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ORIGINAL ARTICLE

Alfalfa Production in Puno: Trends and Implications for Agriculture and Livestock Farming

Producción de Alfalfa en Puno: Tendencia e implicancias en la agricultura y ganadería

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Abstract

This research on alfalfa production in Puno analyzes the transformation of the regional agricultural structure during the last decades, highlighting the strategic role of this crop in the agricultural and livestock contexts. Based on data from the 1996/1997 to 2021/2022 agricultural seasons, trends are identified, such as the increase in the area devoted to fodder, driven by climate change and migration to mining activities. These changes have led to a shift from traditional crops to others that are better adapted to agroecological conditions, such as alfalfa, which supports the growing dairy cattle activity. Based on data from the 2012 National Agricultural Census, techniques such as cluster analysis were used to classify districts according to production patterns, identifying three agricultural groups characterized by levels of specialization and climatic adaptability. On the other hand, with data from the 1996/1997 to 2021/2022 agricultural seasons, the Gompertz model was used to evaluate technological adoption, observing a sigmoidal pattern in the adoption of alfalfa, with a slow initial growth that accelerated in recent years, consolidating it as an important crop. In conclusion, it highlights the need for policies that balance sustainability, productivity and resilience in the face of climate and social challenges.

Keywords: alfalfa, agricultural production, technology adoption, climate change.

Resumen

Esta investigación sobre la producción de alfalfa en Puno analiza la transformación de la estructura agropecuaria regional durante las últimas décadas, destacando el rol estratégico de este cultivo en los contextos agrícola y ganadero. Con base en datos de las campañas agrícolas 1996/1997 a 2021/2022, se identifican tendencias como el incremento en el área destinada a forrajes, impulsado por el cambio climático y la migración hacia actividades mineras. Estos cambios han generado un desplazamiento de cultivos tradicionales hacia otros mejor adaptados a las condiciones agroecológicas, como la alfalfa, que sustenta la creciente actividad ganadera lechera. A partir de datos del Censo Nacional Agropecuario de 2012, se emplearon técnicas como el análisis de conglomerados para clasificar distritos según patrones productivos, identificándose tres grupos agropecuarios caracterizados por niveles de especialización y adaptabilidad climática. Por otro lado, con datos de las campañas agrícolas 1996/1997 a 2021/2022, se utilizó el modelo de Gompertz para evaluar la adopción tecnológica, observándose un patrón sigmoideo en la adopción de la alfalfa, con un crecimiento

inicial lento que se aceleró en años recientes, consolidándola como cultivo importante. En conclusión, se resalta la necesidad de políticas que equilibren sostenibilidad, productividad y resiliencia ante los desafíos climáticos y sociales.
Palabras clave: alfalfa, producción agropecuaria, adopción de tecnología, cambio climático.

1. Introduction

In the Puno region, the agricultural sector accounts for 17.5% of the Gross Domestic Product (GDP), making it the second most important economic sector after Other Services (Instituto Nacional de Estadística e Informática [INEI], 2023). This sector plays an important role in food security, the generation of rural employment and the preservation of ancestral agricultural practices adapted to the highlands, consolidating itself as a strategic sector for sustainable development.

In recent years, the region's agricultural production structure has undergone significant changes, mainly influenced by climate change and labor migration. Rainfall variations have reduced the area devoted to crops for human consumption, while the area devoted to fodder crops such as oats and alfalfa has increased, favoring the raising of dairy cattle. At the same time, male migration to more lucrative sectors such as mining has reduced the availability of labor in the agricultural sector, shifting responsibilities to rural women. This change has increased the relevance of livestock as the main economic activity, capable of adapting to the new social and economic conditions (Chavas, 2001).

In this context, alfalfa (Medicago sativa L.) has emerged as a strategic crop in Puno, being essential for fodder production that supports cattle ranching. However, this productive specialization poses challenges for food security, as the reduction in crop diversity has had a negative impact on the availability of food for human consumption. Currently, only six crops account for 85% of the harvested area in the region, evidencing a transition towards a production structure more concentrated in livestock. This trend promotes efficiency and productivity in the livestock sector, but jeopardizes the resilience and sustainability of the agricultural system in the face of climatic and economic fluctuations.

