beyond the environmental dimension to encompass productive, economic, and institutional spheres.

As extensively documented by the Intergovernmental Panel on Climate Change (IPCC, 2022), rising global average temperatures, increasing irregularity in precipitation regimes, and the growing frequency of extreme weather events have altered ecosystem dynamics, biological cycles, and agricultural production systems worldwide. These transformations directly affect agricultural productivity, yield stability, and product quality, introducing new levels of uncertainty and vulnerability into farming systems.

Despite the substantial body of scientific evidence concerning the impacts of climate change on agriculture, the relationship between climate change and the legal-economic framework of Geographical Indications (GIs) remains a relatively underexplored field of research. Existing literature has focused predominantly on agronomic and environmental impacts, while comparatively limited attention has been devoted to examining how these transformations affect the territorial, qualitative, and regulatory foundations that underpin Designations of Origin.

Assad and Pinto (2011) argue that changes in temperature and precipitation patterns produce structural impacts on agricultural systems by affecting key variables such as production calendars, water availability, and the phytosanitary behavior of crops. In a similar perspective, Bunn et al. (2015) demonstrate that crops highly dependent on specific climatic conditions, such as *Coffea arabica*, exhibit considerable sensitivity to environmental change, with projections indicating a substantial reduction in environmentally suitable cultivation areas under persistent global warming scenarios.

These findings demonstrate that climate instability should not be understood merely as a source of production variability but rather as a factor capable of reshaping the geographical distribution of agricultural suitability, with direct implications for productivity, product quality, and the economic viability of rural activities.

Importantly, these impacts extend beyond the biophysical dimension. The literature indicates that climate change also has significant socioeconomic consequences, particularly in regions where family farming predominates. As highlighted in studies on family agriculture under climate change, smallholder farmers are generally more vulnerable to environmental instability because of technical, financial, and technological constraints. The increasing frequency of extreme climatic events tends to raise production costs, reduce economic margins, and intensify systemic risks, generating cumulative effects on household income, production security, and the long-term sustainability of agricultural systems (UFSM, 2023).

Within the coffee sector, scientific and technical studies indicate that changes in temperature and precipitation regimes directly influence the physiological development of coffee plants by affecting metabolic processes, phenological cycles, fruit maturation patterns, and, consequently, both crop productivity and bean quality (IPCC, 2021; Ghini et al., 2007).

Variations in temperature and rainfall distribution affect not only crop yields but also the formation of chemical compounds responsible for the sensory characteristics of coffee, which are essential for market differentiation and the territorial identity of products protected by Geographical Indications. Rising temperatures and increasingly irregular moisture regimes favor the proliferation of pathogens and insect pests, intensifying phytosanitary pressures, increasing production costs, and elevating risks to production stability. These processes ultimately influence product quality and alter the environmental parameters that support the relationship between the product and its geographical origin (Jornal USP, 2024).

According to Marcolan and Espindula (2015), the edaphoclimatic conditions of the Brazilian Amazon present additional challenges for coffee cultivation, particularly with respect to the occurrence and dynamics of crop diseases. Although these conditions differ substantially from those observed in the Mantiqueira de Minas Geographical Indication region, they illustrate the fundamental role of environmental variables in shaping the phytosanitary dynamics of coffee

production. The table presented below summarizes, in a didactic manner, the relationship between climatic variables and the phytosanitary dynamics of coffee plants.

Furthermore, the year 2026 has been characterized by atypical climatic conditions across several coffee-producing regions, intensifying discussions regarding the influence of environmental variables on crop health. As emphasized by Marcolan and Espindula (2015), the edaphoclimatic conditions of the Amazon region favor the proliferation and severity of fungal and bacterial diseases. Although these environmental conditions differ from those prevailing in the Mantiqueira de Minas Geographical Indication region where a temperate high-altitude climate predominates recent climatic anomalies, including irregular rainfall patterns, rising average temperatures, and an increased frequency of alternating wet and dry cycles, have been associated with intensified outbreaks of coffee leaf rust (*Hemileia vastatrix*) and other phytopathological diseases.

