Aliaga Lordemann, Javier; Caballero Caballero, Adriana Beatriz

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SUSTAINABLE COST OF QUINOA PRODUCTION IN BOLIVIA: A FOODSCAPE APPROACH INTEGRATING THE RECOVERY OF AGRICULTURAL HERITAGE (COSPH)

By:

Javier Aliaga Lordemann
Adriana Beatriz Caballero Caballero

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Sustainable cost of quinoa production in Bolivia: A landscape approach integrating the recovery of agricultural heritage (COSPH)*

Javier Aliaga L.**
Adriana Caballero C.***

Abstract

This study analyzes the sustainable production cost, integrating the recovery of agricultural heritage (COSPH), for quinoa cultivation in the Bolivian High Plateau (Altiplano), seeking to answer: *How much does it cost to make quinoa production sustainable over time in Bolivia?* And*, How does this change when considering agricultural heritage conservation?* Specifically, the study evaluates how good agricultural practices (GAP) can mitigate climate change impacts and whether they are cost-effective, integrating the costs of agricultural heritage, which are particularly important for the quinoa real (royal quinoa) crop in Bolivia.

Methodologically, the research combines a microeconomic model of imperfect competition calibrated for quinoa — capturing price differentiation based on sustainability and heritage conservation — with the NL-CROP model (Non-Linear Crop Optimization Model), which simulates non-linear interactions between climate, soil, and farming practices.

Key findings show that GAP significantly reduce yield losses: under moderate climate conditions, productivity declines decrease from 5-7% to 1.8-2%, while in extreme events, losses drop from 16-30% to 2.5-6.2%, attributed to sustainable soil management. GAP remain viable in scenarios with up to two to three standard deviations, where profit margins cover additional costs. However, in severe crises (50% yield losses), negative margins (-4.7%) make agricultural insurance necessary (premiums of 7-10%), as well as tailored policies to balance climate adaptation with smallholders' economic viability.

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** Senior Research Associate at INESAD (jaliaga@inesad.edu.bo).
*** Junior researcher at INESAD (acaballero@inesad.edu.bo)

When heritage conservation costs are included (COSPH), results show improved resilience (yield loss reduced to 10.5% under a moderate climate scenario) at a moderate additional cost (5.75% compared to 5%), suggesting that preserving agroecological heritage contributes to long-term sustainability. These findings highlight the strategic role of combining sustainable agriculture with the protection of cultural landscapes in vulnerable highland farming in Bolivia.

JEL code: O13, Q12, Q15, Q18, Q54

Keywords: sustainable production costs, agricultural heritage, quinoa economics, agriculture and environment, small farmers, climate change adaptation.

Resumen

Este estudio analiza el Costo de Producción Sostenible integrando la conservación del Patrimonio Agrícola (*COSPH*) para el cultivo de quinua en el altiplano boliviano, tratando de responder ¿Cuánto cuesta hacer sostenible en el tiempo la producción de quinua en Bolivia? ¿cómo varía esto ante la inclusión de costos patrimoniales? Es decir, evaluar cómo las Buenas Prácticas Agrícolas (*BPA*) pueden mitigar los impactos del cambio climático y si éstas son costo-efectivas incluyendo un componente que refleja los costos patrimoniales, que son particularmente importantes para el caso de la Quinua Real.

Metodológicamente, el trabajo combina un modelo microeconómico de competencia imperfecta calibrado para la quinua — que permite capturar la diferenciación de precios por sostenibilidad y conservación del patrimonio agrícola— con el modelo NL-CROP (*Non-Linear Crop Optimization Model*); que simula interacciones no lineales entre clima, suelo y prácticas agrícolas.

Los resultados muestran que, las BPA reducen las pérdidas de rendimiento en quinua: en condiciones climáticas moderadas, la caída de la productividad baja del 5-7% al 1.,8-2% y en eventos extremos, del 16-30% al 2.5-6.2%, gracias al manejo sostenible de suelos. El COSP es viable en escenarios con desviaciones estándar de hasta 2-3, donde los márgenes cubren los costos adicionales. Sin embargo, en crisis severas (pérdidas del 50%), los márgenes negativos (-4.7%) exigen seguros agrícolas (primas del 7-10%) y políticas diferenciadas para equilibrar adaptación climática y viabilidad económica.

Al integrar los costos asociados a la conservación del patrimonio agrícola, se observa una mejora en la resiliencia ya que la pérdida en la producción se reduce a 10,5% en un escenario climático moderado, esto frente a un leve incremento en los costos, pasando de un 5% a un 5,75%. Esto sugiere que la preservación de los sistemas agroecológicos puede contribuir a una sostenibilidad de largo plazo. Los hallazgos resaltan el rol estratégico de combinar agricultura sostenible con la protección del patrimonio agrícola en los productores del altiplano boliviano.

Clasificación JEL: O13, Q12, Q15, Q18, Q54

Palabras Clave: Costos de producción sostenible, Economía de la Quinua, Patrimonio Agrícola, Agricultura y Medio Ambiente, Pequeños Productores, Adaptación al Cambio Climático.

1. Introduction

Climate change has significantly altered the parameters of global agriculture, with an increase in the frequency and intensity of extreme climate phenomena. Recent studies document that prolonged drought, atypical frost and water stress – aggravated by unsustainable agricultural practices – have reduced key crop yield in up to 20% (Lobell and Gourdji, 2012; Tao *et al*., 2018). In such scenarios, assessing the economic stability of agricultural producers demands not only analyzing traditional costs, but also internalizing those associated with sustainable production, by means of robust microeconomic approaches allowing to comprehend the mechanisms for building climate resilience and taking into consideration the conservation of agricultural heritage (COSPH), particularly in territories where traditional production systems represent a living biocultural endowment.

The cost of sustainable production (COSP) encompasses investments aimed at preserving natural resources and ensuring economic viability in the long-term. When the component of agricultural heritage is added (giving COSPH), consideration is given to the cultural and ecological value of traditional agroecological systems, also highlighting their capacity to confront the effects of climate change in the agricultural sector. In the case of quinoa in the Andean regions of Bolivia, such as Salinas de Garci Mendoza, Oruro, this implies practices such as the regeneration of soil, efficient irrigation systems, comprehensive pest management, and obtaining organic certifications. Although these actions increase initial costs by approximately 37.5%, they generate strategic benefits: mitigation of climate risks and enabling access premium markets. For example, the European Union pays up to 30% more for quinoa that is ecologically certified. Along the same lines, including landscape conservation costs follows international trends that value sustainability in agricultural production.

The relevance of the present study is supported by three pillars. Firstly, climate urgency, given that the study zone has shown a 15% reduction in precipitation in the 2000-2025 period (data from the National Meteorology Service of Bolivia), exacerbating soil degradation due to monoculture. Secondly is the gap in knowledge on cost-effective trajectories of sustainability in agriculture, as few studies quantify COSPH, and the topic has been much less studied for Andean crops, making the present approach a methodological innovation that is key for agriculture at the global level. Including agricultural heritage in the cost structure allows considering a strategic resource that contributes towards the sustainability of traditional productive landscapes. Within family agriculture, of which quinoa in the Bolivian Altiplano (High Plateau) is a part, knowledge of local wisdom helps guide decisions on the crop process, and native biodiversity sustains production. Finally, there is the socioeconomic impact (with quinoa sustaining over 70,000 families in Bolivia). Sustainability of the sector is fundamental to local and global food security.

Methodologically, the present work combines a microeconomic model of imperfect competition calibrated for quinoa – which allows capturing the differentiation of prices with sustainability and conservation of the agricultural heritage – with the NL-CROP model (Non-Linear Crop Optimization Model; Aliaga and Caballero, 2024), which simulates non-linear interactions between climate, soil and agricultural practices. The results demonstrate that good agricultural practices (GAP) reduce production contraction to only 2% under moderate climate stress (compared to 5-16.7% with no adaptation), but show a critical threshold: under extreme events, external mechanisms such as agricultural insurance are needed to ensure sustainability.

This research also contributes empirical evidence for designing public policies promoting COSPH as a strategic investment, combining temporary subsidies, risk transfer instruments and differentiated sales platforms. The case of Bolivian quinoa not only illustrates the present climate challenges, but also the opportunities for transforming Andean agriculture into a resilient and competitive system, while conserving its heritage essence.

The present article's structure is as follows: a literature review on COSPH and climate effects in Andean agriculture (Section 2), the methodology based on NL-CROP and microeconomic models (Section 3), results applied to the Bolivian case (Section 4), and conclusions with recommendations for public and private actors (Section 5).

2. Literature review

Modelling agricultural markets is an intricate process involving the integration of different economic, social and environmental variables. According to Abbott and McCalla (2002), understanding the interrelationship between agriculture and microeconomics is essential for developing models that reflect the agricultural sector's complexity (Yotopoulos *et al.*, 1976). These models allow analyzing how agricultural policies, changes in the economic environment, and market conditions affect production costs and sustainability in the long-term. Also, the effect of climate change and climate variability on agricultural production has been widely demonstrated in the literature. Given this, several forms of predicting the performance of crops have been explored, integrating the components of the agricultural system (Hernández *et al.,* 2009).

Along these lines, the following presents the literature review done for these two key pillars of the present document: on the one hand the costs of agricultural production and how the aspect of sustainability is included; and then going deeper into the effect of climate change on agricultural production and the models of crop yield simulation.

2.1. Production costs, sustainability and agricultural heritage

Production costs stand out as a key component in agricultural modelling. Schimmelpfennig (2018) argues that a precise estimate of these costs is essential for farmers and so that those responsible for policies make informed decisions. The integration of technologies can reduce costs and improve the sustainability of agricultural practices.

In the context of climate change, it is essential to incorporate climate variables allowing to evaluate their effects on production costs and agricultural resilience (Aliaga Lordemann and Salas, 2009). This approach must be complemented by models that consider access to loans (Feder *et al.*, 1990) and the efficient use of agricultural inputs (Daioglou *et al.*, 2016), factors that have a direct effect on production sustainability. Access to financing is crucial for farmers to be able to invest in technologies and practices that improve efficiency. This underlines the importance of integrating technology into the economic models for optimizing production. In the sphere of the international agricultural markets, Aliaga *et al.* (2021) and Boyd, *et al.* (2020) identify key factors that affect the prices of agricultural commodities. Understanding these factors is vital for modelling supply and demand in this market, which in turn affects the production costs and economic viability of farmers. The present analysis reveals how market dynamics can affect crop profitability and sustainability.

