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# TRENDS IN LIMITING CLIMATE FACTORS IN THE SUPPLY OF FORAGE INPUTS FOR THE DAIRY INDUSTRY IN THE BOLIVIAN CENTRAL ALTIPLANO

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## ABSTRACT

Bolivia's Central Altiplano has transformed much of its subsistence agriculture into a market-oriented dairy farming system, underpinned by the cultivation of forage crops such as alfalfa and oats. This transformation coincides with a stage of locally complex climatic changes: although mean maximum and minimum temperatures show significant positive trends between March and September, extreme minimum temperatures (the ones that produce destructive frosts) do not show a comparable reduction, so the risk of frost persists throughout much of the forage growth cycle. Added to this is a documented delay in the onset of the rainy season and a greater concentration of precipitation, which intensify the atmospheric water deficit. This article integrates recent field studies on the Northern and Central Altiplano with scientific literature on the climatic sensitivity of forage crops and on the effect of heat and water stress on milk production, to argue that these climatic variations (persistent frosts, delayed and intensified rainfall, and greater evapotranspirative demand) constitute a concrete threat to forage availability and, through that pathway, to milk production in the Central Altiplano. Tables and figures are presented with climatic, productive, and Bolivian dairy-sector data, along with a synthesis of the climate–forage–dairy impact chain and its implications for the food and economic security of producer families.

*Keywords: climate change, Central Altiplano, dairy farming, forage, frosts, food security.*

## 1. INTRODUCTION

The Bolivian Altiplano has undergone, over the last four decades, a profound transformation of its agricultural production systems. Taboada et al. (2017) report that, from subsistence agriculture oriented toward family food security until the 1980s, communities have evolved toward systems more connected to the market, with intensive onion and commercial potato production in communities of the Northern Altiplano, and (of particular interest to this article) dairy farming in the Central Altiplano.

This productive specialization is no accident: it coincided with the arrival of the PIL-La Paz dairy industry in the 1990s, the establishment of the first communal dairy modules, the availability of extensive land and soils suited to forage, and a secure and steady market for dairy products. However, the dependence of dairy farming on forage availability (mainly alfalfa, oats, and forage barley) makes this production system particularly sensitive to the climate variability that characterizes the Central Altiplano, with low nighttime temperatures, high daily thermal

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amplitude, a short and concentrated rainfall regime, and a strong dependence on water availability to sustain forage growth throughout the year.

Recent climate studies in the region reveal a paradox that is critical for dairy farming: while mean and maximum temperatures tend to rise significantly, extreme minimum temperatures (responsible for the frosts that damage crops and forage regrowth) do not show the same trend, so the risk of forage loss to frost remains present even in a context of general warming. Added to this is the documented delay in the onset of the rainy season and the concentration of precipitation into fewer days, which intensifies dry spells and the atmospheric water deficit faced by cultivated forage.

The aim of this article is to integrate the climatic, productive, and social evidence generated (Garcia et al., 2025; Yucra et al., 2025) on the Bolivian Altiplano, focused, respectively, on local climate trends, on the transformation of production systems, and on an initial summary of the impacts of climate change on Altiplano agriculture, with additional scientific literature on the sensitivity of forage crops to frost and drought, and on the effects of heat and water stress on dairy cattle, in order to argue and document that these climatic variations could cause severe losses to the Central Altiplano's dairy production sector due to a lack of sufficient, quality forage.

## 2. METHODOLOGY

This article integrates and synthesizes evidence from field studies conducted in the same communities of the Bolivian Northern and Central Altiplano between 2006 and 2024 (Taboada et al., 2017; Garcia et al., 2025; Yucra et al., 2025), complemented with additional scientific literature and official statistics from the Bolivian dairy sector, following three methodological lines:

First, the climate trend analysis was based on data from local weather stations, the ERA5 (temperature) and CHIRPS (precipitation) reanalysis series for a 40-year reference period, contrasted with records from the National Meteorology and Hydrology Service (SENAMHI) in Patacamaya and Ancoraimes. The significance of monthly trends was assessed using the Mann-Kendall test (MAKESENS software), applied to climate indices standardized by the World Meteorological Organization (mean and extreme maximum and minimum temperature, days with frost, accumulated precipitation, days with rain, seasonality index, and aridity index) (Garcia et al., 2025).

