RESEARCH ARTICLE

Classification, technical efficiency, and economic performance of producers in the main productive region of quinoa in Peru

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Abstract
Classifying small agricultural producers based on their technical efficiency and economic performance allows us to gauge the potential to improve yield in the quinoa crop, promote local food security, and improve rural incomes. Consequently, the objective of this study was to characterize and classify quinoa producers at the Peruvian Altiplano based on their productive, economic, and social attributes, so the technical efficiency and economic performance of the identified groups can be analyzed. Hence, 409 surveys conducted among quinoa producers in the Puno region were used to run the statistical analysis using two-stage cluster techniques, stochastic frontier, linear regression, and ANOVA tests. The results revealed that three groups of producers exhibited discriminating variables in the use of fertilizers, organic fertilizers, weed control, application of fungicides, production of quinoa, the total area of all crops, and achievement of economic benefits. It was evidenced that the use of seeds and fertilizers, in optimal quantities, increased yield, and in combination with quinoa sales, were the significant variables to differentiate technical efficiency. The high Andes are characterized by smallholdings, subsistence agriculture and, agrobiodiversity conservation and, although cultivation practices are predominantly low technical efficient, it would be possible to rapidly increase agricultural performance with a better allocation of external inputs. However, this could be done to regional limits, for this reason, the role of public policy is very important so that producers can get broader access to production inputs and technical services.

Keywords: technical efficiency; classification of producers; stochastic frontier analysis; two-stage cluster; quinoa.

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1. Introduction
Tejada (2020) indicates that quinoa (Chenopodium quinoa Wild.) is possible to be produced in the five continents due to its diversity and adaptability (i.e., able to grow from sea level to 4000 meters above sea level). Quinoa is cultivated along the whole Andes, with the center for the highest diversity of Chenopodiaceae in the Peruvian-Bolivian Altiplano region (Mujica & Jacobsen, 2006). According to Gamboa et al. (2020a), the interest in quinoa is changing the way production and consumption are done among small farmers in the Andes of Peru. Pinedo-Taco et al. (2018) indicate that recent production models are accentuating conventional and organic options, relegating the use of mixed and traditional production systems. Thus, in the last 10 years, because of growing international demand, cultivated areas have increased in Peru – moving from diversified production systems for self-consumption in the Andean region, to monoculture farming of improved varieties on the coast, to meet the characteristics demanded by the market (Pinedo-Taco et al., 2021) for exportation (Gamboa et al., 2018; 2020a; 2020b).

Increases in yields are the result of the intensification of small-scale production as well as greater use of fertilizers, pesticides, and mechanization (MIDAGRI, 2021. Gamboa et al., 2020b).

Accordingly, Pando & Aguilar (2016) reported that the systems with the highest quinoa production in Peru are found in two agroecological zones: the Inter-Andean valleys (between 2500 to 3500 masl) and, the Altiplano zones (3600 to 4000 masl). In the Puno region, traditional systems of diversified and multi-varietal production for this crop are still found (Pinedo-Taco et al., 2021. Pinedo-Taco et al. 2018; and Pando & Aguilar, 2016) which take place under adverse conditions caused by high elevations (3850 meters above sea level) and the extreme climatic variations of the Peruvian Altiplano.

Jacobsen (2003). Jacobsen et al. (2003) and Ruiz et al. (2014) indicated that in the traditional quinoa producing regions of Peru, yield is limited by climatic and agroecological conditions like drought, frost, wind, hail, soil salinity and soils with low fertility. FAO (2018) pointed out that quinoa is an alternative to climate change
because of its adaptability to diverse ecological levels, efficiency in the use of water and tolerance to drought. However, in the Puno region, considered the major place for quinoa production in Peru, there is limited knowledge about characterizing quinoa producers. This lack of knowledge includes insights on agricultural yields, in connection to technical efficiency in the use of productive inputs and economic performance (Khanal et al., 2018; Tenaye, 2019; Soares & Spolador, 2019; Fáre et al., 1994). All applied to family farming which contributes to the preservation of ecosystems and conservation of local varieties using agroecological and traditional techniques (Zebeiro & Aguirre, 2014) coupled with difficult access to technical services (Minaya & Chinguel, 2021). This also reveals the risks of food insecurity even with respect to goods that are produced and consumed locally (Rosalés & Mercado, 2020), and finally, the articulation of the local economy with market products and factors (Escobal et al., 2015).