These observations reinforce the critical role of environmental factors in the phytosanitary dynamics of coffee cultivation, indicating that climatic variability, even under distinct geographical conditions, may converge toward similar consequences for plant health. The following table provides a synthesized overview of the relationship between climatic variables and the phytosanitary dynamics of coffee plants, illustrating how the climatic anomalies observed in 2026 fit within the broader framework of climate–pathogen–host interactions.

Table – Coffee Diseases and Pests Associated with Climatic Conditions in Brazil

Disease/Pest	Associated Climatic Conditions
Coffee berry borer (Hypothenemus hampei)	Favored by higher temperatures and prolonged dry periods, which accelerate the insect's life cycle.
Coffee leaf rust (Hemileia vastatrix)	Associated with high relative humidity and moderate to high temperatures (approximately 20–28 °C).
Pink disease (Corticium salmonicolor)	Favored by high humidity, frequent rainfall, and mild temperatures.
Brown eye spot / Cercospora leaf spot (Cercospora coffeicola)	Associated with water stress, high solar radiation, and nutrient deficiency.
Root rot	Associated with excessive soil moisture and poor drainage conditions.
Spider mites (e.g., red spider mite)	More prevalent under high temperatures and low relative humidity.
Coffee leaf miner (Leucoptera coffeella)	Favored by high temperatures and prolonged dry periods.

Source: Prepared by the authors based on EPAMIG (2023), Ghini et al. (2007), Marcolan and Espindula (2015), and IPCC (2021).

This relationship becomes even more significant when examined from the perspective of Geographical Indications. The identity and reputation of products protected under a Designation of Origin are intrinsically linked to the environmental conditions of their geographical territory.

Accordingly, as emphasized by the IPCC (2021), production systems that depend on specific edaphoclimatic conditions are particularly vulnerable to the impacts of climate change. In the coffee sector, growing evidence suggests that environmental changes may affect the sensory

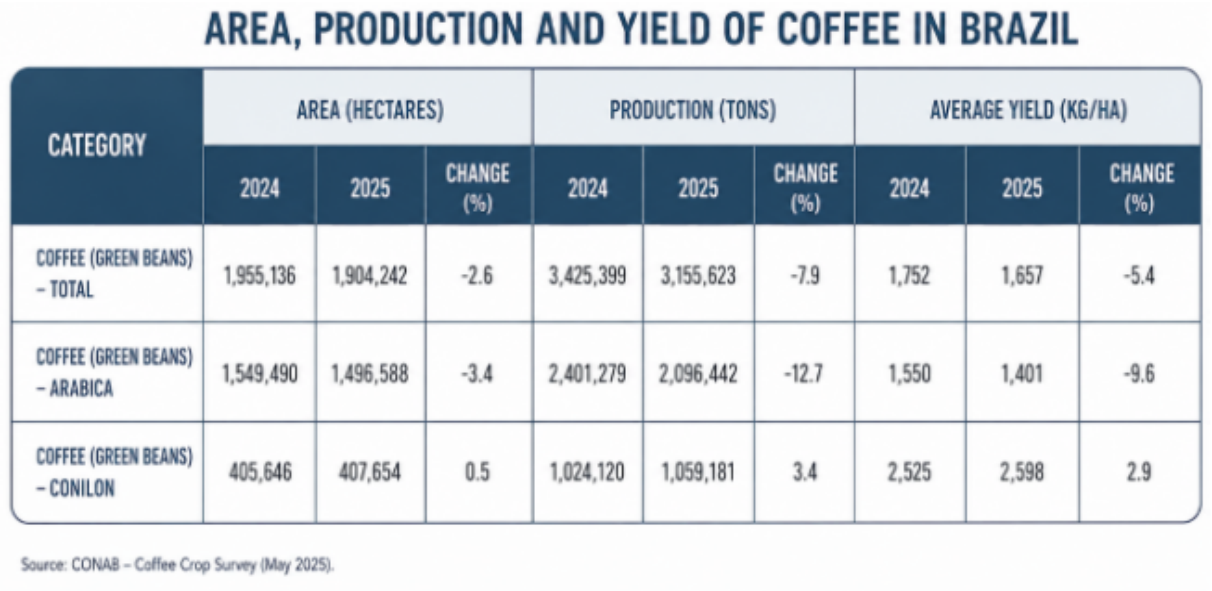
attributes historically associated with *terroir*, thereby influencing key elements that underpin territorial differentiation.