Changes in the production structure also respond to global and local factors such as the adoption of new technologies, changes in agricultural policies and risk management needs. For example, climate change has intensified uncertainty in agricultural production, driving the need for agricultural insurance and diversification strategies to mitigate adverse effects. Likewise, public policies that incentivize livestock production have generated positive impacts on producer incomes, but have also contributed to the displacement of traditional crops, exacerbating food insecurity risks (Macdonald et al., 2013; Sumner et al., 2010).

At the social level, migration and income diversification have transformed rural dynamics in Puno. Circular migration (Solomon et al., 2024) and off-farm income are important strategies for coping with fluctuations in farm income and ensuring the economic well-being of rural producers. These dynamics reflect the growing interdependence between agricultural and non-agricultural activities in the region.

In this context, the objective of this research is to analyze the evolution of alfalfa production in Puno and its implications for agriculture and livestock, highlighting the trends that shape the regional production structure.

2. Materials and Methods

In order to analyze the changes in the agricultural productive structure of the highland region of Puno, information on 21 crops corresponding to the 1996/1997 and 2021/2022 agricultural campaigns was used. The evolution of the alfalfa adoption process was analyzed from the series of annual statistics corresponding to the Gerencia Regional de Desarrollo Agrario de Puno (Gerencia Regional de Desarrollo Agrario, n.d.).

On the other hand, the cluster analysis was carried out with information corresponding to the IV National Agricultural Census 2012 (National Institute of Statistics and Informatics [INEI], n.d.). This analysis included the most important livestock species: cattle, sheep and alpacas. In the case of crops, the most important crops were prioritized in relation to the total harvested area of the department of Puno (170 634.27 ha.). The selected crops were: potato (24.5%), quinoa (10.5%), fodder oats (19.5%) and alfalfa (14.4%)[1].

Cluster analysis. This technique makes it possible to identify structures among a set of observations that express a profile in multiple dimensions. It groups individuals or objects into clusters so that within a cluster are those most similar to each other, but different with respect to those found in other clusters. The grouping procedure used was hierarchical, using Ward's method, which minimizes the total intra-group variance and allows well-defined groupings to be formed (Hair et al., 1999; Peña, 2002). Thus, the districts of the department of Puno were grouped based on similarities and differences, considering the harvested area of the most important crops and livestock.

Gompertz model. It is a mathematical model characterized by its ability to represent events whose evolution is sigmoidal, where the initial phase is of exponential growth and decelerates as it reaches its maximum value. It is represented as:

$$Y_t = Ae^{-e^{B-Ct}}$$

Where: Y_t is the value of the dependent variable in period t, $A > 0$ is the asymptotic value, $B > 0$ controls the difference between the initial value and the final value at time t, and $C > 0$ describes the maturity index or specific growth rate.

The inflection point occurs when $Y = \frac{A}{e}$ y $t = \frac{B}{C}$ (Casas et al., 2010).

The technology adoption process is represented by logistic, Gompertz and Bass models that are S-shaped with phases of introduction, growth and saturation (Franco & Rodriguez, 2009; Jabbar et al., 1998). The theoretical percentages include innovators (2.5%), early adopters (13.5%), early and late majorities (34% each) and laggards (16%) (Colton, 2015; Rogers, 1983). These models explain how economic, social and technological factors influence adoption, assessing the speed of adoption and the dynamics of innovation growth and maturity (Dissanayake et al., 2022; Kalaitzandonakes et al., 2018; Lartey, 2020).

The information was processed in Excel and the statistical program SAS OnDemand for Academics SAS Institute Inc., 2023).