Second, the analysis of production systems was based on participatory assessments (workshops, in-depth interviews, case histories, and surveys of 80 households in 2023) carried out in the study communities to reconstruct changes in productive orientation since the 1980s, identifying the institutional, social, technological, market, and climatic factors that drove specialization toward dairy farming in the Central Altiplano (Taboada et al., 2017; Yucra et al., 2025).

Third, to relate these climatic and productive trends to the vulnerability of the dairy sector, additional scientific literature was reviewed on the sensitivity of forage crops grown in the Bolivian high-Andean dairy zone (alfalfa, oats, barley) to frost and drought, and on the effect of water deficit and heat stress on milk production; official statistics were also compiled from the Ministry of Productive Development and Plural Economy, the National Institute of Statistics (INE), and university studies (UMSA) on the Bolivian dairy sector and the production performance of dairy farming in the Altiplano. From this integration, a conceptual synthesis, (not a new, direct

measurement) was constructed of the impact chain linking climate variability, forage availability, and milk production in the Central Altiplano.

## Study area

The analysis initially focuses on the municipality of Umala (Aroma province, La Paz department), which includes the communities of Iñacamaya, Sabilani, and Incamaya, commercially linked to the urban center of Patacamaya in Bolivia's Central Altiplano. This area lies at an average altitude of 3,780 to 3,860 m in an arid setting where the larger difference between daily maximum and minimum temperatures reflects lower atmospheric humidity and a poorly buffered nighttime loss of infrared radiation, which intensifies the occurrence and severity of frosts compared with communities near Lake Titicaca. The region is part of the Central Altiplano dairy basin (the Desaguadero zone and the eastern zone, comprising the provinces of Ingavi, Murillo, and Aroma in La Paz, and Cercado and Abaroa in Oruro), one of the country's main dairy basins along with the Northern Altiplano.

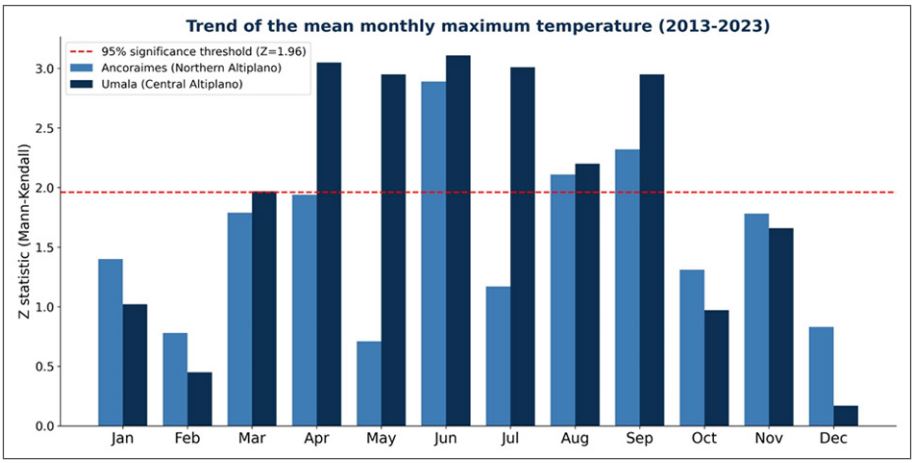
As a comparative reference, the municipality of Ancoraimes is used (Northern Altiplano, communities of Chojñapata, Calahuancani, and Chinchaya), which shares the same regional climate system but has milder thermal and water conditions due to its proximity to Lake Titicaca.

## 3. RESULTS

### 3.1. Climate trends observed in the Central Altiplano

The analysis of historical trends (Mann-Kendall, reference period available through 2020) confirms that the mean monthly maximum temperature shows statistically significant increases in Umala (Central Altiplano) for much of the year, with the most pronounced values between March and September, a period that includes the end of the forage growing season and much of the subsequent regrowth. In Ancoraimes (Northern Altiplano), trends are also positive, but less widespread. Figure 1 compares the Mann-Kendall Z statistic for both zones, month by month.