An important factor to highlight is that agricultural sustainability is not limited to production costs; it also involves the economic viability of agricultural practices. Brodt *et al.* (2011) underscore the importance of assessing economic viability of sustainable agricultural practices for promoting their adoption. For measuring agricultural sustainability, Hayati *et al.* (2011) propose indicators that assess the use of resources and costs, allowing to adjust policies and economic models according to sustainability goals (Bloemmen *et al.,* 2015; Hansen, 1996). Designing agricultural policies must also take into consideration their impact on sustainability. Klerkx and Leeuwis (2009) suggest that an adequate policy framework can promote sustainable practices and improve cost efficiency. Creating policies that provide an incentive for sustainability is essential to ensuring that farmers adopt practices that benefit both the economy and the environment. Along these lines, Oude Lansink (1997) shows how policy changes in Dutch agriculture affect production costs and sustainability.

The internalization of these costs associated with sustainability is essential for promoting agricultural practices that are both economically viable and environmentally responsible. Tilman *et al.* (2011) demonstrate that sustainability can be profitable, providing evidence on the environmental and economic benefits of sustainable practices. On their part, Wu *et al.* (2019) demonstrate that adequate infrastructure can facilitate more sustainable and efficient agricultural practices, while Zhang and Huang (2018) reaffirm the need for models that integrate the impacts of climate change on productivity from a microeconomic approach.

Additionally, it was considered pertinent to incorporate in the costs analysis an element associated with the cost of agricultural heritage. Regarding this, the concept of agricultural heritage has gained increasing attention in recent decades, fostered by the need to protect traditional agroecological systems that combine biodiversity, local knowledge and sustainable practices. One of the most influential frameworks is Globally Important Agricultural Heritage Systems (GIAHS) fostered by FAO (Food and Agriculture Organization), which recognizes and protects heritage systems as living examples of interaction between humans and nature (Koohafkan and Altieri, 2011). This perspective not only highlights the cultural and ecological value of traditional agricultural areas, but also their resilience capacity in the face of climate change and the globalization of agriculture.

A prominent line of research centers on agricultural biodiversity as an axis of heritage. Studies have demonstrated how traditional agricultural practices conserve critical genetic diversity, particularly in native crops and local varieties, which constitute a strategic resource for global food security (Brush, 2004; Zimmerer, 2013). This biodiversity is not limited to cultivated species, but also includes its associated flora and fauna, soil microorganisms and the water systems managed by means of ancestral technology. The interactions between these elements make possible complex biocultural landscapes that support both production and the cultural identity of communities.

Another key current deals with the role of local or indigenous knowledge and practices in the makeup of these productive landscapes. Ethnoecological studies have documented how traditional knowledge guides decisions on crop rotation, water management, seed selection, and soil conservation, contributing towards the sustainability of agroecological systems (Altieri and Toledo, 2011). This knowledge is at risk due to loss of intergenerational transmission, rural migration and agricultural policies aimed at monoculture. However, traditional knowledge has begun to be revalued in the context of agroecology and food security.

Traditional agricultural landscapes are increasingly being seen as productive and cultural landscapes, a notion that links agricultural heritage with territorial planning and sustainable tourism. Authors such as Antrop (2005) and Plieninger *et al*. (2015) have argued that these landscapes constitute a synthesis between productivity, conservation and quality of life, challenging the dichotomy between nature and culture. Besides, the notion of agricultural cultural landscape allows integrating multiple scales of analysis, from individual crop plots to regional territory, and provide interdisciplinary approaches that combine ecology, history, rural economics, and landscape design.

There has also been a proliferation in recent decades of case studies on specific territories that have been recognized as agricultural heritage, such as the platforms of Valle Sagrado de los Incas in Peru, the terraced rice fields of Ifugao in the Philippines, or the agroforestry systems of the Kayapó in Brazil. This research shows how traditional agricultural practices of land management coexist, sometimes under tension, with the dynamics of modernization, urbanization and changes in land use

(Barrera-Bassols and Zinck, 2003). In many cases, recognition of land as agricultural heritage has contributed towards revitalizing local economies through rural tourism and the sale of products with added value.

Finally, an emerging field links agricultural heritage with the approaches of environmental justice and the rights of native peoples. Recent research highlights the importance of ensuring the free, prior and informed consent of communities in the processes of heritage recognition, and of strengthening their governance capacity over territorial resources (Díaz-Reviriego *et al.*, 2016). Agricultural heritage cannot be understood simply as an inheritance from the past, but must be taken rather as a living process of cocreation between nature and culture, oriented towards the future.

2.2. The effects of climate change and agricultural yield

Climate change represents one of the main challenges for food security and agricultural sustainability. Forecasts indicate an increase in at least 3 °C in global temperature and a reduction of between 10 and 30% in precipitation by 2100, which will intensify the frequency of drought and the loss of soil humidity (Boulanger *et al*., 2014; Valdivia *et al*., 2013). Latin America is particularly vulnerable to these impacts, and this compromises its economic development and deepens rural poverty (Field *et al.*, 2014; Magrin *et al*., 2014).

In Bolivia, the Altiplano region has extreme conditions: low levels of precipitation, temperature that ranges between -11 °C and 30 °C, frequent frost (up to 200 days/year) and highly saline soil (Jacobsen, 2011). This variability in climate, which is increasingly intense, has heightened the vulnerability of quinoa, one of the Altiplano's most sensitive crops (McDowell and Hess, 2012; Twomlow *et al*., 2008).

In the face of this context, crop yield simulation models become an essential tool for assessing the impact of different shocks (i.e., in climate, technology and economics) or the implementation of certain strategies or potential new practices (Hernández *et al.,* 2009). Models such as APSIM (Agricultural Production Systems Simulator) and DSSAT (Decision Support System for Agrotechnology Transfer) integrate climate, edaphic and agricultural engineering variables for precisely simulating crop yield (Jones *et al*., 2003; Holzworth *et al*., 2014; Hoogenboom *et al*., 2010). Others, such as CropSyst, have allowed analyzing agricultural engineering practices in the face of climate change (Stöckle *et al.*, 2003), while Boote *et al*. (1983) expanded the analysis by integrating biological factors such as pests. Others, such as CropSyst, have contributed towards evaluating the impact of agricultural engineering practices and climate phenomena in yield (Stöckle *et al.*, 2003), while Boote *et al*. (1983) introduced a new dimension by integrating pest models, which expanded the capacity of simulators for estimating losses due to biological factors. Collaborative projects such as AgMIP have fostered protocols for comparing and improving models at the global level (Rosenzweig *et al*., 2013), and studies such as that of Asseng *et al.* (2013) underscore the need for greater precision in simulations, such as those for wheat.

Among more recent approaches, the one of Antle *et al.* (2014) stands out; it incorporates economic, social and ecological dimensions in the models, and Ewert *et al*. (2011) propose multi-spatial scales for understanding local and global impacts. Authors such as Rötter *et al.* (2011) and Rivington and Koo (2010) call for redesigning the present models integrating more complex interactions and climate variables, while Fodor *et al.* (2017) emphasize the need for jointly evaluating thermal and water stress. The SIRIUS model, for example, has demonstrated its usefulness in wheat yield simulation under variable conditions (Semenov and Stratonovitch, 2015). And studies with APSIM have shown the impact of different management practices in agricultural productivity and their potential for guiding adaptation strategies (Shibu *et al*., 2010).

Together, these models constitute fundamental tools for understanding the complex relationships between climate, agricultural engineering decisions and agricultural production. The evolution of the models has strengthened the analytical capacity to formulate agricultural policies that are more sustainable and resilient.

3. Methodological framework

To adequately evaluate the economic stability of small agricultural producers, it is necessary to go beyond the traditional analysis of production costs. Conventional approaches generally focus on direct and variable costs, which are key to understanding short-term profitability but insufficient to capture the broader sustainability challenges faced by farmers. In a context where climate change is intensifying risks and threatening crop yields, it becomes essential to incorporate a more comprehensive framework that includes both traditional and sustainable production costs.

The proposed methodological approach therefore integrates a second block of costs: the sustainable production cost (COSP), which accounts for investments in soil recovery, organic certification, and adaptive practices that strengthen resilience to climate shocks. Within this block, a novel contribution of this study is the explicit consideration of agricultural heritage conservation, linked to the global trend toward valuing productive landscapes. Institutions such as the Food Agriculture Organization of the United Nations (FAO), through its Globally Important Agricultural Heritage Systems (GIAHS), and United Nations, Educational, Scientific and Cultural Organization (UNESCO), through its initiatives on cultural landscapes and foodscapes, highlight these systems as strategic because they: (i) preserve native biodiversity, soil and water management practices; (ii) sustain cultural identity and community governance; and (iii) build adaptive capacity to climate stressors such as droughts, frost, and salinity. Traditional agroecological systems in the Andes are more than production models, they are living biocultural systems shaped by generations of indigenous knowledge and adaptation.

Building on this dual-cost framework, the research design combines two complementary tools. First, a microeconomic model with product differentiation is calibrated to the Bolivian quinoa market, allowing for the evaluation of price dynamics when sustainability and heritage conservation are valued by consumers. Second, the NL-CROP model is applied to simulate the impact of climate variability on quinoa yields. The integration of these two components leads to the development of the COSPH model, which quantifies sustainable production costs while explicitly valuing the conservation of agricultural heritage as a cornerstone of resilience in Andean agriculture.

Following, we develop a sustainable production model that analyzes the organic quinoa market. Considered are characteristics of imperfect competition, product differentiation, climate change impact, and costs associated with sustainability. The model includes a detailed microeconomic structure that allows evaluating the interaction between costs, profit margins and external restrictions. Below is a presentation of the model's characteristics and assumptions.