In the 1996/1997 crop year (Table 1), the agricultural production structure showed a marked concentration in ten main crops, which together accounted for 93% of the total harvested area. Within this group, potato stood out as the predominant crop, with a 27% share of the total area, followed by barley (14%), fodder oats (12%), quinoa (11%), and feed barley (11%). Other crops of lesser relative importance included coffee (5%), cañihua (3%), alfalfa (3%), dry bean (3%), and oca (3%). This distribution reflects the prevalence of traditional crops oriented mainly to satisfy subsistence needs, with a strategic focus on the production of staple foods and fodder essential for food security and livestock production in the region.

However, when analyzing the production structure in terms of gross value added (GVA), there are significant differences between the distribution of harvested area and the economic capacity generated by each crop, due to price differences in the market. Potato is positioned as the predominant crop, leading in both harvested area (40 190 ha) and economic value generation, with a contribution to GVA of S/ 133 746.99. However, crops such as fodder oats (18 537 ha) and fodder barley (16 921 ha), which occupy relevant positions in terms of area, have a lower share in GVA. In contrast, products such as coffee and alfalfa, although with smaller harvested areas, contribute a considerably higher economic value, due to their higher market prices. This contrast highlights the importance of market prices in the economic valuation of crops, where those with higher commercial value can compensate for their limited territorial extension, highlighting their strategic importance in the generation of income and wealth.

1. It does not include associated crops due to the lack of specific information on the exact area of each crop in the different associations.

3. Results

3.1 Production structure

In order to analyze the changes in the agricultural production structure between the 1996/1997 and 2021/2022 crop years, a comparative analysis was carried out in relative terms. This analysis allowed us to determine the relative importance of each crop, measured by two important indicators: the harvested area (ha) and the gross value of production (S/) used as a proxy to represent the economic capacity generated by each crop in the context of the region.

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Table 1. Agricultural production structure of the 1996/1997 crop year.

	Harvested area			Gross Value of Production (GVP)		
	Cultivation	Hectares	Accumulated participation	Cultivation	VBP (S/)	Accumulated participation
1	Potato	40190	0.266	Potato	133746.99	0.353
2	Barley grain	20437	0.402	Fodder oats	68336.46	0.533
3	Fodder oats	18537	0.525	Feed barley	51855.39	0.670
4	Quinoa	17195	0.639	Coffee	27400.28	0.742
5	Feed barley	16921	0.751	Alfalfa	22232.94	0.801
6	Coffee	6940	0.797	Oca	19161.35	0.851
7	Cañihua	5220	0.832	Other pastures	14154.56	0.888
8	Alfalfa	5095	0.865	Quinoa	13180.89	0.923
9	Haba G. S. (a)	5007	0.899	Barley grain	8869.98	0.947
10	Oca	4274	0.927	Onion	5390.55	0.961
11	Oat grain	3505	0.950	Haba G. S. (a)	4035.57	0.971
12	Other pastures	3065	0.971	Olluco	3047.56	0.979
13	Haba G. V. (c)	1101	0.978	Haba G. V. (c)	2565.15	0.986
14	Tarhui	1055	0.985	Canihua	1782.39	0.991
15	Olluco	895	0.991	Oat grain	1411.00	0.995
16	Onion	562	0.994	Izaño	1276.00	0.998
17	Izaño	518	0.998	Tarhui	529.47	0.999
18	Peas G.S. (b)	190	0.999	Peas G.S. (b)	121.68	1.000
19	Rye grain	100	1.000	Carrot	41.40	1.000
20	Carrot	13	1.000	Rye grain	38.40	1.000
21	Lettuce	12	1.000	Lettuce	38.13	1.000
	Total	**150832**			**379216.14**	

Notas: (a) Bean dry bean, (b) Pea dry bean , (c) Bean Green bean

After 25 years, the first major change in the productive structure of the region is the significant increase in the total harvested area, which went from 150,832 (ha) in the 1996/1997 crop year to 365,748 (ha) in 2021/2022, representing an increase of 242%. This growth reflects a substantial expansion of agricultural activity, possibly driven by factors such as the development of new arable areas, a greater need for fodder and population growth. It also shows an increase in productive capacity and has direct implications in terms of food security, rural employment generation and contribution to the region's GVA, highlighting the strategic role of agriculture as an economic engine at the local and regional level.