Therefore, the objective of this study was to characterize and classify quinoa producers in the Puno region in relation to their productive, economic, and social characteristics, and to assess technical efficiency and economic performance in each of the identified groups.

2. Materials and methods

The study was non-experimental using primary and secondary sources of information. The study area was the Puno region, located in the eastern part of Peru near the border with Bolivia. Puno includes 13 provinces and 110 districts and covers an area of 71,999 km² which represents about 6.0% of the Peruvian territory. This region consists of highlands in 61.0% of its territory, rainforest in 32.1% with widespread population groups and limited road infrastructure, an insular region of about 0.02% and the Peruvian part of Lake Titicaca in 6.9% (BCRP, 2021). The population size in 2017 was 1,172,697 people, being the urban population the majority (53.8%). The agricultural area is 4,464,473 ha (BCRP, 2021). The cultivated area of quinoa in the growing season of August 2020 - July 2021 was 36,868 hectares, and in 2020 it corresponded to 39.6% of the national quinoa production (MIDAGRI, 2021). The declaration of the International Year of Quinoa by FAO (2013) made this grain to be considered a "superfood" because of its nutritional qualities that include good levels of proteins and micronutrients. That classification has generated growing interest in consumers in higher-income countries (Escurodo et al., 2014; Nowak & Charrondière, 2016; Nowak & Charrondière, 2016; Simnadis at al., 2015).

Quinoa is considered a strategic food for world food security and an income opportunity for small farmers in the Andean region (FAO & CIIRAD, 2015).

The International Year also had a significant impact on national production as the numbers increased from 33,000 tons in 2005 to 100,000 tons in 2020. In Puno, quinoa production went from 28,000 t in 2005 to 40,000 t in 2020. For the period 2005-2020, the growth rate nationwide in quinoa production was 11.0% per year with a coefficient of variation (CV) of 0.47. In Puno, the production grows at an annual rate of 3.1% with a CV of 0.17. The producer’s price, from 2005 to 2020, grew at an annual rate of 13.9%, with
risks before maximizing profitability, and the sale of agricultural products or labor. Mercado et al. (2020) emphasize the need of setting up typologies given the heterogeneity that they present in the territory and the double economic estimate that comes from family units of production and of consumption. Thus, a Two-Stage cluster method was used to group the data and generate an optimal number of clusters. Euclidean distances allow us to identify to what degree each pair of observations have a greater similarity and belong to the same group, given the objects $i_1, i_2, \ldots, i_n$; measured according to variables $x_1, x_2, \ldots, x_p$, their distance was obtained according to equation 2.

$$d_{i_1i_2} = \sqrt{\sum_{k=1}^{p} (x_{ik} - x_{2k})^2} \ldots (2)$$

The determining variables for the classification of homogeneous clusters were: Productive: use of organic fertilizer (island guano, manure, compost, etc.); weeding, use of fertilizers (ammonium nitrate, ammonium sulfate, urea, etc.), application of fungicides or insecticides; total area of all crops in ha; total area of quinoa cultivation in ha; quinoa yield quantity expressed in t; use of equipment in hours/ha; labor in hours/ha. Economic: Quantity of quinoa production destined for self-consumption in t; quantity of quinoa production destined for sales in t; source of income of the head of household; net economic benefit in Peruvian soles. Social: Spoken language; the age of the head of household.