A first element to highlight is that the assumption is made of imperfect competition with product differentiation. It is assumed that the producers have a certain level of market power due to product differentiation, particularly farmers of organic quinoa. Imperfect competition occurs when products are not homogenous and consumers value specific characteristics such as sustainability or quality, which in the present case is associated with organic production. Besides, the producers are *cuasi* price takers in the international market, given that they face international prices set by global forces and have no considerable influence over them. This situation is typical in international agricultural markets where prices are established by global supply and demand. The model also considers the limitations of production due to environmental and technological conditions. Soil degradation and climate change restrict total production, and consideration must also be given to the fact that in general the producers have limited access to advanced technology. Thus, these three elements are introduced as restrictions in the model.

Besides, explicit sustainability costs are assumed, as well as decreasing returns to scale. Organic production includes additional costs related to certifications, sustainable practices and environmental management. In this exercise we include as sustainability costs those related to certification and the recovery of soil fertility, the latter allowing to have soil that is more resistant to the effects of climate change, and constitutes an *ex ante* mechanism of adaptation to climate change. These sustainability costs directly affect cost structures and thus the prices of the differentiated products. On its part, the production function employed presents diminishing returns due to limitations in the efficient use of inputs such as labor and capital. This characteristic is relevant, as it reflects actual limitations in agricultural yield under adverse conditions.

Additionally, included among the costs of environmental sustainability is the cost of agricultural heritage related to the conservation of productive Andean landscapes. These environmental costs include costs for the conservation (recovery) of natural green infrastructure (live fences), and biological conservation (use of native seeds). By integrating these costs, the production of quinoa in the Bolivian Altiplano is valued and the conservation and sustainability of traditional agroecological systems is fostered.

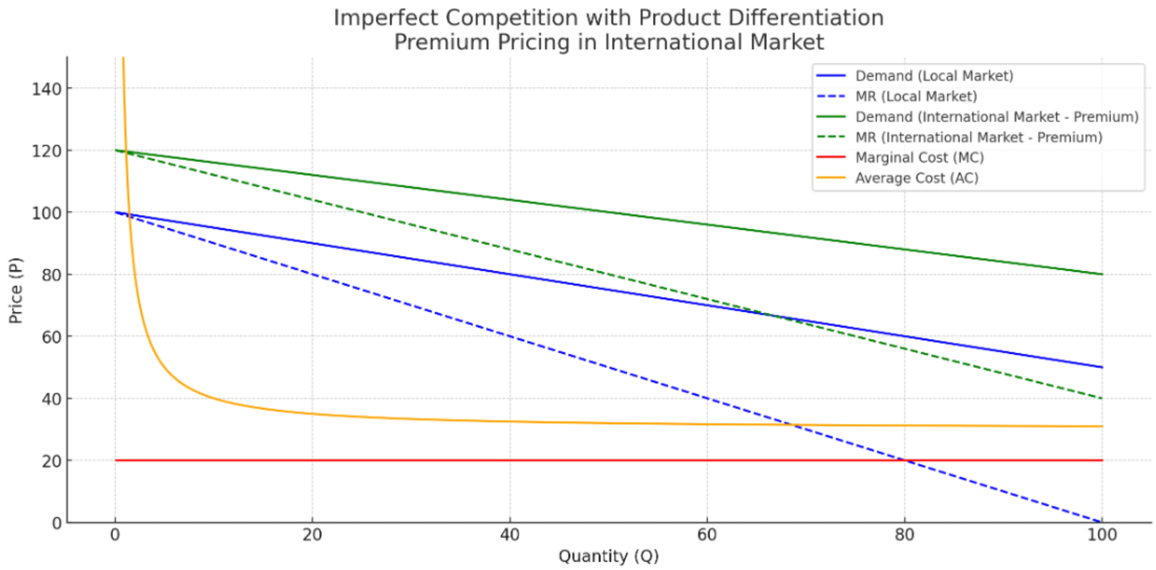
Finally, consideration is given to the impact of climate change in agricultural production: its components both of variability and of change. Variations in temperature, precipitation and extreme events directly affect the crop's performance. For dealing with this aspect, the NL-CROP model is employed, which allows incorporating the results of agroclimatic shocks in our model of imperfect competition.

3.1. Rationale of the model

Agricultural markets often display segmentation arising from differences in product quality, consumer preferences, and access to international versus domestic buyers. Two standard approaches to represent this heterogeneity are: (i) market segmentation models, which treat each consumer group as isolated, and (ii) product differentiation models, which emphasize a continuous spectrum of quality and willingness to pay. In the present study, the latter perspective is adopted. Specifically, the quinoa market is modeled as one of imperfect competition with product differentiation, where organic and sustainably produced quinoa — particularly when linked to agricultural heritage — commands premium pricing in international markets, while local markets exhibit more constrained demand.

This rationale can be illustrated with a stylized diagram of cost and revenue functions (Figure 1). The average cost (AC - orange line) curve follows the traditional U-shape, reflecting diseconomies of scale at levels of output required for this market size. The marginal cost (MC - red line), assumed constant, is represented by a flat line. On the demand side, two curves are considered: international demand (green) with its respective marginal revenue (MR-int), flatter and positioned higher, reflecting premium prices for quality and heritage attributes; and local demand (blue) with its marginal revenue (MR-loc), steeper and positioned lower, indicating limited willingness to pay and smaller market size.

Figure 1: Market structure



The interpretation of this diagram is central to the methodological approach. Firms able to access international markets can operate at a larger scale, setting prices above AC, and thereby obtaining positive economic profits. These profits are sustained by consumer willingness to pay for certified sustainability and heritage-linked products. In contrast, firms serving primarily the local market face restricted demand, such that equilibrium output is closer to the minimum efficient scale, and prices may barely cover average costs. In these cases, profitability is fragile, and resilience depends on adopting practices that reduce costs or on policies that support minimum prices. This duality illustrates why valuing agricultural heritage and sustainability is not merely symbolic: it has direct implications for the economic viability of smallholders under climate risk.

By framing quinoa production under imperfect competition with differentiated products, the model captures how premium segments in international markets coexist with more vulnerable domestic demand. This rationale provides the foundation for the subsequent specification of demand, supply, cost structures, and climate constraints in the COSPH framework.

3.2. Structure of the model

The model's structure include both supply and demand, cost structure, including the agricultural heritage, the impact of climate change, the determination of prices, and the equilibria of both the local and international markets.

Demand

Quinoa market demand has a local component (equation 1) and an international component (equation 2). Local demand (Q_D^L) is a function that depends on the price of the product in the local market (P^L) and on the level of organic quantity (Q_O) as shown in the following equation:

$$Q_D^L = a - bP^L + eQ_0 \qquad (1)$$

where Q_D^L represents the quantity demanded in the local market, P^L is the local price of the product and Q_O is the proportion of quinoa production that is organic ($0 \leq Q_O \leq 1$). Parameter a indicates the initial level of demand which is independent of price, and parameters b and e are elasticities of price and quality, respectively. Price elasticity shows the sensitivity of response of the quantity demanded given changes in the local price, while quality elasticity reflects consumer preference for organic products.

As to international demand, the producers are *cuasi* price takers, with quantity demanded (Q_D^I) determined by external factors. These exogenous factors are: the international price (P_I) above which domestic producers have no power of decision, and the level of exports (k) which depends on specific factors of the economies of the rest of the world. This is shown in equation 2 as follows:

$$Q_D^I = P_I \cdot k \qquad (2)$$

Supply

Similarly, the supply segment has two components: on the one hand, the total quantity offered in the market (Q_S) (equation 3), and on the other, the individual quantity produced (Q) (equation 4).

The total quantity offered (Q_S) is influenced by the product's quality, the profit margin and environmental and technological restrictions, as observed in equation 3, as follows:

$$Q_S = h \cdot T \cdot (1 - Sd) \cdot (1 - Cc) \cdot (1 + Markup) - d \qquad (3)$$

where Q_S is the total quantity offered, which depends on T, that represents the level of technology available in proportion h (technological scale parameter). Furthermore, $Sd \; and \; Cc$ are soil degradation and climate change impact indexes which are introduced with an inverse relationship with respect to the quantity offered. Contrarily, the profit margin ($Markup$) has a positive relationship and a fixed component and another one that depends on the proportion of organic production ($Markup = m_0 + m_1 Q_O$). Finally, parameter d represents the structural costs that negatively affect supply.

On its part, equation 4 reflects the function for the quantity produced (Q) which depends on the productive inputs – labor and capital – in addition to external factors:

$$Q = A \cdot L^{\alpha} \cdot K^{\beta} \cdot (1 - Sd) \cdot (1 - Cc) \cdot Q_O \qquad (4)$$

where Q is the quantity produced by the producer, A is the initial efficiency factor, $L \; and \; K$ are the factors of production of labor and capital, with their respective elasticities α and β, the values of which are in a range of more than 0 and less than 1. As is the case for the total quantity offered, restrictions are included for soil degradation (Sd) and climate conditions (Cc), which limit production. Finally, with a greater proportion of organic quinoa (Q_O), the quantity produced increases.

Impact of climate change

The effect of the climate crisis is introduced as a limiting factor that negatively affects quinoa supply, both at the macro level in the total quantity offered (equation 3), and at the individual level with the quantity produced (equation 4). This impact is shown as a function of environmental variables, as represented in equation 5:

$$Cc = \gamma_1 T_e + \gamma_2 H_e + \gamma_3 E + \varepsilon \qquad (5)$$

where the environment factors are summarized in three components: T_e, which represents thermal stress, H_e , which indicates the presence of water stress, and E , which groups together the frequency of extreme events. Parameters $\gamma_1, \gamma_2, \gamma_3$ are sensitivity of production for each variable. Finally, an error term ε is included for unforeseen variations.

For introducing specific scenarios of agroclimatic stressors, the instrument used is a satellite model of optimization called NL-CROP (Non-Linear Crop Optimization Model), which allows simulating yield under different climate scenarios. The non-linear characteristic of this model is based on a Gompertz-type equation, allowing to integrate in the analysis multiple local equations forming a function of "S pieces".