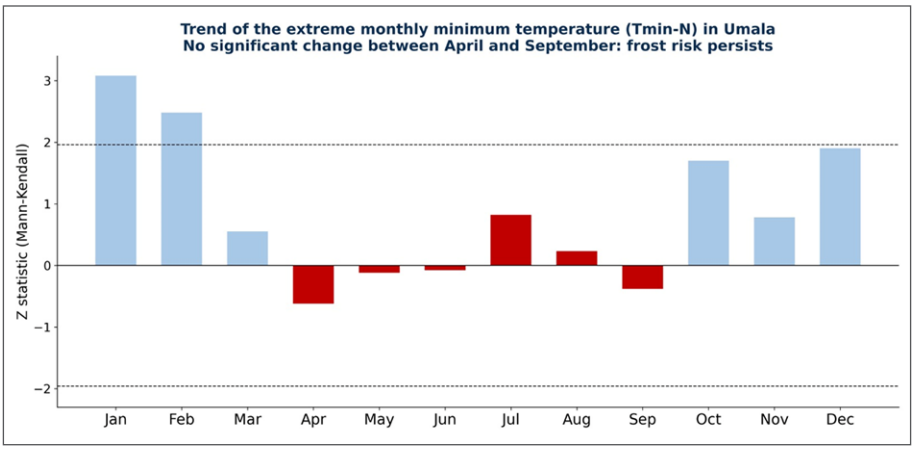
Figure 1. Trend of the mean monthly maximum temperature (Mann-Kendall Z statistic) in Ancoraimes and Umala. Values above the red line (Z = 1.96) indicate a statistically significant positive trend at 95%.




Source: Own elaboration based on García et al. (2025)

However, the critical variable for forage is not the mean temperature but the extreme monthly minimum temperature (Tmin-N), which determines the occurrence of destructive frosts. As Figure 2 shows, in Umala this variable shows no significant trend of change between April and September (the period in which the greatest frost risk for forage crops is concentrated), while it does increase in the summer months (January, February) and in the transition months toward the rainy season (October, December). This means that, although the climate is perceived and measured as warmer on average, the extreme frost capable of destroying an alfalfa cutting or an oat regrowth continues to occur with a frequency similar to that of past decades during winter.

Figure 2. Trend of the extreme monthly minimum temperature (Tmin-N) in Umala. The red bars mark the months (April–September) with no significant trend toward reduced frost risk, coinciding with much of the forage growth cycle




Source: Own elaboration based on García et al. (2025)

Added to this persistent frost risk is a documented delay in the onset of the rainy season. In the Central Altiplano, the small September precipitation peak that historically moistened the soil for October planting has virtually disappeared since the year 2000, and planting can now only take place in the second half of November (García et al., 2025). Since the end of the rainy season has not shifted to the same degree, the growth window with low probability of frost and sufficient water has narrowed, affecting both food crops and rainfed and supplementary-irrigation forage. Table 1 summarizes the main climate indices used in this analysis and their relevance to forage production.

Table 1. Climate variables and indices relevant to forage availability in the Central Altiplano.

| Variable | Index | Relevance to forage |
|---|---|---|
| Maximum temperature (Tmax) | Mean, extreme maximum, extreme minimum monthly. | Determines evapotranspirative demand (ETo) and crop water stress. |
| Minimum temperature (Tmin) | Mean, extreme maximum, extreme minimum (Tmin-N), days with frost. | Tmin-N defines the risk of frost damage to forage shoots and regrowth. |
| Precipitation | Monthly accumulated, days with rain, seasonality index. | Determines water availability for rainfed forage growth. |
| Aridity Index | PP / ETo (FAO Penman-Monteith) | The lower the value, the greater the atmospheric water deficit for forage. |

Source: Adapted from Garcia et al. (2025)

### 3.2. Transformation toward dairy systems in the Central Altiplano

The participatory evidence gathered in Iñacamaya, Sabilani, and Incamaya shows that, since the 1980s, the Central Altiplano's production system shifted from subsistence agriculture (potato, quinoa, cañahua, sheep farming) toward a system specialized in forage and dairy, driven by road improvements, the arrival of the PIL industry, the availability of extensive land, and, according to the producers themselves, the persistence of frost risk, which limited rainfed commercial potato farming (Yucra et al., 2025). Table 2 summarizes this shift, as described by the farmers themselves.