The evaluation of the cluster analysis considered multicollinearity between cluster variables and, the multivariate classification model was estimated in two phases (Rubio-Hurtado & Baños, 2017). The statistical software SPSS validated the precision of the clusters, and the silhouette measures of cohesion and separation, and determined the importance of the variables for each group. The continuous variables assumed a normal distribution, the categorical variables were multinomial and independent. The variables were subjected to an ANOVA test to determine the difference in efficiencies between the groups, test the variances between them, and estimation of $p$-values at a significance level of 0.05 for each one of them.

Technical efficiency is commonly assessed using Data Envelopment Analysis (DEA) and Stochastic Frontier Analysis (SFA) (Nguyen et al., 2019; Guesmi et al., 2015) to verify the use of the least inputs to produce, given technology, the greatest quantity of products within a frontier of efficient production. Inefficient producers would be unable to find that frontier (Mammit et al., 2020). This study used a Stochastic Frontier model calculated with Stata Software, where a Cobb-Douglas behavior function was postulated, assuming noise disturbances (symmetric). A probabilistic distribution was formulated for the technical efficiency disturbances (semi-normal) to analyze them by producer’s clusters. According to Debreu (1951) and Farrell (1957), technical efficiency from “x” and “b”, vector of N inputs used in production and vector of technological parameters, within the amount of product $y = f(x; b)$, from which equations 3 and 4 were obtained.

$$TE(y,x) = \frac{Y_i}{f(x)}; 0 \leq TE \leq 1 \ldots (3)$$

$$Y_i = TE(y,x) + f(x) \ldots (4)$$

$Y_i$ reaches its maximum possible value at $TE = 1$. From the Cobb-Douglas function, it is disregarded considering compounded error $e_i = v_i + \mu_i$ in equation 5, with the definition in 6:

$$\log y_i = \beta_0 + \beta_1 \log x_1 + \beta_2 \log x_2 + \beta_3 \log x_3 + \beta_4 \log x_4 + \beta_5 \log x_5 + v_i + \mu_i \ldots (5)$$

$\beta$ is defined:

$$\beta_0, \beta_1, \ldots, \beta_5 > 0 \ldots (6)$$

Where: $\log y_i$ = logarithm of quinoa yield in t/ha; $\log x_1$ = logarithm of the total area cultivated in ha; $\log x_2$ = logarithm of labor in hours per ha; $\log x_3$ = machinery logarithm in hours per ha; $\log x_4$ = logarithm of quinoa seeds in kg/ha; $x_5$ = age of the head of the household; $v_i$: stochastic error, collects the impact of effects that are not under control, presented normal distribution $N(0, \sigma^2 v_i)$; $\mu_i$: technical efficiency index, non-negative and asymmetric, technical inefficiency of semi-normal distribution, since the output can only decrease below the limit (equation 7).

### Table 1

<table>
<thead>
<tr>
<th>Province</th>
<th>Planting (ha)</th>
<th>Yield (t)</th>
<th>Number of Producers</th>
<th>Number of Districts</th>
<th>Number of Surveys Applied*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total Districts</td>
<td>Surveys Taken</td>
</tr>
<tr>
<td>Azángaro</td>
<td>6 180</td>
<td>8 81</td>
<td>14 921</td>
<td>18</td>
<td>14</td>
</tr>
<tr>
<td>Puno</td>
<td>4 151</td>
<td>5 365</td>
<td>13 048</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>Chucuito</td>
<td>3 274</td>
<td>3 531</td>
<td>10 759</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>El Collao</td>
<td>4 903</td>
<td>4 139</td>
<td>8 924</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Huancañé</td>
<td>2 967</td>
<td>2 850</td>
<td>6 137</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>Lampa</td>
<td>2 210</td>
<td>2 004</td>
<td>3 642</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>San Román</td>
<td>4 600</td>
<td>4 200</td>
<td>3 636</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Melgar</td>
<td>1 017</td>
<td>1 161</td>
<td>3 440</td>
<td>9</td>
<td>7</td>
</tr>
<tr>
<td>Otras 5 provincias</td>
<td>976</td>
<td>1 067</td>
<td>3 067</td>
<td>39</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>30 278</td>
<td>30 198</td>
<td>67 574</td>
<td>409</td>
<td></td>
</tr>
</tbody>
</table>