In the Mantiqueira de Minas region, this environmental sensitivity has deep historical roots. Geomorphological studies have identified evidence of Quaternary geocryogenic processes on the summits of the Mantiqueira Mountain Range, demonstrating that the region has experienced significant climatic fluctuations throughout geological time (Revista IG, n.d.; SBICAFE, n.d.). From a contemporary perspective, climatological analyses indicate a gradual increase in average temperatures across southern Minas Gerais over recent decades (Mendes & Souza, 2023), a trend that may progressively modify the environmental parameters supporting the region's distinctive coffee production.

At the empirical level, recent statistical evidence, summarized in Figure 3, provides strong support for the proposed analysis. According to the Systematic Survey of Agricultural Production conducted by the Brazilian Institute of Geography and Statistics (IBGE), reductions were observed in planted area, total production, and average coffee yield, with national coffee production declining by 7.9% between 2024 and 2025 (IBGE). Complementary analyses by the National Supply Company (Conab) indicate that fluctuations in production may coexist with complex market dynamics, including higher coffee prices and increased market volatility (Conab; IBGE).

In contrast, projections for 2026 indicate a scenario of recovery and expansion in Brazilian coffee production, representing a marked reversal from the decline observed between 2024 and 2025. According to the first coffee crop survey released by the National Supply Company (Conab), Brazil's coffee production for the 2026 harvest is estimated at approximately 66.2 million 60-kg bags of processed coffee, representing an increase of approximately 17.1% compared with the previous crop year and, if confirmed, establishing a new historical production record for the country.

Figure 3. Coffee planted area, production, and yield in Brazil.



Source: Projeto Colabora (2024); IBGE (2025). Artwork by Pablo Candeia.

International experiences corroborate the trend identified in the present study, demonstrating that the impacts of climate change on agricultural systems dependent upon

specific environmental conditions are simultaneously biophysical, economic, and territorial in nature. Research conducted in traditional coffee-producing regions, particularly in Colombia and Central America, indicates that increasing thermal instability and irregular precipitation patterns have led not only to reductions in productivity but also to substantial reorganization of production systems, including crop diversification, altitudinal shifts in cultivation, and modifications to agricultural management practices (Federación Nacional de Cafeteros, 2021; FAO, 2021).

Similarly, studies addressing production systems protected under Geographical Indications, such as the European wine industry and Mediterranean olive cultivation, demonstrate that global warming is challenging the traditional concept of *terroir* by altering fruit maturation regimes, quality parameters, and sensory profiles historically associated with specific geographical environments (IPCC, 2022; Pouzenc, 2020; FAO, 2021; Melançon, 2021).

Although these transformations have not, to date, resulted in the widespread legal invalidation of Designations of Origin, the literature indicates that the environmental identity underlying such protected designations is increasingly subject to processes of technical adaptation and regulatory reinterpretation. These findings reinforce the view that the territorial stability traditionally assumed within classical Geographical Indication protection systems may be structurally challenged under persistent climate change scenarios.

It is important to recognize that climate naturally exhibits interannual variability (IPCC, 2021). The principal challenge, therefore, lies not in ordinary climatic fluctuations but in persistent and structurally transformative climatic trends capable of shifting the environmental conditions historically associated with geographically defined production areas (Assad & Pinto, 2011; IPCC, 2022).

Within this context, the findings indicate that climate change creates a structural tension between territorial stability and productive adaptation. In the specific case of the Mantiqueira de Minas Designation of Origin, the analysis highlights the need for more comprehensive technical assessments regarding regional climate vulnerability.