Table 2. Change in productive activity in communities of the Central Altiplano

| Period | Productive activity | Factors of change |
|---|---|---|
| 1980s | Rainfed commercial potato, sheep for meat, quinoa and cañahua for self-consumption. | Subsistence; smaller-scale, low-risk agriculture and livestock. |
| Present day (2023-2024) | Dairy farming and forage (alfalfa), diverse potatoes and commercial quinoa. | Secure, stable biweekly market; extensive plots; forage more frost-resistant than rainfed commercial potato. |

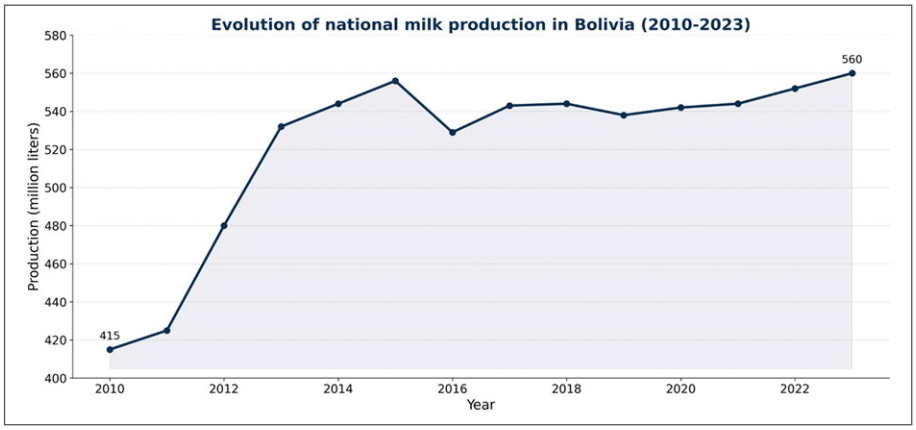
Source: Prepared by the authors based on Yucra et al. (2025) and Taboada et al. (2025).

Unlike communities in the Northern Altiplano such as Chinchaya, where available irrigation allowed production to specialize in high-value vegetables (onion), in dairy communities of the Central Altiplano winter frost risk has not decreased significantly and irrigation remains a costly and difficult option, so farmers chose to integrate annual-cycle forage (mainly alfalfa) alongside various rainfed potato varieties, taking advantage of the greater land area available compared with northern communities (Yucra et al., 2025). This decision, however, concentrates the family's productive risk on forage as virtually the sole critical input, whose availability depends directly on the same climatic variables that affect the other crops: persistent frosts and delayed rains.

### 3.3. Overview of the Bolivian dairy sector and the role of the Central Altiplano

At the national level, Bolivia produced close to 560 million liters of milk in 2023, with a declining growth rate over the last three decades: 75.6% between 1990 and 2000, 34.2% between 2001 and 2011, and only 15.2% between 2012 and 2022 (Ministry of Productive Development and Plural Economy [MDPyEP], 2025). Figure 3 shows this trend.

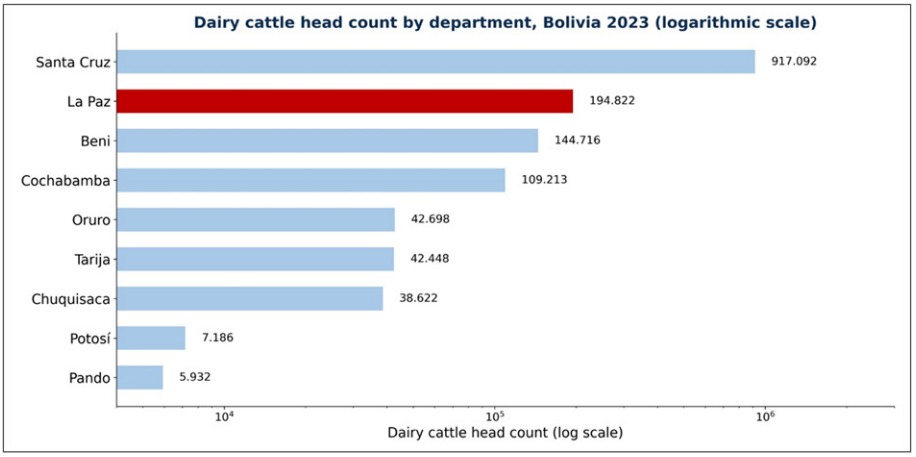
Figure 3. Evolution of national milk production in Bolivia, 2010–2023.