The simulation structure of the model employs multiple iterative methods for establishing the parameters that are most adequate for the data corresponding to the study. To solve the model, initially the potential yield of the crop is determined in the absence of agroclimatic stressors. Then equations of the climate conditions that act as restrictions to the potential yield specifically affecting two parameters are included: i) the point of inflexion within the phenological cycle; that is, at the point of transition between a phase of slow growth to one of faster growth; and ii) the parameter that directly influences the rate of growth as such. Once the restrictions are included, the NL-CROP model once again performs the simulations, giving as a result the actual yield under the specified climate conditions[1]. These restrictions represent thermal stress, water stress and other climate factors which in this model of sustainable production are found in variables T_e, P_r, E, and their respective impact is captured in parameters $\gamma_1, \gamma_2, \gamma_3$ respectively.

Costs

The total costs function (C) is a classic function that contains a fixed costs part (F) and a variable costs part (VC). Furthermore, explicitly introduced in the model are the sustainable costs (S), which depend both on the quantity produced and the proportion that is organic. Equation 6 shows the cost structure to consider:

$$C = f_0 + vQ + s_0 + s_1 Q_0 \cdot Q \qquad (6)$$

where f_0 represents fixed costs (such as infrastructure and machinery), and v is the variable cost per unit produced. The sustainable costs are also divided into a fixed part, s_0 (including elements such as certifications and audits) and a variable part, s_1 per unit produced, which is associated with the proportion of organic production.

Price and margin

In this market, the local price is not equal to the marginal cost as in the case of perfect competition; this is because of the product differentiation between conventional quinoa and organic quinoa, which allows the producers to have a profit margin. This relationship is observed in equation 7, where the local price (P^L) includes the marginal cost (MC) and the margin applied:

$$P^L = MC \cdot (1 + m_0 + m_1 Q_O) \qquad (7)$$

where the marginal cost is obtained from the derivation of the total cost (equation 6) in relation to the quantity produced (Q):

$$MC = v + s_1 Q_O \qquad (8)$$

Finally, the determination of the local price, which includes the profit margin given the differentiation of the product with organic quinoa is reflected in the producers' income. Specifically, total income

[1] The main equations of the NL-CROP model are found in the Annex.

(R) is the sum of income in the local and international markets, which is shown in equation 9 which follows:

$$R = [(v + s_1 Q_O) \cdot (1 + m_0 + m_1 Q_O)] \cdot Q_D^L + P_I \cdot Q_D^I \qquad (9)$$

Equilibrium in the local market

Having specified the equations for each of the aspects included in the model, it is possible to determine equilibrium in the local market. This equilibrium occurs when the quantity demanded locally (Q_D^L) is equal to the quantity offered locally (Q_S^L), as is observed in equation 10:

$$Q_D^L = Q_S^L \qquad (10)$$

The quantity demanded in the local market depends on the local price and on the organic quality (Q_O) (equation 11):

$$Q_D^L = a - bP^L + eQ_O \qquad (11)$$

And local supply is a fraction of total supply $(1 - \theta)$, adjusted by exports (θ), as shown in equation 12:

$$Q_S^L = (1 - \theta) \cdot Q_S \qquad (12)$$

Substituting both expressions in equation (10), the following is obtained:

$$a - bP^L + eQ_O = (1 - \theta) \cdot Q_S \qquad (13)$$

Then, replacing Q_S with equation (3) of total supply, the condition of equilibrium in the local market is in equation 14 which follows:

$$a - bP^L + eQ_O = (1 - \theta) \cdot [h \cdot T \cdot (1 - Sd) \cdot (1 - Cc) \cdot (1 + Markup) - d] \qquad (14)$$

Solving for the local price (P^L) is the marginal cost, a proportion determined by the markup, as observed in equation 7, where the marginal cost (MC) includes variable and sustainability costs (equation 8).

Equilibrium in the international market

On its part, equilibrium in the international market is determined by the international fixed price (P_I) and the quantity exported (Q_D^I), with the latter equaling the portion of total supply destined to exports (θQ_S), as shown in equation 15 as follows:

$$Q_D^I = \theta Q_S \qquad (15)$$

Once again substituting equation (3) of total supply gives equation (16) which shows the condition of equilibrium in the international market:

$$Q_D^I = \theta[h \cdot T \cdot (1 - Sd) \cdot (1 - Cc) \cdot (1 + Markup) - d] \qquad (16)$$

where basically the quantity exported depends on parameter θ, which determines the quantity of total supply destined to the international market.

Agricultural heritage cost

Having this base structure, it is possible to include in the model the cost of agricultural heritage as an additional element of the total costs function, such that it be a proportion of the quantity produced by the farmer. This notion is reflected in equation (6´) as follows:

$$C = f_0 + vQ + s_0 + s_1 Q_0 \cdot Q + C_M \quad (6')$$

where C_M is the cost of maintaining agricultural heritage, modeled as: $C_M = m \cdot Q$, where m is the cost per unit of agricultural heritage.

Given that heritage cost consists of a term which is a percentage of quantity produced, its inclusion is reflected only in the derivation of marginal cost (CM), which in turn participates in determining the local price (P^L). This modification is reflected in equation (8´):

$$MC = v + s_1 Q_O + m \quad (8´)$$

That is, the inclusion of the heritage cost becomes a term of lump-sum within the marginal cost. Thus, the local price equation (7) is maintained; the difference is that in amounts there is a positive translation reflected also in total income (9).

In this sense, the equations of equilibrium both in the local market (14) and in the international market (16) conserve their form, even though in magnitude the inclusion of agricultural heritage cost is reflected in a translation of the local price, present in the equilibrium of the local market.

Additionally, a ceiling may be established, defined as a minimum price such that it covers the costs of maintaining the agricultural heritage. This price would be above the international market price and below the local price:

$$P^L \geq P_{min} \geq P^I \ (17)$$

When establishing this limit, also determined is a proportion of production which can be sold at this price level:

$$Q_{min} = \omega Q \ (18)$$

3.3. Implications of the model

Quinoa producers operate in a setting of imperfect competition with product differentiation under the criteria of quality. Each farm or cooperative differentiates its product through sustainable practices, organic certification, or the preservation of ancestral cultivation techniques. This higher quality allows producers to obtain a higher price (P^*), improving their profit margin ($P^* - C$) and hence its' profitability; this fosters the competitiveness of organic producers in relation to conventional ones both in the domestic and international markets.

However there is a key difference between local and international market. In the domestic market, the demand curve is steeper and positioned lower, reflecting limited price elasticity ($|EP|$) and weaker preferences for sustainability attributes among local consumers. As a result, consumers are more price sensitive, and the market does not fully internalize the cultural or ecological value of quinoa production. The equilibrium price remains low, output is restricted, and profit margins are narrow or close to zero in long-run equilibrium. Producers often sell at or near average variable cost (close to break-even), leaving little room for profitability. This fragility makes smallholders particularly vulnerable to climate shocks and market fluctuations, given that they cannot accumulate sufficient surplus to reinvest in sustainable practices.

In contrast, the international market is characterized by a higher and flatter demand curve, representing a larger consumer base with greater willingness to pay for sustainability, fair trade, and the cultural heritage embedded in quinoa production. These attributes shift the demand curve upward and create a price premium. At equilibrium, producers obtain a higher price and larger output, allowing them to capture short-run economic profits. However, most of the value added in international trade is appropriated by downstream actors — exporters, processors, distributors, and retailers — rather than by producers. Empirical estimates suggest that small-scale farmers receive only around 10% of the final retail price of quinoa, despite the high premiums paid by end consumers.

This asymmetry translates into persistent challenges mainly faced by local producers: i) low margins, farmers receive very low prices at the farm gate, leaving them with minimal profits or even losses in years with bad yields or market fluctuation; ii) Unsustainable Practices: Because their revenue share is limited, many producers cannot afford the long-term costs of sustainable practices, such as: soil restoration, organic certification, biodiversity conservation; iii) heightened climate vulnerability, smallholders face increasing costs from climate stressors such as drought, frost, or crop failures, but lack the financial resilience or institutional support to adapt. Without adequate institutional support, these structural disadvantages may ultimately force producers out of quinoa cultivation, undermining rural livelihoods and sectoral sustainability, thihs means, an increase in market exist risk.

In terms of costs, both markets share the same underlying cost curves. The U-shaped average cost curve reflects the possibility of economies of scale at intermediate levels of production. Producers integrated into international markets are more likely to expand output, thereby lowering per-unit costs and improving efficiency. By contrast, those restricted to the local market cannot exploit these economies, remaining stuck at higher average costs and narrower margins. This duality underscores how market access is central to determining whether sustainable practices are economically viable.

A third important characteristic is that of the sustainability costs. For modelling organic production adequately, consideration must be given to the fact that the costs associated with this type of production (C_O) tend to be higher due to investments in certifications and environmental practices. These additional costs ($C_O - C_C$) open up international market opportunities with high standards, diversifying producer income. Notwithstanding, these costs can be prohibitive for small producers with limited access to loans or technology, generating inequalities in the capacity to compete. In fourth place is the impact of climate change, which can be exemplified under different scenarios (El Niño, La Niña). An increase in the climate change index (C) directly reduces production (Q) through crop yield, and thus total supply. This introduces uncertainty in supply, with the possibility of generating lack of supply in local markets and difficulties for fulfilling export contracts. However, it may also motivate the adoption of resilient technologies (such as crops resistant to drought) or agroecological practices, stabilizing production in the long-term. Under this context, it is necessary to have robust climate scenarios for improving the understanding of the effects; for this purpose, we add to the microeconomic model the NL-CROP model.

Additionally, there is an interrelationship between the local and international market equilibria. An increase in the export proportion $\left(\frac{X}{Q}\right)$ reduces the quantity available for the local market $(Q - X)$. In turn, this may generate lack of supply and an increase in local prices (P^L), affecting domestic consumers. Also, an intensive level of exports can prioritize external markets at the expense of local food security, particularly under situations related to climate or production crises.