In the 2021/2022 crop year (Table 2), the agricultural productive structure of the region shows significant transformations compared to the 1996/1997 crop year, highlighting a change in the relative importance of crops. Alfalfa is positioned as the predominant crop, representing 25% of the total harvested area, followed by fodder oats with 22%. Potato, although still a relevant crop, occupies third place with a 17% share, reflecting a shift from its predominant position in the 1996/1997 season. Likewise, quinoa maintains its relevance with 10%, consolidating its position as a strategic crop, while grain barley and feed barley have decreased their relative importance, representing 6% and 4%, respectively.

This change, with a predominance of crops such as alfalfa and forage oats, is a strategic response to the challenges imposed by abrupt climatic changes and the displacement of the labor force to mining activities. The prioritization of fodder crops supports dairy cattle raising, an economic activity that is less risky than traditional crops in the face of climate variability, although it is not exempt from being affected by extreme events. This strategy ensures greater productive stability in a context of climate vulnerability and reduction of agricultural labor due to displacement to mining.

On the other hand, the agricultural productive structure according to GVA shows significant changes with respect to 1996/1997, reflecting a reconfiguration in the economic contribution of crops. Potato continues to lead with 34% of GVA, consolidating its relevance both in terms of area and value generation. However, fodder oats, with a contribution of 33%, stands out as the second most important crop, reflecting the growing influence of fodder crops in the region's agricultural economy.

Alfalfa ranks third with 17%, while traditional crops such as quinoa (4%) and feed barley (3%) show a low share. On the other hand, crops such as coffee (2%), along with grain barley, pasture, goose and grain oats, each with barely 1% of GVA, have significantly reduced their economic importance. This reflects a strategic shift towards fodder crops, more closely linked to livestock activity, as response to new production dynamics and the challenges imposed by climate change and the reduction of agricultural labor.

During the period analyzed, the crops with the highest year-on-year growth rates were alfalfa (13.3%) and fodder oats (5.0%), which shows a clear prioritization of fodder crops in the region. On the other hand, crops for human consumption, such as quinoa (3.2%) and potato (1.9%), showed lower growth rates, showing a shift towards livestock activities, based on the development of a solid fodder base to guarantee the economic stability of dairy farming.

3.2 Productive structure: Grouping of districts by agricultural and livestock importance.

The cluster analysis classified the districts of the Puno region into three representative groups, using as variables the harvested area of the main crops (potato, quinoa, fodder oats and alfalfa) and the number of heads of the most important livestock species (cattle, sheep and alpacas). These variables, extracted from the IV National Agricultural Census 2012, made it possible to identify patterns that reflect the agricultural production structure of the region. The results of the analysis are visualized in the dendogram in Figure 1, which shows how the districts were grouped according to similarities.

Based on the results shown in Table 3, the characterization of the clusters is as follows:

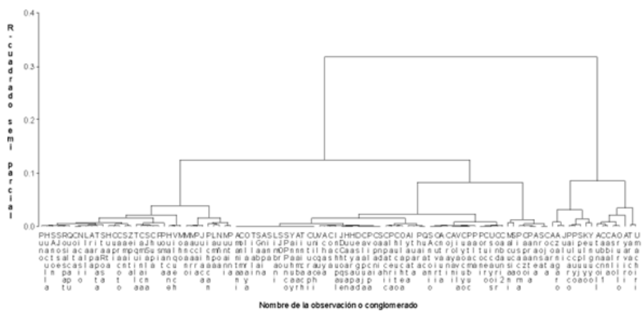
a. Alpaqueros producers with limited agriculture It comprises 57 districts whose production is marked by the predominance of alpaca raising, with an average of 957,402 head and a standard deviation of 16,796.5, reflecting the adaptation of this activity to the high altitudinal levels and extreme climatic conditions, such as low temperatures and frequent frosts. Agricultural activities are limited, with small areas dedicated to crops such as alfalfa (1,066.5 ha), quinoa (1,260.3 ha), potatoes (10,142.8 ha) and forage oats (2,476.4 ha), characterizing these districts as dependent on resources adapted to cold climates and marginal soils.
b. Intermediate level Agricultural Producers It is made up of 35 districts and is characterized by a balance between agriculture and livestock, with activities defined by intermediate altitudinal levels where climatic conditions are more moderate, allowing for greater productive diversity. Cattle