Source: Own elaboration based on data from the National Institute of Statistics, cited in MDPyEP (2025)

The department of La Paz accounts for 9.7% of national milk production, and 32.5% of its cattle herd is dairy cattle, being the second-highest proportion in the country after Oruro (MDPyEP, 2025). Within La Paz, the dairy basin is divided between the Northern Altiplano (the lakeside zone and the Andean plain, comprising the provinces of Omasuyos, Los Andes, and Ingavi) and the Central Altiplano (the Desaguadero zone and the eastern zone, comprising the provinces of Ingavi, Murillo, and Aroma), where Umala and Patacamaya are located (MDPyEP, 2025). Figure 4 situates La Paz within the national context of dairy cattle numbers.

Figure 4. Dairy cattle head count by department, Bolivia 2023 (logarithmic scale).




Source: Own elaboration based on data from the National Institute of Statistics, cited in MDPyEP (2025).

Bolivian dairy yields are low by regional standards: 8.4 liters/cow/day on national average, compared with 15.8 liters/cow/day in South America and 22.9 liters/cow/day in Argentina (MDPyEP, 2025). In the La Paz Altiplano, the reported yield is even lower: a study in the Northern Altiplano reports an average of 6.5 liters/cow/day (Cortez Quispe, 2017), while UMSA's Choquenaira Experimental Station (Central Altiplano) recorded an average production of 9.0 liters/cow/day in Holstein cattle, but with a marked difference between the wet season (11.9 kg/day) and the dry season (6.6 kg/day): a drop of approximately 45% in daily production during the months of lowest forage and water availability (Apthapi magazine, n.d.). Table 3 compares these yields.

Table 3. Comparison of dairy yields at the regional, national, and local (Altiplano) levels.

| Geographic reference | Yield (liters/cow/day) | Source |
|---|---|---|
| South America average | 15.8 | MDPyEP (2025) |
| Argentina | 22.9 | MDPyEP (2025) |
| Bolivia national average | 8.4 | MDPyEP (2025) |
| Santa Cruz | 9-10 | MDPyEP (2025) |
| Cochabamba | 15 | MDPyEP (2025) |
| La Paz (departmental average) | 10 | MDPyEP (2025) |
| Northern Altiplano (small-scale producer) | 6.5 | Cortez Quispe (2017) |
| Central Altiplano, Choquenaira, wet season | 11.9 | Revista Apthapi (s. f.) |
| Central Altiplano, Choquenaira, dry season | 6.6 | Revista Apthapi (s. f.) |

This seasonal gap of nearly half the daily production at UMSA's Choquenaira Experimental Station (also in the Central Altiplano) is consistent with what the scientific literature describes as a direct effect of lower forage availability and quality, and not solely of heat stress (which is itself heightened even in a climate of moderate temperatures like that of the Altiplano), since rainfed and supplementary-irrigation forage production depends on the rainy season, and its scarcity or delay reduces both the quantity and protein quality of the feed available to livestock (Ministry of Productive Development and Plural Economy, 2025; Riquezas de Bolivia, 2021).

### 3.4. Climatic sensitivity of forage crops grown in the Central Altiplano

The main forage crops grown in the Central Altiplano (alfalfa (Medicago sativa), forage oats (Avena sativa), and forage barley (Hordeum vulgare)) were originally introduced to the Altiplano zones, among other reasons, for their greater relative tolerance to frost and drought compared with vegetables or other commercial crops (Forage Research Center, CIFUMSS, n.d.). However, this relative tolerance does not make them immune to climate variability: agronomic research in the region documents that the sharp temperature swing between day and night (worsened by the Central Altiplano's low atmospheric humidity) remains the main threat to forage crop growth between April and September, while water scarcity between August and November limits regrowth before the start of the rains (Jiménez & Mendoza-Pedroza, 2017).

Bolivian forage research explicitly recognizes the need to develop alfalfa and other legume varieties with greater tolerance to pests, disease, drought, and frost, an objective that remains valid because currently available varieties are still vulnerable to these climatic factors (CIFUMSS, n.d.). In this context, the introduction of alternative pastures such as maralfalfa grass (Pennisetum sp.) has been evaluated at UMSA's Choquenaira Experimental Station as a possible way to increase forage yield per hectare in tempered environments, precisely in response to the need to ensure forage availability for the Central Altiplano's dairy cattle (Jiménez & Mendoza-Pedroza, 2017).