Also, the inclusion of the agricultural heritage cost (C_M) allows covering the costs associated with the productive landscape, which motivates producers to opt for the conservation and protection of the agroecological systems in the region. Including these landscape conservation costs is an approach aligned with international trends that value the sustainability of agricultural production. This may facilitate access to markets that demand sustainability certifications and responsible practices, such as that of the European Union under regulations such as that pertaining to free deforestation.

Finally comes the sphere of particular interest of the present research, total income and economic sustainability of agricultural producers. Total income ($P \cdot Q$) is influenced by climate conditions (Cc), costs (C_O), the margin ($P - C_O$) and the proportion of exports $\left(\frac{X}{Q}\right)$. A greater proportion of organic quality $\left(\frac{Q_O}{Q}\right)$ raises the margin and local income, compensating for the additional costs and fostering the economic and environmental sustainability of producers. However, if the sustainability costs increase more quickly than the margins, net income ($P \cdot Q - C_O \cdot Q$) could become negative, leading to indebtment and abandoning sustainable practices.

To close up this section, it is mportant to highlight some policy implications that stand up from the model and the producer strategy that can take place. The coexistence of segmented markets highlights the need for mechanisms that allow producers to appropriate a larger share of the international premium. Certification systems (organic, fair trade, geographical indications) and supply chain traceability can secure higher prices while signaling sustainability and heritage value to consumers. Complementary investments in infrastructure, logistics, and producer organizations are equally necessary to strengthen bargaining power and enable participation in high-value markets. Ultimately, the model shows that the observed price differential between domestic and international markets (dual-market structure) is not cost-driven but rather a reflection of consumer valuation — a clear manifestation of monopolistic competition with heterogeneous preferences. Leveraging this differentiation through COSPH provides a pathway to balance economic viability, climate resilience, and the conservation of productive landscapes in the Bolivian Altiplano.

3.4. Configuration of the model

In this section we describe our microeconomic model's set-up; that is, we define its key structural components: rules of interaction and parameters. Specifically, we specify: 1) the agents (quinoa producers, consumers, etc.); 2) the market conditions (product differentiation due to sustainability); and 3) the critical variables (production costs, price elasticity of demand and climate externalities). This framework seeks to capture how individual decisions, such as adopting good agricultural practices (GAP) affects market equilibria under asymmetric information and limited competition. The configuration is adapted to analyze how COSP influences quinoa agricultural competitiveness. The main assumptions are incorporated: i) producers face increasing marginal costs when implementing GAP; ii) consumers value sustainability; and iii) climate introduces exogenous shocks in productivity. For estimating the model, a dynamic accounting system was prepared that quantifies COSP under different climate and market scenarios. This interface integrates several modules, where calibration is done by means of econometric techniques (panel regressions with data of Bolivian farms, 2015-2025) validated by robustness tests such as the bootstrap method. The tool[2] is designed for analyzing economic sustainability of agricultural production under different scenarios of costs and climate shocks.

[2] The tool is intellectual property shared by the authors of the present article and INESAD.

Table 1: Configuration of the model

Set-up		Description	
a	0.15-0.20	Initial level of local demand	Small producers have a low level of autonomous consumption.
b	0.5-0.8	Price elasticity of local demand	Quinoa consumption is moderately inelastic in the local market.
e	1.0-1.4	Quality elasticity of local demand	There is a niche of organic consumers who highly value quality and sustainability attributes
PL	0.5-0.8	Local price of the product relative to PI	Small producers are price takers in international markets and set local prices at a discount.
QO	0.25-0.35	Share of quinoa production that is organic	Small producers manage to sell only a limited proportion of their production as organic compared to conventional.
h,T	0.5-0.65	Technological scale parameter relative to maximum capacity	Small producers have more limited access to production technologies than large producers.
Sd	0.60-0.85	Soil degradation index	Small quinoa producers face low soil quality
d	0.30-0.35	Structural costs affecting supply (relative to fixed costs)	Small producers have lower investment in infrastructure and machinery, reducing their fixed costs.
v	0.5-0.60	Variable cost per unit produced (relative to local price)	Small producers typically face higher variable costs per unit due to less favorable economies of scale.
***s*0**	0.20-0.30	Fixed sustainability costs	Small producers face higher costs to obtain and maintain organic certification, including their practices.
m	0,15-0,18	Fixed cost of conserving and/or recovering agricultural heritage	This is the economic valuation of quinoa's biological conservation.
***s*1**	0.20-0.35	Variable sustainability costs associated with organic production:	Small producers often adopt more labor-intensive practices to comply with organic standards.
MC	0.4-0.6	Marginal cost relative to local price	Small producers experience lower economies of scale and efficiency, resulting in higher marginal costs.
PI	1.5-1.8	International price relative to local price	Small producers have less bargaining power in international markets.
θ	0.6-0.75	Proportion of total supply allocated to international market	Small producers allocate a larger share of their production to export markets, focusing less on the local market and autonomous consumption

Source: Own elaboration based on primary data collected through surveys from the project *Creating Indigenous Women's Green Jobs Under Low-Carbon COVID-19 Responses and Recovery in the Bolivian Quinoa Sector*, conducted in plots from the Southern Altiplano of Bolivia.

Through the introduction of key data on farms (ex.: area cultivated, type of soil), production (historical yield) and costs (inputs, labor, certifications), it is possible to evaluate the impact of price variations and climate conditions on producer profitability. The tool is structured into two main steps: 1) farm profile, operating costs and sale prices; 2) scenario analysis (simulation of climate phenomena and/or international price fluctuations). The scope allows to: 1) evaluate profitability under extreme economic and climate conditions; 2) calculate net margins considering indirect costs (ex.: soil degradation); 3) simulate impacts of climate events with different levels of severity; and 4) generate recommendations for optimizing decisions. Additionally, it provides an analytical framework for negotiating prices with premium buyers and adjusting productive strategies. Table 1 allows observing the calibration of the accounting model.

4. Results

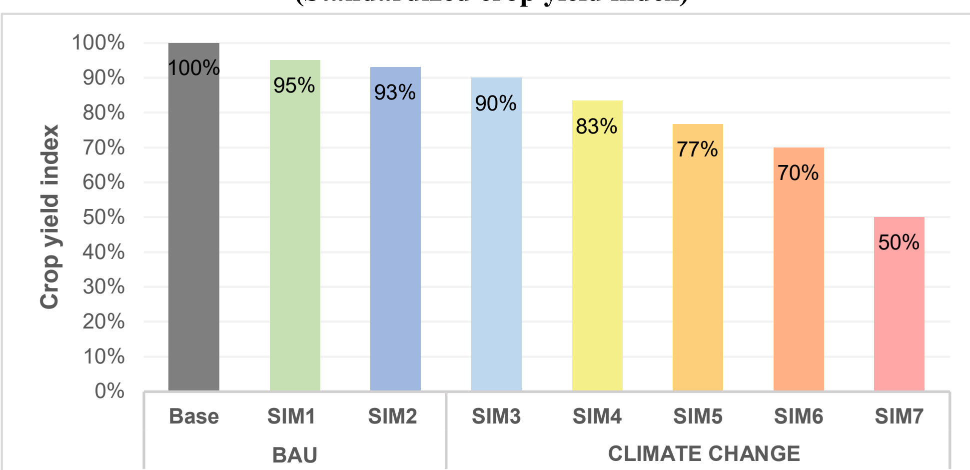
The results of the present study are presented in two parts, firstly the effect of climate change on crop yield under different climate scenarios, and then the second part, which consists of identifying the effect of this on the costs and profit of producers considering the variation parameters estimated.

4.1. Climate scenarios and crop yield

The analysis of this section evaluates the behavior of crop productivity considering two climate change scenarios for the 2025-2050 period: i) a normal scenario, also referred to as business as usual (BAU), in which climate variability continues its standard trajectory without the presence of adverse shocks; and ii) a scenario that considers the presence of the El Niño phenomenon, which is characterized by water stress with harsh drought. For the BAU scenario, two categories are included. BAU1 represents a situation of 1 SD (standard deviation) in relation to the normal trajectory, while BAU2 considers 1.5 SDs. Furthermore, for modelling the scenario of climate change under the El Niño phenomenon, five categories are established considering different levels of severity. We begin with a light scenario (SIM3), followed by a moderate one (SIM4) and then comes a strong level (SIM5). The final two categories correspond to a severe scenario (SIM6) and a catastrophic one. For simulating the scenarios, the base taken is that of the criteria and parameters of the Third Report of the Intergovernmental Panel on Climate Change (IPCC, 2022).

Figure 2 and Table 2 summarize the results obtained from the crop yield simulation with the NL-CROP model, introducing the climate scenarios[3]. For the simulation, crop yield is standardized to an index equal to the base year unit. In this way, the change given the different scenarios can be understood directly as a percentage variation in relation to the initial level of the crop's performance.

Figure 2: Climate change scenarios 2025-2050
(Standardized crop yield index)



Source: Own elaboration based on the calibrated NL-CROP model

[3] The colors of each of the scenarios are related to the severity of the climate events, simulating a heat map.

Under the business as usual scenario, crop yield can be affected by a reduction of 5% (SIM1), which is a moderate event, and 7% (SIM2), which is a strong event, considering the 2025-2050 period. Yield variations may be clearly observed in Table 2. For modelling these impacts, historical meteorological information is used, of at least 30 years, which allows identifying climate trends and categorizing[4] extreme events based on their standard deviation (SD) in relation to the mean.