Table 2. Agricultural production structure for the 2021/2022 crop year.

Harvested area				Gross Value of Production (GVP)		
Order No.	**Crops**	**Hectares**	**Accumulated participation**	**Crops**	**VBP (S/)**	**Accumulated participation**
1	Alfalfa	91617	0.250	Potato	1608351.12	0.344
2	Fodder oats	79137	0.467	Fodder oats	1519760.17	0.670
3	Potato	63120	0.639	Alfalfa	810223.59	0.843
4	Quinoa	36864	0.740	Quinoa	176685.08	0.881
5	Barley grain	23573	0.805	Feed barley	131652.79	0.909
6	Feed barley	14871	0.845	Coffee	110863.76	0.933
7	Coffee	10975	0.875	Barley grain	53363.14	0.944
8	Other pastures	10915	0.905	Other pastures	53208.68	0.956
9	Haba G.S. (a)	9689	0.932	Oca	48139.62	0.966
10	Oat grain	8590	0.955	Olluco	43150.16	0.975
11	Canihua	5601	0.970	Haba G. S. (a)	32501.70	0.982
12	Oca	3485	0.980	Canihua	29142.84	0.988
13	Olluco	2900	0.988	Izaño	14321.61	0.992
14	Izaño	1101	0.991	Oat grain	12364.15	0.994
15	Tarhui	1101	0.994	Haba G. V. (c)	10096.07	0.996
16	Arveja G. S. (b)	1085	0.997	Tarhui	9206.11	0.998
17	Haba G. V. (c)	710	0.999	Onion	5520.52	0.999
18	Onion	358	1.000	Pea G. S. (b)	2122.66	1.000
19	Rye grain	35	1.000	Carrot	170.19	1.000
20	Carrot	16	1.000	Rye grain	68.96	1.000
21	Lettuce	5	1.000	Lettuce	34.87	1.000
		365748			**4670947.77**	

Notas: (a) Bean dry bean, (b) Pea dry bean , (c) Bean Green bean

Figure 1. Dendogram and definition of clusters



(272,708 head) and sheep (906,880 head) have a prominent presence, while alpacas (379,594 head) are less representative than in Conglomerate 1. Agriculture includes larger areas dedicated to alfalfa (11,216 ha), forage oats (14,036.9 ha) and potatoes (12,986.1 ha), reflecting a favorable environment for crops with higher water demand and relatively productive soils.

c. Producers with the highest agricultural intensity It is made up of 16 districts and corresponds to areas located at lower altitudinal levels, with relatively less extreme climates and greater availability of water resources, which allows for greater productive intensity. Although alpacas (103,277 head) and sheep (533,548 head) are less represented, cattle (218,650 head) and crops such as alfalfa (13,029 ha) and fodder oats (15,317 ha) stand out with the largest areas and average values. The higher standard deviations observed in this group reflect a diversity in production practices, possibly related to a better adaptation to climatic conditions and a better use of available technologies.