Under the Brazilian legal framework, revisions to Geographical Indication registrations including those granted as Designations of Origin are governed by Industrial Property Law No. 9,279/1996, which establishes the rights and obligations relating to industrial property (Brazil, 1996), together with complementary administrative regulations issued by the Brazilian National Institute of Industrial Property (INPI), particularly the *Geographical Indications Manual* (INPI, 2023). The regulatory framework formally allows amendments to the Technical Specifications Manual, the document defining the product's distinguishing characteristics, geographical boundaries, and production requirements. Such revisions may include modifications to the delimited geographical area, technical product specifications, or production methods, provided they are supported by adequate technical justification.

However, revision of a Geographical Indication registration is neither automatic nor initiated by the registration authority itself. According to established administrative practice, amendments must be requested by the legally authorized entity typically the representative producers' association which is required to submit a formal application accompanied by technical and documentary evidence demonstrating that the essential link between the product and its geographical environment remains intact (INPI, 2023; INPI, 2020). INPI performs a legal and administrative review to verify procedural regularity and compliance with the

statutory requirements governing Geographical Indications, but it does not function as a permanent institution responsible for agronomic or climatic monitoring of protected territories.

Although the current regulatory framework provides procedural flexibility by allowing revisions to the Technical Specifications Manual, it does not establish structured guidelines for the systematic incorporation of dynamic climatic variables or prospective climate risk assessments. Administrative review remains primarily focused on demonstrating the relationship between the product and its geographical environment at the time of registration or upon submission of a proposed amendment, without explicitly requiring formal climate vulnerability assessments or evaluations of the impacts of long-term environmental change (Brazil, 1996; INPI, 2023).

Consequently, adaptation to climate-related transformations depends largely on the organizational capacity and technical expertise of local producers to identify significant changes in edaphoclimatic conditions and formally request administrative revisions. To date, no specific regulatory mechanism has been established to integrate continuous climate monitoring or environmental risk assessment as a structural component of the legal framework governing Designations of Origin. This regulatory gap highlights an area that remains insufficiently developed in light of the growing body of scientific evidence concerning climate variability and long-term climate change (IPCC, 2021; IPCC, 2022).

This regulatory gap becomes particularly significant in view of recent scientific and empirical evidence documenting the increasing occurrence of heat waves across Brazil's coffee-producing regions. In this context, the systematic incorporation of scientific evidence particularly data and climate assessments produced by institutions such as the Brazilian National Institute of Meteorology (INMET) could play a strategic role in supporting both adaptive production practices and future revisions of regulatory instruments, thereby enabling the Geographical Indication system to respond to environmental change while preserving its legal integrity and credibility.

CONCLUSION

This study demonstrated that persistent changes in critical environmental variables, particularly temperature and precipitation regimes, have the potential to simultaneously affect production dynamics, yield stability, and the sensory attributes of coffee. The scientific and technical evidence analyzed indicates that these transformations extend beyond ordinary agricultural variability, reflecting environmental processes capable of reshaping the edaphoclimatic conditions historically associated with *terroir*. In the case of the Mantiqueira de Minas Designation of Origin, such changes have direct implications for the protected territorial identity and for the elements that legally establish the relationship between the product and its geographical environment.

From a regulatory perspective, the findings indicate that the Brazilian Geographical Indication system provides institutional flexibility by allowing revisions to the Technical Specifications Manual, as established under the Industrial Property Law and complementary administrative regulations issued by the Brazilian National Institute of Industrial Property (INPI). However, this flexibility is predominantly reactive, as revisions depend upon formal requests submitted

by the holders of the Geographical Indication rather than being supported by permanent institutional mechanisms for environmental monitoring. Furthermore, the current regulatory framework remains largely based on descriptive and historical climatic parameters, without systematically incorporating prospective climate vulnerability assessments or specific guidelines for integrating dynamic environmental risks into the regulatory process.