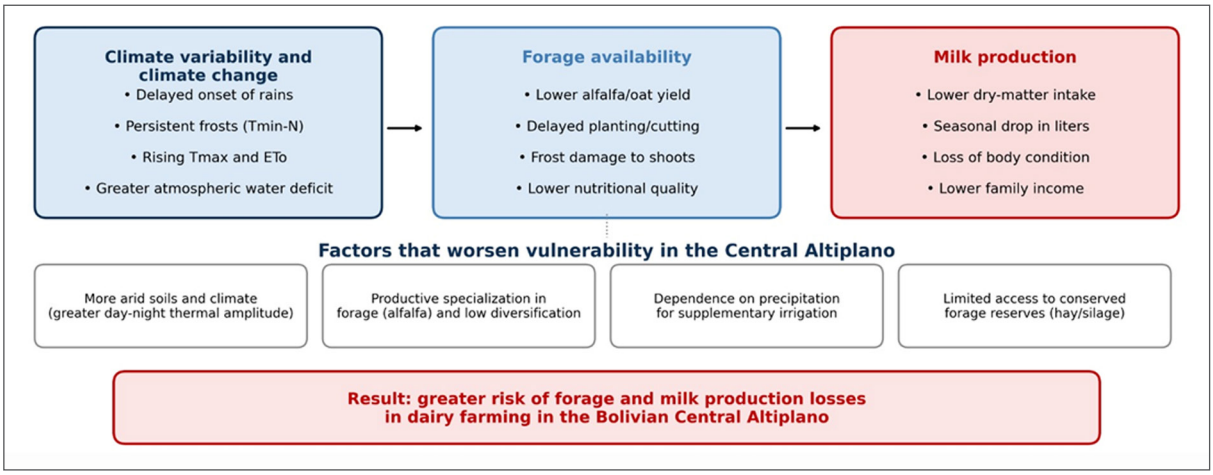
Internationally, scientific evidence on pastures and forage confirms that both water deficit and late frosts reduce the yield and nutritional quality of alfalfa and other forage legumes, effects that intensify when these events occur during the regrowth or first-cutting stages of the crop, precisely the period in which, according to the trend analysis presented in section 3.1, the Central Altiplano's frost risk has not declined significantly.

### 3.5. Cascade of impacts: from climate variability to milk production

Integrating the climatic, agronomic, and productive evidence presented makes it possible to build a conceptual synthesis of the impact chain that links climate variability to milk production in the Central Altiplano, illustrated in Figure 5.

This synthesis does not replace direct measurements of the economic effect on dairy production, which were not the subject of the baseline studies reviewed, but it organizes the available evidence into a causal sequence verifiable against the cited literature.

Figure 5. Conceptual cascade of impacts: from climate variability to dairy production in the Central Altiplano.




Source: Own elaboration based on a synthesis of the sources cited in this article.

**First,** the persistence of frost risk (Tmin-N with no significant reduction trend between April and September) and the delay and intensification of rainfall concentration reduce the safe forage growth window and increase the atmospheric water deficit (higher ETo due to the rise in Tmax). **Second,** this translates into lower forage availability and quality: delayed planting and first cutting, damage to tender shoots from late frosts, and lower protein content in forage harvested under water stress. **Third,** lower forage availability reduces dry-matter intake by dairy cattle, which, according to local evidence from Choquenaira, (where production falls from 11.9 to 6.6 liters/cow/day between the wet and dry seasons) translates directly into a seasonal drop in liters produced, with a consequent loss of income for producer families.

This process is worsened in the Central Altiplano by four structural factors: (a) a more arid climate than the Northern Altiplano, with greater day–night thermal amplitude; (b) growing productive specialization in forage and dairy, with less crop diversification than in the Northern Altiplano; (c) dependence on supplementary irrigation (costly and hard to access in Iñacamaya) to sustain forage outside the rainy season; and (d) producer families' limited access to forage conservation methods (hay, silage) that would help buffer seasonal scarcity, a practice that Bolivian technical literature identifies as necessary but not widespread among small-scale producers (Riquezas de Bolivia, 2021).