Table 3. Characteristics of the clusters

	No. of districts	Total	Media	Standard deviation
Conglomerate 1: Alpaqueros producers with limited agriculture				
Cattle	57	101397.0	1778.9	1622.0
Sheep	57	576277.0	10110.1	9279.9
Alpacas	57	957402.0	16796.5	25795.2
Alfalfa	57	1066.5	18.7	50.4
Quinoa	57	1260.3	22.1	45.3
Potato	57	10142.8	177.9	266.3
Fodder oats	57	2476.4	43.4	80.2
Conglomerate 2: Intermediate level agricultural and livestock producers				
Cattle	35	272708.0	7791.7	3625.8
Sheep	35	906880.0	25910.9	11440.7
Alpacas	35	379594.0	10845.5	14487.5
Alfalfa	35	11216.0	320.5	314.6
Quinoa	35	5731.6	163.8	149.0
Potato	35	12986.1	371.0	316.0
Fodder oats	35	14036.9	401.1	245.0
Conglomerate 3: Producers with higher agricultural intensity				
Cattle	16	218650.0	13665.6	5010.0
Sheep	16	533548.0	33346.8	17323.1
Alpacas	16	103277.0	6454.8	10572.0
Alfalfa	16	13029.0	814.3	726.7
Quinoa	16	8471.2	529.4	241.4
Potato	16	15584.9	974.1	663.6
Fodder oats	16	15317.0	957.3	669.4

Due to the variables used in the cluster analysis, the districts of the jungle region were classified within cluster 1, since it was difficult to clearly separate districts located in transition zones between the highlands and the jungle. In particular, the districts of Ajoyani and San Gaban, in the province of Carabaya, and Phara, San Juan del Oro, Yanahuaya, Alto Inambari and San Pedro de Putina Punco, in the province of Sandia, showed zero or less than 10% participation in the variables analyzed, with respect to the provincial total. This shows that the predominant productive activities in these districts do not conform to the main agricultural patterns considered in the other clusters (Figure 1).

In addition, the district of Ilave stands out as an atypical case. On the one hand, it has the largest harvested area of quinoa, with 2,389 hectares, complemented by significant potato production (5,455 hectares) and forage oats (1,413 hectares). On the other hand, its livestock activity is also outstanding, whose livestock capital consists of 24,408 cattle, 71,627 sheep and 19,630 alpacas.

3.3 Alfalfa production trend

In the agricultural context, the Gompertz model is important for understanding the process of adoption or adaptation of technologies, since it allows us to analyze the speed and limitations inherent to this process. In the case of production, the results of the model reflect a sigmoidal growth pattern, evidencing a slow initial behavior, followed by a progressive stabilization around an asymptotic limit of 257,764.6 hectares. The estimated model was as follows:

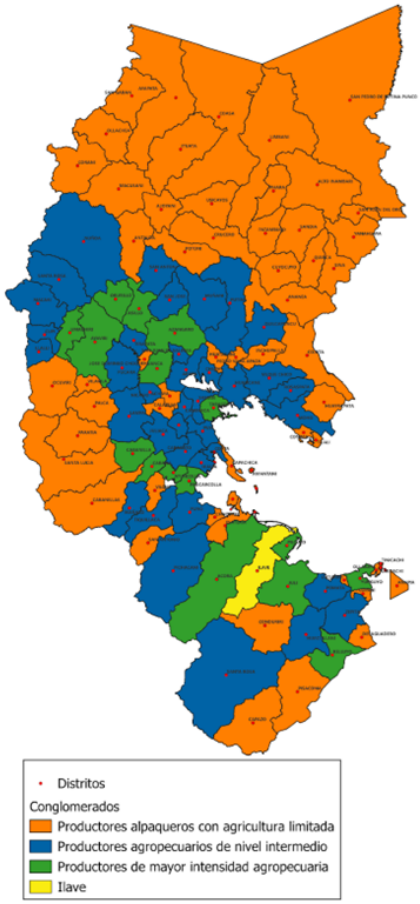
$$Y_t = 257764.6\, e^{-e^{(1.8229 - 0.0702t)}}$$

Where Y_t is the alfalfa production in period t, A (257764.6) is the asymptotic value of production, B (1.8229) is the parameter that controls the curve fit, and C (0.0702) is the growth rate of the process. According to the estimation, the "adaptation" period lasted approximately 12 years [2] culminating in

2. In the Gompertz model, it is calculated as:

$$t = \frac{B - 1}{c}$$

Figure 2. Spatial distribution of clusters.