At the same time, the results demonstrate that the impacts of climate change extend beyond the biophysical dimension, producing significant economic and productive consequences, including greater yield instability, increased production and management costs, and heightened systemic risks for coffee producers. These findings suggest that the long-term sustainability of Designations of Origin depends not only on maintaining their formal legal protection but also on the adaptive capacity of production territories to respond to persistent environmental change.

It can therefore be concluded that preserving the legitimacy, authenticity, and strategic function of Geographical Indications requires an analytical and institutional framework compatible with the dynamic nature of contemporary environmental systems. The incorporation of mechanisms integrating climate monitoring, territorial governance, and legal certainty constitutes a fundamental requirement for ensuring that the Designation of Origin regime continues to fulfill its role in protecting territorial identity under increasingly unstable climatic conditions.

FUTURE PERSPECTIVES

Within the global coffee sector, prospective analyses indicate that export dynamics are increasingly influenced by multiple structural factors. International demand remains the principal driver sustaining global coffee trade, although its future evolution will depend on the productive capacity of exporting countries, market fluctuations, and ongoing environmental transformations (FAO, 2021). Simultaneously, climate change, price volatility, and public policy have become increasingly important determinants of the stability of international coffee supply chains (IPCC, 2022).

Current projections suggest that global demand for coffees distinguished by superior quality attributes particularly those associated with geographical origin, sensory excellence, and distinctive territorial characteristics will remain strong. Nevertheless, the literature consistently indicates that climate variability is likely to intensify production instability, affecting both production volumes and quality standards (Bunn et al., 2015). In this context, climate should no longer be viewed solely as an agronomic variable but rather as a strategic determinant of the economic performance and competitiveness of the coffee sector.

From this perspective, the impacts of climate change extend beyond the biophysical sphere, generating significant economic and social consequences for coffee production. Previous studies indicate that production instability associated with temperature fluctuations and irregular precipitation patterns may increase production costs, reduce economic returns, and heighten the vulnerability of producers, particularly within agricultural systems dependent upon specific environmental conditions (Assad & Pinto, 2011; Silva, 2019).

Despite persistent environmental and market uncertainties, institutional analyses indicate that the international coffee market remains dynamic, although characterized by greater price volatility and increasing risks associated with climate variability (FAO, 2021; IPCC, 2022). This scenario reinforces the need for integrated approaches capable of linking climate,

agricultural production, market dynamics, and territorial governance an issue of particular relevance for products protected by Geographical Indications (Melançon, 2021).

The Mantiqueira de Minas Coffee Designation of Origin should evolve through the incorporation of dynamic environmental parameters and climate adaptation mechanisms into its Technical Specifications Manual. Periodic revisions based on continuous climate monitoring and robust scientific evidence are essential for preserving both the authenticity and the productive viability of the protected product (INPI, 2023; Melançon, 2021; IPCC, 2022). Furthermore, strengthening territorial governance will be crucial to enhancing the resilience of Geographical Indications under increasingly unstable climatic conditions by promoting greater coordination among producers, research institutions, and regulatory authorities to mitigate risks and preserve the essential relationship between product, territory, and reputation.

In this context, geographical research focusing on edaphoclimatic conditions assumes increasing importance as a scientific tool for understanding the territorial dynamics underlying Geographical Indications. The integrated analysis of topography, soil characteristics, altitude, temperature, precipitation, and atmospheric circulation provides a more comprehensive understanding of the interactions between geographical environments and the quality of protected products, particularly in Designations of Origin whose reputation is intrinsically linked to their environmental conditions.

Given the increasing frequency and intensity of extreme climatic events associated with phenomena such as El Niño and La Niña, whose effects on rainfall distribution, temperature patterns, and water availability are characterized by considerable variability and uncertainty, the integration of continuous geographical and climatic monitoring into the management of Geographical Indications has become indispensable. Such an approach strengthens the adaptive capacity of producing regions, provides scientific support for evidence-based revisions of the Technical Specifications Manual, and contributes to preserving the authenticity, typicity, and long-term sustainability of certified products in the face of the challenges imposed by climate change.

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