## 4. DISCUSSION

The results presented support the argument that the climatic changes documented for the Central Altiplano (particularly the persistence of frost risk during the forage growth cycle, despite the general warming of mean temperatures, together with the delay and intensification of rainfall) constitute a concrete and verifiable threat to forage availability and, through that pathway, to dairy production in the Central Altiplano's dairy-producing zones (analyzed using information from communities in the Municipality of Umala and climate data from Patacamaya). This reading is consistent with the productive transformation described in section 3.2, since farmers in Iñacamaya themselves explain that they shifted toward dairy farming partly because frost risk remained too high to sustain rainfed commercial potato farming, turning instead to forage for its greater relative tolerance.

However, the agronomic evidence reviewed (section 3.4) shows that this relative tolerance does not eliminate forage's vulnerability to late frosts and water deficit, but only reduces it compared with other crops.

The magnitude of the economic risk becomes clearer when looking at the seasonal variability documented at the Choquenaira Experimental Station itself, within the Central Altiplano: a drop of nearly 45% in daily production per cow between the wet and dry seasons. While this figure comes from a controlled experiment and cannot be mechanically generalized to family producers as a whole (whose animals, management, and access to conserved forage differ from experimental conditions) it offers an order of magnitude consistent with the international literature on the effect of forage deficit on milk production, and suggests that prolonged droughts, delayed rains, or late frosts that further reduce forage availability could deepen this seasonal gap, particularly in years with climate conditions more adverse than average, for example, the very strong ENSO event with a high probability of occurring in the 2026–2027 agricultural season (CIIFEN, 2026).

It is important to note that, unlike dairy systems in hot or temperate climates, where heat stress (measured using the temperature-humidity index, THI) is the main mechanism of production loss, in the Central Altiplano the dominant vulnerability mechanism is not heat but the combination of persistent frosts and water deficit that limits forage production. The international literature on THI is useful as a conceptual reference framework, showing that even moderate reductions in dry-matter intake (associated, in hot climates, with lower consumption due to heat stress) consistently translate into lower milk production; however, its direct application to the Bolivian Altiplano requires adapting the analysis to the region's own climatic mechanisms, which favor the impact of frost over high temperatures, and forage deficit over direct heat stress on the animal.

The combination of growing productive specialization toward dairy farming, low diversification of income sources, and limited access to irrigation and conserved forage suggests that producer families in the Central Altiplano could face growing economic vulnerability in the face of extreme climate events, underscoring the need for risk-management strategies specific to the dairy sector: forage diversification, efficient irrigation systems, forage conservation for the dry season, and early-warning mechanisms for late frosts.

## 5. CONCLUSIONS

- The evidence integrated in this article indicates that the Bolivian Central Altiplano, and particularly communities in the Municipality of Umala and Patacamaya, face a specific climatic combination that threatens forage availability and, through that pathway, milk production in Bolivia's high-Andean zones (rising mean and maximum temperatures that do not translate into a comparable reduction in extreme frost risk during the forage growth cycle, and a delay and intensification of rainfall concentration that shortens the safe growth window). This combination is consistent with the sharp seasonal production drop observed locally (from 11.9 to 6.6 liters/cow/day between the wet and dry seasons in Choquenaira), and with the agronomic literature documenting the sensitivity of alfalfa and other forage crops to late frost and water deficit.

- The productive specialization toward dairy farming, adopted by Central Altiplano families partly as an adaptation strategy in response to the persistence of frost risk in other crops, may be generating a new form of vulnerability, concentrating the family's productive risk on forage availability as a critical input, whose production depends on the same climatic variables (frosts, rains) that originally drove the shift in

activity. In light of this scenario, it is suggested that: (a) research and dissemination of forage varieties with greater frost and drought tolerance be strengthened; (b) access to efficient irrigation and forage conservation technologies (hay, silage) that would help buffer seasonal scarcity be expanded; (c) early-warning systems for late frosts, specifically geared to the forage planting and cutting calendar, be developed; and (d) strategies for productive diversification and climate risk management that reduce dependence on a single production system be promoted, in view of increasingly uncertain future climate scenarios.

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