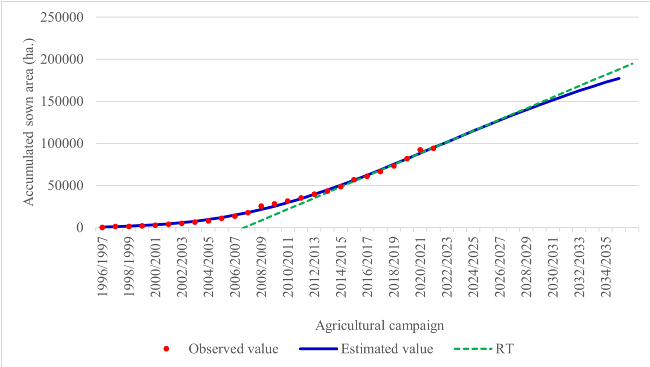


the 2007/2008 crop year. In the context of technology adoption, this period represents the initial early adoption phase or the stage of technology introduction and testing. During this stage, growth was slow due to various constraints: diffusion, initial barriers such as management problems or resistance to change. On the other hand, the highest growth rate occurred after 26 years, i.e., in the 2021/2022 crop year (Figure 2).

In addition, it is important to note that alfalfa was introduced in the Puno region during the 1960s, and the first available statistics date from 1970, with a harvested area of 20 hectares. In 1988, a significant expansion was registered, reaching 3,588 hectares harvested (Ccama, 1991). However, the lack of continuity in the statistical record during this period suggests that the process of initial adoption of alfalfa spanned more than 37 years, a considerably long period for a process of technological diffusion in agriculture.

Therefore, it is concluded that the process of adoption of alfalfa was initially slow, but after overcoming the limitations, it has been consolidated as an important and strategic component in the agricultural productive structure of the region.

Figure 3. Alfalfa adoption process: 1996/1997 to 2021/2022.



4. Discussion

Changes in the productive structure of the Puno region reflect a process of adaptation to climatic, economic and social factors, which have led to the predominance of forage crops such as alfalfa and oats, essential to sustain dairy cattle ranching. According to Chavas (2001), the adoption of new technologies, the management of climatic risks and the transfer of labor to more lucrative activities are determining factors in productive transformations. In this sense, the growing importance of livestock in Puno is also explained by local agricultural policies that have prioritized incentives to the livestock sector, to the detriment of traditional crops such as potato and barley (Macdonald et al., 2013; Sumner et al., 2010). This transition has generated income for producers, but also states challenges related to the loss of agricultural diversity and food security by concentrating production in activities that are less resilient to extreme events, as warned by Solomon et al. (2024). These findings underscore the need for an integrated approach that balances economic demands with the sustainability of the regional agricultural system.

The prioritization of forage crops such as alfalfa and oats, together with the expansion of dairy cattle farming, have been identified as key climate change adaptation strategies (Taonda et al., 2024). These practices respond to the need to guarantee a source of feed for livestock, especially in contexts of greater climate variability (Baraj et al., 2024), and allow stabilizing the income of rural producers, mitigating the risks associated with traditional crops. Dairy farming, being less exposed to catastrophic losses from extreme weather events compared to agriculture, offers greater economic predictability, reducing the vulnerability of rural families (Lobell & Gourdji, 2012). The transition to a livestock-dominated model reflects an adaptive response to climate change and a structural shift in the rural economy, where economic stability has gained priority, although at the cost of food security and crop diversity (Zerbo et al., 2024).

On the other hand, the importance of migration as an adaptation and response strategy to climate change reflects how people seek new opportunities and resources in challenging contexts. This is a process of labor transfer to more lucrative activities to improve economic conditions amid complex scenarios (Boas et al., 2019). In this scenario, mining activity is a source of income and livelihood for vulnerable households, characterized by informality, income inequality and marked gender roles: women in lower paid tasks and men in better paid positions. This highlights the need for policies to improve working conditions and reduce inequalities (Goetz, 2022).