Table 2: Variation in crop yield under climate change scenarios

Scenarios		Yield index KQH	Change from Base Year	Cathegory
BAU	**Base**	1,00		
	SIM1	0,95	**-5,0%**	BAU1
	SIM2	0,93	**-7,0%**	BAU2
Climate Change	**SIM3**	0,90	**-10,1%**	Mild
	SIM4	0,83	**-16,7%**	Moderate
	SIM5	0,77	**-23,3%**	Steong
	SIM6	0,70	**-30,0%**	Severe
	SIM7	0,50	**-50,0%**	Catastrophic

Source: Own elaboration based on the calibrated NL-CROP model

In the normal (BAU) scenario crop yield may be affected by a reduction of between 5% (SIM1) and 7% (SIM2) considering the time period up to 2050. When considering the impact of climate change under the presence of the El Niño phenomenon, harm increases at a growing rate depending on the phenomenon's severity. With a light level (SIM3), crop yield reaches 90% compared to the level registered as the baseline, only 3 percentage points (pps) less than the normal scenario of SIM2. When going to a moderate level (SIM4), crop performance is reduced by an additional 7 pps, equivalent to 16.66% less than the level reached in the base year. Marginal variation with the strong (SIM5) and severe (SIM6) scenarios is 7 pps for each of them; however, when comparing with the initial (base) yield level, the reduction is 23.3% and 30% respectively. Finally, with a catastrophic climate change scenario (SIM7), production is reduced to half; that is, crop yield reaches only half of its potential level observed in the base year.

The climate conditions of El Niño are characterized by the presence of drought over a long period, resulting in extremely high levels of soil aridity. Besides water stress, the high temperatures also generate thermal stress, with a harmful effect on crop growth and development. The loss of the quinoa plants' capacity to absorb nutrients and retain water reduces their yield and vulnerates production stability. In turn, thermal stress aggravates the conditions of water stress by accelerating humidity evaporation in the soil. This highlights the need for adaptation mechanisms focusing on irrigation systems, for producers to be able to confront the challenges of the climate crisis.

4.2. Sustainable production and income level

Having estimated the effect of climate change on quinoa production (yield) considering the different scenarios, we go on to analyze how this impact affects producer income. For the estimates we use a computable model developed by Aliaga and Garrón (2024) based on the microeconomic model of sustainable production costs presented in the methodological section. Specifically, we begin by analyzing the effect of the climate shock on the level of total production with the parameter of

[4] Moderate event: standar deviation between ±1σ and ±1.5σ (ex.: drought that reduces yield by 10-15%). Strong event: standard deviation between ±1.5σ and ±2σ (ex.: hail with losses of 20-25%). Severe event: standard deviation between ±2σ and ±3σ (ex.: late frost cuasing reductions of 30-40%). Catastrophic event: standard deviation >±3σ (ex.: extrema flooding with losses above 50%).

variation of the crop yield index found in the prior step. In what follows, we observe the impact of the climate shock on production costs and we evaluate the difference between production with traditional practices (with no adaptation) and with the introduction of good agricultural practices (GAP) as an adaptation strategy. Finally, we observe how producer profitability varies, and we specify what the unit cost of sustainable production is, and add a scenario in which costs also include an element for the cost of agricultural heritage, also per unit produced. Tables 3 and 4 show the results for the normal scenario under the BAU1 (SIM1) and BAU2 (SIM2) specifications.

Table 3: Sensitivity under normal climate scenario (BAU 1)

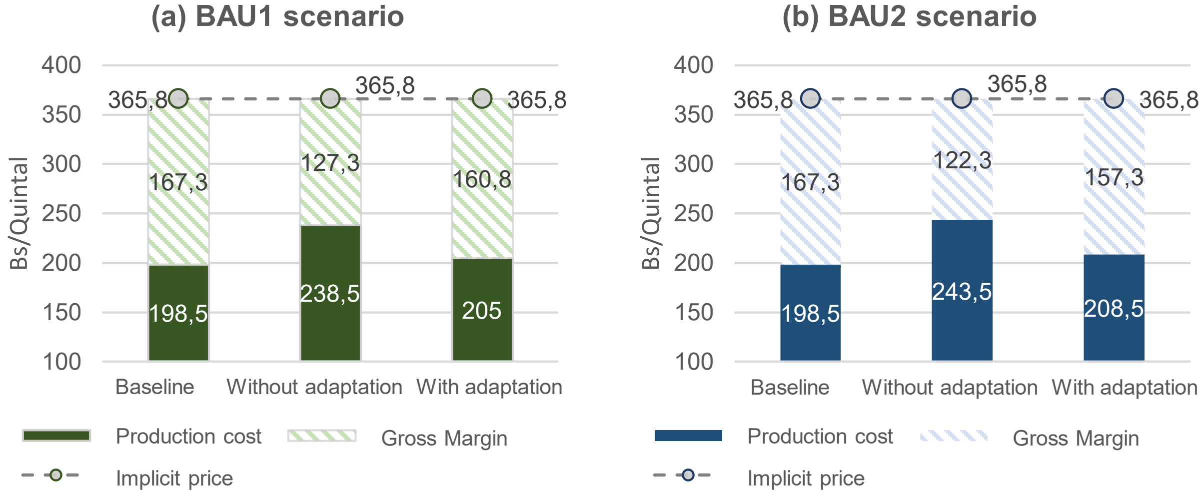
Scenario (-5%)	**Units**	**Baseline**	**Without Adaptation**	**With adaptation**
Average cost increase	(%)	4,30%		
Quinoa sales revenue	(Bs)	724.086	687.722,29	711.115,2
Total quinoa production	(Quintals)	1.979,00	1.880,05	1.944,00
Implicit price	(Bs/Quintal)	365,8	365,8	365,8
Production cost	(Bs/Quintal)	198,5	238,5	205
Gross margin	(Bs/Quintal)	167,3	127,3	160,8
Gross margin	(%)	45,74%	34,80%	43,96%
COSP	**(Bs/Quintal)**			**61,37**

Source: Own elaboration based on the sustainable production model.

The normal scenario (BAU1), corresponds to a drop in quinoa production of 5%, going from 1,979 to 1,880.05 quintals [100-kg units]. However, with the implementation of GAP, the negative impact is mitigated, reaching a production of 1,944 quintals; that is, a reduction of only 1.8% compared with the baseline. This shock implies an increase of 4.3% in total production costs, going from a unit cost of 198.5 to 238.5 Bs./quintal; however, with the adaptation strategies, the cost of the product is 205 Bs./quintal, equivalent to an improvement of 14%. All of this translates into a reduction of the benefits of quinoa sales for producers, going from Bs. 724,086 to Bs. 687,722 after the shock, with no adaptation, and to Bs. 711,115 with the implementation of GAP. Although the decrease in income cannot be avoided, the adaptation strategies allow mitigating the harm.

The analysis of cost and unitary margin is observed in panel (a) of Figure 3. As to the cost of sustainability associated with production (COSP), it is estimated that it reaches 61.37 Bs./quintal. For analyzing the implementation of good agricultural practices, it is necessary to compare this cost with the profit margin. Given that the latter reaches 160.80 Bs./quintal, the adaptation strategies are profitable for producers, at least under this climate scenario.

Figure 3: Costs and profits under the normal scenario (Bs./Quintal of quinoa)



Source: Own elaboration based on the sustainable production model.

The second variant of the normal scenario (BAU2) (Table 4) implies a reduction of 7% in production; however, with the implementation of adaptation strategies, reduction is only 2%, going from 1,979 to 1,939 quintals. Additionally, the unit cost increases from 198.5 to 243.5 Bs./quintal, reducing the gross margin from 45.74% to 33.43%. Similarly, the adaptation strategies help to mitigate the harm, reducing costs to 208.5 Bs./quintal, allowing a margin of 43%, only 2 pps less than the baseline margin. Panel (b) of Figure 3 shows the behavior of cost and unitary margin for the three specifications of this scenario. In this case, the cost of sustainable production is 64.87 Bs./quintal, while the unitary margin of profit reaches Bs. 157.30. This implies that the introduction of adaptation strategies is also profitable.

Table 4: Sensitivity under normal climate scenario (BAU 2)

Scenario (-7%)	Units	Baseline	Without Adaptation	With adaptation
Average cost increase	(%)	4,45%		
Quinoa sales revenue	(Bs)	724.086	673.243,9	709.286,2
Total quinoa production	(Quintals)	1.979,00	1.840,47	1.939,00
Implicit price	(Bs/Quintal)	365,8	365,8	365,8
Production cost	(Bs/Quintal)	198,5	243,5	208,5
Gross margin	(Bs/Quintal)	167,3	122,3	157,3
Gross margin	(%)	45,74%	33,43%	43,00%
COSP	**(Bs/Quintal)**			**64,87**

Source: Own elaboration based on the sustainable production model.

Tables 5 to 9 show the results of the El Niño climate shock under different levels of severity. Given a light scenario (Table 5), the impact of climate change translates into a reduction of 10% in production, going from 1,979 to 1,781 quintals, but with a production adaptation strategy, it reaches 1,934 quintals, equivalent to a reduction of only 2.3%. In this case, the average increase in total costs is 4.63%, only 0.2 pps more than in scenario BAU2.