With respect to cluster analysis, this technique is used to identify "recommendation domains", it means, groups of farmers with similar needs and circumstances for which a specific recommendation would be appropriate. This approach, according to Byerlee et al. (1980), facilitates the targeting of research, the efficient allocation of resources and the design of more effective policies. By classifying farmers according to their production patterns, resources and constraints, researchers can better understand the diversity of farming systems and tailor interventions to the specific needs of each group (León-Velarde & Quiroz, 1994; Williams, 1994). Cluster analysis, therefore, contributes to a better understanding of the complexities of agriculture and allows the development of more relevant and sustainable strategies for rural development (Escobar & Berdegue, 1990; Tatis Diaz et al., 2022).

In this context, altitudinal levels configure climatic and edaphic conditions that affect crop selection and agricultural practices, promoting productive specialization through systems adapted to each level. These variations influence the productive structure, reflecting in the management strategies, intensity and diversity of agricultural systems, which highlights the importance of analyzing them considering the specific particularities and limitations of each altitude (López Rodríguez et al., 2024).

In relation to the adoption process and adoption curves, it highlights the dynamic and multifactorial nature of the integration of new technologies or innovations into society. According to Rogers (1983), this process is characterized by a progression from innovators to laggards, going through phases defined as introduction, growth and saturation. The adoption curve follows a sigmoidal pattern, where initial introduction is slow, followed by rapid growth during early and late majority adoption, until stabilization is reached when the market is saturated. This behavior can be modeled using mathematical tools such as the Gompertz and logistic models, which capture growth and maturity dynamics, as well as underlying factors such as social and economic contagion (Franco & Rodriguez, 2009; Jabbar et al., 1998; Lartey, 2020).

Economic, socio-cultural and technological factors play a crucial role in adoption, where elements such as perceived advantages, compatibility and simplicity of innovations significantly influence their acceptance. Studies such as Kalaitzandonakes et al. (2018) and Dissanayake et al. (2022) highlight that education, access to credit and social networks are determinants in the speed and extent of the process. In addition, the success of innovations lies in their ability to meet market needs and expectations, which varies by context and stage of adoption. These patterns reflect the importance of understanding adoption dynamics to design effective strategies that maximize the impact of innovations (Colton, 2015).

5. Conclusion

The productive structure of the Puno region has evolved towards greater specialization in forage crops such as alfalfa, which reached an estimated stabilization area of 257,764.6 hectares. The cluster analysis classified the districts into three groups according to their agricultural characteristics, highlighting areas with high agricultural intensity and a balance between agriculture and livestock, while in areas of extreme altitude, limited systems based on alpaca raising predominate. Finally, the alfalfa adoption curve, modeled with Gompertz, reveals a slow initial introduction process followed by accelerated growth and stabilization, consolidating this crop as a strategic axis for livestock sustainability in the region. These changes underscore the need for policies that balance productive specialization, agricultural diversity and climate resilience.

Author Contributions

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Annex 1. Harvested area (Ha.)

Harvested area (Ha.)

Agricultural campaign	Fodder oats	Alfalfa
1996/1997	18537	5095
1997/1998	26999	5223
1998/1999	28029	5111
1999/2000	29195	5349
2000/2001	24533	5479
2001/2002	38460	5935
2002/2003	37936	6121
2003/2004	38833	6881
2004/2005	40873	7570
2005/2006	43915	9632
2006/2007	44717	10250
2007/2008	45318	13695
2008/2009	51139	15960
2009/2010	50940	19382
2010/2011	53402	26970
2011/2012	53776	28716
2012/2013	56978	33299
2013/2014	59946	36186
2014/2015	62162	42231
2015/2016	63075	47180
2016/2017	68040	55406
2017/2018	75165	59242
2018/2019	75010	64664
2019/2020	76086	71146
2020/2021	76983	80138
2021/2022	79137	91617

Source: Regional Management of Agrarian Development of Puno.