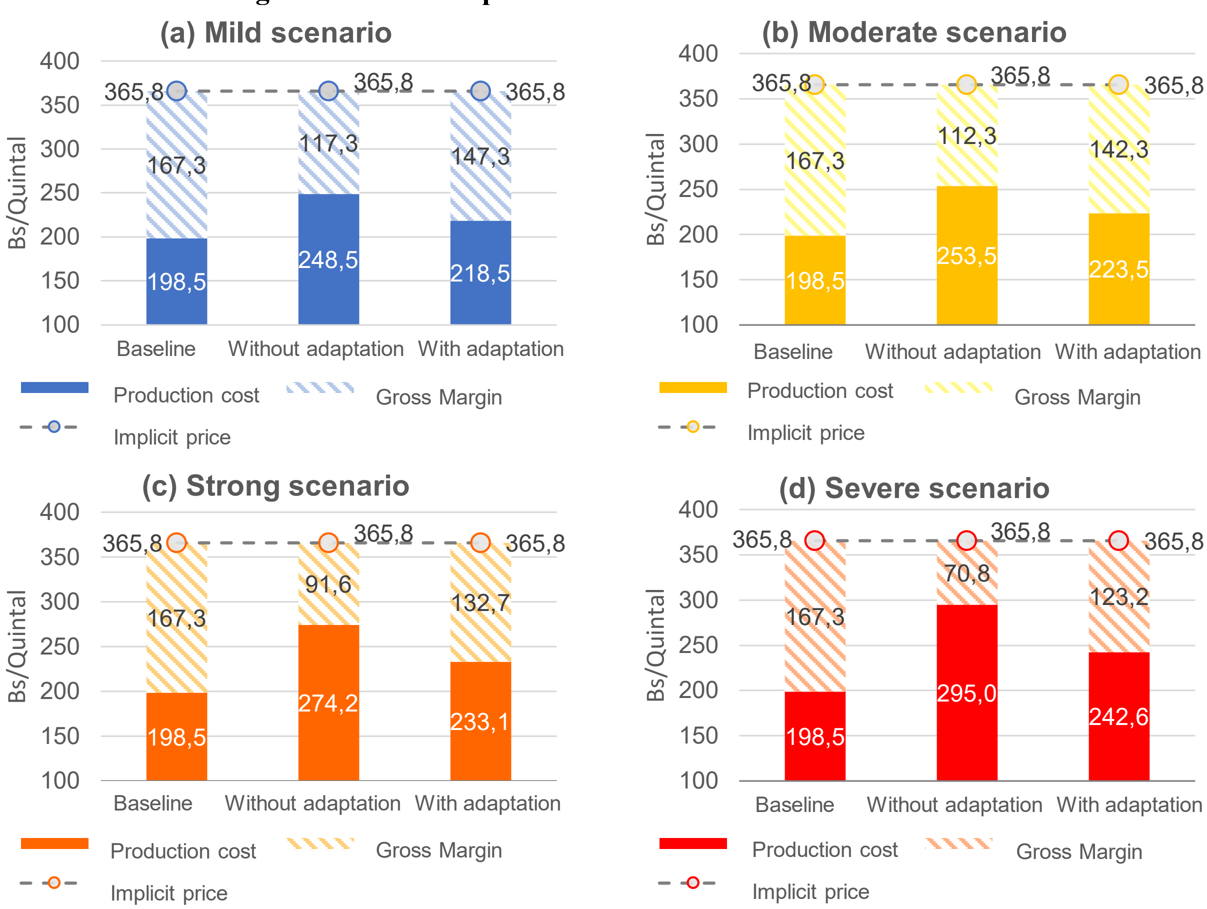
Table 5: Sensitivity under mild climate scenario - El Niño

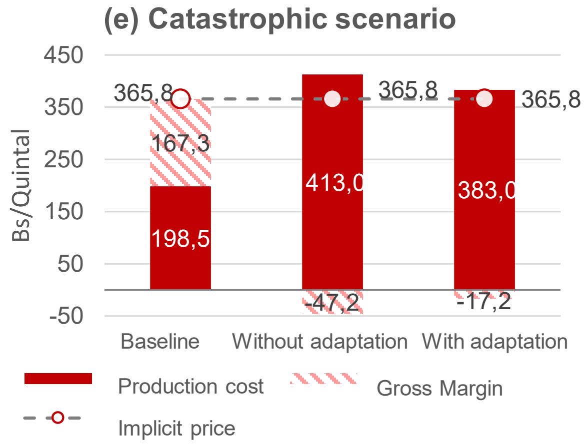
Scenario (-10%)	Units	Baseline	Without Adaptation	With adaptation
Average cost increase	(%)	4,63%		
Quinoa sales revenue	(Bs)	724.086	651.526,38	707.457,2
Total quinoa production	(Quintals)	1.979,00	1.781,10	1.934,00
Implicit price	(Bs/Quintal)	365,8	365,8	365,8
Production cost	(Bs/Quintal)	198,5	248,50	218,50
Gross margin	(Bs/Quintal)	167,3	117,3	147,3
Gross margin	(%)	45,74%	32,07%	40,27%
COSP	**(Bs/Quintal)**			**56,58**

Source: Own elaboration based on the sustainable production model.

Without adaptation strategies, the cost of the product goes from 198.5 to 248.5 Bs./quintal and the margin goes down from 167.3 to 117.3 Bs./quintal, while with the implementation of GAP, the unit cost increases only to 218.5 and the margin reaches 147.3 Bs./quintal (Figure 4, panel (a)). Similarly, the adaptation strategies allow increasing income from Bs. 651,526.38 to Bs. 707,457.20. GAP are profitable in this light scenario, as the cost of sustainable production is 56.58 Bs./quintal, and may be covered by the unitary profit margin.

Figure 4: Costs and profits under climate scenario - El Niño





Source: Own elaboration based on the sustainable production model.

Regarding a moderate climate shock (Table 6), production goes down by 16.66%, going from 1,979 to 1,649.37 quintals, but with adaptation strategies, the fall in production is only 2.5%; that is, a mitigation of 14.1 pps is achieved. On its part, the climate shock increases costs by 5% on average, going from a unit cost of 198.50 Bs./quintal in the base year to 253.50 Bs./quintal with no adaptation, which reduces the gross margin from 167.30 to 112.30 Bs./quintal, as may be observed in panel (b) of Figure 4. The adaptation strategies allow increasing the profit margin to 142.30 Bs./quintal, which is equivalent to 38.9%. Under this scenario, the sustainable production cost increases to 79.87 Bs./quintal; this increase is attributable to the need to counter the magnitude of the effect of climate change. Even so, the implementation of best practices continues to be sustainable, as it can be covered by the margin and continue to allow a percentage of profit.

Table 6: Sensitivity under moderate climate scenario - El Niño

Scenario (-16,7%)	Units	Baseline	Without Adaptation	With adaptation
Average cost increase	(%)	5,00%		
Quinoa sales revenue	(Bs)	724.086	604.086	684.086
Total quinoa production	(Quintals)	1.979,00	1.649,37	1.930,00
Implicit price	(Bs/Quintal)	365,8	365,8	365,8
Production cost	(Bs/Quintal)	198,5	253,5	223,5
Gross margin	(Bs/Quintal)	167,3	112,3	142,3
Gross margin	(%)	45,74%	30,70%	38,90%
COSP	**(Bs/Quintal)**			**79,87**

Source: Own elaboration based on the sustainable production model.

With a higher climate shock, corresponding to the category of a strong phenomenon (Table 7), it is estimated that production decreases by 23.3%, reaching a production of 1,517.51 quintals, while with the implementation of adaptation strategies, production of 1,855.70 quintals is achieved, representing a reduction of 6.2% compared to the baseline. From this point onward, it may be observed that harm due to climate change increases, because even with adaptation strategies, the drop in production is 4 pps higher than in the previous scenarios.

Table 7: Sensitivity under strong climate scenario - El Niño

Scenario (-23,3%)	Units	Baseline	Without Adaptation	With adaptation
Average cost increase	(%)	7,00%		
Quinoa sales revenue	(Bs)	724.086	555.473	667.878
Total quinoa production	(Quintals)	1.979	1.517,51	1.855,78
Implicit price	(Bs/Quintal)	365,8	365,8	365,8
Production cost	(Bs/Quintal)	198,5	274,24	233,06
Gross margin	(Bs/Quintal)	167,3	91,565	132,74
Gross margin	(%)	45,74%	25,03%	36,29%
COSP	**(Bs/Quintal)**			**89,43**

Source: Own elaboration based on the sustainable production model.

The same trend is observed in the behavior of costs in terms of product and the unitary margin, as is shown in panel (c) of Figure 4. With a strong climate phenomenon, an average increase of 7% is estimated for total costs and the unit cost becomes 274.24 Bs./quintal. Although the cost with adaptation strategies has a certain benefit, this benefit is increasingly lower; this is reflected in the profit margin. With adaptation, the margin is now only equivalent to 36.29%, almost 10 pps less than in the base scenario. All in all, the implementation of good agricultural practices continues to be profitable for producers, given that the cost of sustainability is 89.43 Bs./quintal and the margin is 132.70 Bs./quintal.

Table 8 allows observing that in the face of a severe scenario, with a decrease of 30% in quinoa production, the total cost of production increases by 9%. The implementation of adaptation strategies plays a crucial role for mitigating the negative impacts and conserving the economic viability of the activity.

In the absence of adaptation, quinoa production goes down to 1,385.65 quintals, generating a significant decrease in income from sales, which go from Bs. 724,086 in the base scenario to Bs. 506,860. This, in addition to an increase of 49% in the product cost of 198.50 Bs./quintal to 295.00 Bs./quintal leads to a strong contraction of the gross margin, which goes from 45.74% in the base scenario to 19.36%.

Table 8: Sensitivity under severe climate scenario - El Niño

Scenario (-30%)	Units	Baseline	Without Adaptation	With adaptation
Average cost increase	(%)	9,00%		
Quinoa sales revenue	(Bs)	724.086	506.860	651.670
Total quinoa production	(Quintals)	1979	1385,65	1781,55
Implicit price	(Bs/Quintal)	365,8	365,8	365,8
Production cost	(Bs/Quintal)	198,5	295,0	242,6
Gross margin	(Bs/Quintal)	167,3	70,83	123,19
Gross margin	(%)	45,74%	19,36%	33,68%
COSP	**(Bs/Quintal)**			**98,98**

Source: Own elaboration based on the sustainable production model.

However, with the implementation of adaptation strategies, quinoa production recovers to 1,781.55 quintals, which allows for an increase in sales income to Bs. 651,670. Besides, the product cost goes down to 242.60 Bs./quintal, an improvement of 17.8% compared to the scenario with no adaptation. As a result of this, the gross margin recovers by 33.68%; though it continues to be below that of the base scenario, the negative impact is reduced. A comparison of the changes in the cost and margin under the three situations may be observed in panel (d) of Figure 4. It is worth noting that in this severe scenario COSP is estimated at 98.98 Bs./quintal. Given that the gross margin with adaptation is 33.68%, this indicates that the profitability of the activity does allow for covering COSP and leaving a margin for implementing a commercial insurance. An insurance premium of between 7 and 10% of production cost is recommended for covering climate risks and ensuring the activity's viability under this severe scenario. In this way, the combination of adaptation strategies and the implementation of adequate agricultural insurance would allow maintaining economic sustainability of quinoa production, even in a scenario of a 30% reduction in productivity.

In what follows, under the scenario of a catastrophic climate shock (Table 9), quinoa production is affected by 50% with no adaptation. This makes total production decrease from 1,979 quintals (baseline) to 989.5 quintals, which represents a decrease of 49.9%. On the other hand, with the implementation of adaptation strategies, production recovers to 1,159.5 quintals. This implies that adaptation allows bringing down the 49.9% drop in production without adaptation to 41.4% with adaptation: an improvement of 7 pps.

Table 9: Sensitivity under catastrophic climate scenario - El Niño

Scenario (-50%)	**Units**	**Baseline**	**Without Adaptation**	**With adaptation**
Average cost increase	(%)	15,01%		
Quinoa sales revenue	(Bs)	724.086	361.959	424.145
Total quinoa production	(Quintals)	1979	989,5	1159,5
Implicit price	(Bs/Quintal)	365,8	365,8	365,8
Production cost	(Bs/Quintal)	198,5	413,0	383,0
Gross margin	(Bs/Quintal)	167,3	-47,2	-17,2
Gross margin	(%)	45,74%	-12,90%	-4,70%
COSP	**(Bs/Quintal)**			**239,37**

Source: Own elaboration based on the sustainable production model.

In terms of production costs, we have that the catastrophic climate shock increases total production costs by 15%. Without adaptation, the product cost is 413 Bs./quintal, while with adaptation, the product cost goes down to 383 Bs./quintal, an improvement of 7.3%. Continuing with the profitability analysis, gross margin goes down from 45.74% in the base scenario to -12.90% without adaptation; that is, the market price does not cover the production cost entirely. With adaptation, the gross margin improves to -4,70%, but continues to be negative. This indicates that even with adaptation, the scenario is not profitable for producers from a financial perspective; this may be observed in panel (e) of Figure 4. Finally, COSP (cost of sustainable production) represents 65% of the implicit price, a very high value. Together with the negative gross margin, this suggests the need for implementing risk transfer mechanisms such as agricultural insurance, for protecting the economic viability of the production activity.

Finally, Table 10 considers a moderate climate change impact scenario for including a situation in which besides the adoption of adaptation practices, a simulation with agricultural heritage conservation is considered. Consideration of conservation of the agricultural heritage reveals a positive effect on the resilience of quinoa crops. In particular, loss of production caused by climate change is reduced from an initial state of -16.2% to -10.5%, noticeably nearing the behavior seen under a scenario of light climatic impact (Table 5), where the reduction in production is 10.1%. Although this result suggests that heritage conservation acts as a complementary mechanism of adaptation by mitigating the impact of climate change, the change in costs must also be considered. Heritage costs imply an increase of 0.75 pps in costs. Table 5 indicates that under a moderate climate scenario costs increase by 5%, and when agricultural heritage costs are considered, the increase in costs is 5.75% (Table 10). In this sense, it is necessary to do a comparison between the change in costs and the change in income to see whether the recovery in the level of production allows this practice to be cost effective, given that although the levels of production surpass those of the moderate scenario, they remain slightly below those of the light scenario.

Lastly, the increase in costs associated with heritage conservation makes the margins be below those obtained in the moderate scenario (without conservation). Even so, agricultural heritage conservation is sustainable under this scenario, as the costs associated with agricultural heritage (COSPH is 84.65 Bs./quintal) may be covered by the margin, with a percentage of profit still made.

Table 10: Sensitivity under moderate climate scenario including agricultural heritage costs

Scenario (-10,5%)	Units	Baseline	Moderate		With conservation
			Without adaptation	With adaptation	
Average cost increase	(%)	5,75%			
Quinoa sales revenue	(Bs)	724.086	647.906	703.526	706.637
Total quinoa production	(Quintals)	**1979**	**1.771,2**	**1.923,26**	**1.931,76**
Implicit price	(Bs/Quintal)	365,8	365,8	365,8	365,8
Production cost	(Bs/Quintal)	198,5	266,0	226,1	228,3
Gross margin	(Bs/Quintal)	167,3	99,8	139,7	137,5
Gross margin	(%)	45,74%	27,3%	38,2%	37,6%
COSPH(Bs/Quintal)	**(Bs/Quintal)**				**84,65**

Source: Own elaboration based on the sustainable production model with heritage costs.

5. Conclusions

Climate change has generated significant impacts on quinoa crop yield, with reductions going from 5% under normal scenarios (BAU) to 50% with catastrophic events such as severe El Niño periods. These effects are explained by greater frequency and intensity of water and thermal stress. GAP have shown to be efficient in mitigating these losses, reducing yield contraction to just 1.8-2% under BAU conditions and to a maximum of 6.2% even under strong scenarios (SIM5), showing that their role is key in climate adaptation.

Notwithstanding, the implementation of GAP implies additional costs which go from 56.58 to 98.98 Bs./quintal according to the event's severity. These costs are covered by the profit margins in the scenarios up to SIM6, where the gross margins remain at 33-43%. However, with catastrophic events (SIM7), the margins go down to -4.7%, making the independent adoption of GAP unsustainable. This highlights the need for complementary mechanisms such as agricultural insurance with premiums of 7-10% of the total cost, for ensuring the economic viability of producers in the face of extreme risks.

The results also reveal that including agricultural heritage conservation – which is associated with the conservation of productive landscapes, traditional knowledge and local biodiversity – within the cost structure (COSPH), allows improving the resilience of quinoa crops. Under a moderate climate change scenario production loss improves from -16.2% to -10.5% when such preservation actions are included, nearing the behavior observed in climate scenarios of less magnitude. Although this improvement implies an additional increase in costs (from 5.0% to 5.75%), it reinforces long-term sustainability by conserving cultural and ecological assets that are key for Andean communities. This finding contributes with evidence for considering agricultural heritage as an effective strategy of climate adaptation; however, it is necessary to complement this with an analysis of cost effectiveness for reaching a more precise conclusion.

Market differentiation emerges as a critical strategy. Certified organic quinoa obtains premiums of up to 30% in markets such as that of the European Union, partially compensating the COSPH which includes heritage costs. Notwithstanding, price elasticity of local demand requires policies of temporary subsidies for avoiding a shift towards substitutes, particularly in contexts of high prices due to sustainability costs. This equilibrium between access to premium markets, local affordability and conservation of traditional agroecological systems must be a priority in public policies.

The study identifies a clear threshold of sustainability: GAP are profitable when climate events do not surpass 2-3 standard deviations (SIM1-SIM6), but they require intervention beyond this limit. This finding is particularly relevant for the Bolivian Altiplano, where soil degradation and a decrease in precipitations of 15% (2000-2025) have already increased the vulnerability of 70,000 families that depend on quinoa.

Microeconomic modelling with the NL-CROP model confirms that GAP together with heritage conservation not only reduce variability in production, but also stabilize income. For example, with SIM4 (moderate), income decreases by 16.7% with no adaptation, but only 2.5% with GAP. This stability is crucial for the financial planning of small farmers, who face limitations in accessing loans and technology. And the adoption of GAP and strategies for conserving agricultural heritage carries with it structural barriers. The initial fixed costs (certifications, irrigation infrastructure) imply a 37.5% increase in investment, which represents a challenge for small farmer economies. In this sphere, financing programs with preferential rates and technical training are indispensable, together with platforms that connect producers with market niches that value sustainability and heritage.

The present study also identifies the need for localized climate monitoring protocols. The categorization of events by standard deviation must be integrated into early warning systems, allowing farmers to activate specific measures in the face of signals of thermal stress or water stress. This would optimize the use of scarce resources and would reduce operating costs.

At the general level, the recommendation is made to design policies that combine temporary subsidies for GAP with risk transfer instruments and mechanisms for valuing agricultural heritage. This would not only allow reducing the information asymmetry and facilitate risk management, but would also foster an Andean agricultural model that is more resilient, inclusive and culturally rooted. Besides, insurance based on weather parameter indexes (ex.: days of drought) are a viable option, as they avoid information asymmetries and reduce premiums by linking payments to objective data. Countries such as Peru and Colombia have already implemented such schemes successfully.

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7. Annexes

The NL-CROP model (Aliaga and Caballero, 2024) has the aim of estimating crop yield under a non-linear structure; hence, the base equation is as follows:

$$Y = Ae^{-be^{-ct}} \qquad (16)$$

where:

Y is the crop's potential yield in the absence of water stress, measured in tons per hectare.
A is the crop's maximum potential yield or asymptotic yield.
b determines the point of inflexion; that is, the moment at which the crop goes from a slow growth phase to one of more accelerated growth.
c controls the crop's rate of growth; the higher this parameter, the faster the crop's growth.
t is the time (generally measured in days, weeks or months).
e is the Euler number.

For introducing the agroclimatic stressors, the expression of equation (16) is re-expressed in terms of biomass (*B*) and the harvest index (*H*), as shown in equation (17):

$$Y = B \cdot H = Ae^{-be^{-ct}} \quad (17)$$

where:

B is the crop's biomass (in tons per hectare);
H is the harvest index, which depends on the specific characteristics of the quinoa crop.

Solving the equation in terms of biomass we obtain:

$$B = A_i e^{-be^{-ct}} \quad (18)$$

where now A_i is the effective production of biomass adjusted by the harvest index; that is: $\frac{A}{H}$ (in tons per hectare).

The agroclimatic stressors – thermal and water – are introduced as limiting factors that may affect parameters *b* or *c.* The functional form depends on the response case that exists. In what follows a presentation is made of the case in which the agroclimatic stressors affect the inhibition of the expansion of the vegetation cover.

Thermal stress negatively affects the rate of growth, and its impact will depend on the crop's sensitivity to changes in temperature (K_1) as may be observed in equation (19):

$$B = A_i \, e^{-be^{-c(1-K_1 \cdot T)t}} \quad (19)$$

In the case of water stress, the soil's humidity deficit $(\theta_c - \theta)$ is introduced, and the magnitude of its impact depends on parameter K_2, which quantifies the crop's sensitivity to lack of water; this is observed in equation (20):

$$B = Ae^{-be^{-c[1-K_1 \cdot T+K_4(\theta_c-\theta)]t}} \qquad (20)$$

For the present document, these are the essential equations; however, for more details on the model, see Aliaga and Caballero (2024).