Source: IV CENAGRO 2012 for surveys applied in October 2017, see Figure 2 (Map).
The variables defined that include *dummy* which take the value of one and two as follows: Efficiency =  ε\text{ffic}_\text{gen}3 = individual technical efficiency
\begin{align*}
\beta_1 &= \text{received training, } \beta_2 = 2 \text{ if not; } \beta_3 = 1 \text{ belongs to an association, } \beta_4 = 2 \text{ if not; } \beta_5 = 1 \text{ applies fertilizer (organic), } \\
\beta_6 &= 2 \text{ if not; } \beta_7 = 1 \text{ applies fungicide or insecticide, } \\
\beta_8 &= 2 \text{ if not; } \beta_9 = 1 \text{ puts quinoa for sale, } \\
\mu &= \text{variable not included in the ANOVA test to review differences in economic benefits between groups at a significance level of 0.05.}
\end{align*}

### 3. Results and discussion

#### 3.1 Characterization of the quinoa producers in Puno

The characterization, based on the surveys, found that for crop management: 24% of the producers apply organic fertilization, 51% use plowing, 86% apply harrow and 11% do level. At planting, 62% make rows and 33% do coverings; 48% use chemical fertilizers, 20% perform leveling, 67% do weed control and 18% apply fungicide or insecticide. There was a low percentage doing leveling and using fungicides or insecticides. Recommended amounts of seed to use are between 15 to 20 kg per ha (Pando & Aguilar, 2016); the survey found that 54% use

\begin{align*}
\mu_i &= \{\beta_0 + \beta_1 \log x_1 + \beta_2 \log x_2 + \beta_3 \log x_3 + \beta_4 \log x_4 + \beta_5 \log x_5 + \nu_i \} - \log y_i 
\end{align*}

The stochastic frontier parameters and technical efficiencies were estimated for each unit involved, arranging them to detect the most efficient of the clusters formed. The significance (p-value) of the variables was also analyzed. The technical efficiency for each unit involved (Efficiency) was evaluated, considering the qualitative variables involved in the formation of groups in the Two-Stage cluster and the variable sales. Regression is defined in equation 8, considering equation 9:

\begin{align*}
\text{Efficiency} &= y_0 + y_1 d_1 + y_2 d_2 + y_3 d_3 + \cdots + y_4 d_9 + \mu_i ... (8) \\
y_2, y_3, ..., y_9 < 0 ... (9)
\end{align*}

Sources: This study. Based on 409 surveys from October 2017.
In the classification of family farming (FF) conducted by MINAGRI (2015), 57% were subsistence FF, 38% were intermediate, and 4% were consolidated FF. The net economic benefits, considering income from total production destined for sales at the local price, showed that consolidated FF had a higher net economic benefit in relation to intermediate and subsistence FF (Table 3).

3.2 Homogeneous clusters of quinoa producers in Puno

The assessment with the Two-Stage cluster analysis identified three groups of producers with the following seven influential variables used in the classification: Uses chemical fertilizers (yes / no); does weed control (weeding) (yes / no); use organic compost (yes / no); apply fungicide and insecticide (yes / no); total quinoa production (t); total area of all crops (ha); and net economic benefit (soles). The ANOVA test was significant for quinoa production (t) ($p = 0.03$), crop's total area (ha) ($p = 0.05$), economic benefit (Peruvian soles) ($p = 0.034$), labor (hours/ha) ($p = 0.011$), sale of quinoa (t) ($p = 0.020$) and age ($p = 0.000$).

Table 3 summarizes the results of the Two-Stage cluster. Some significant variables of interest were incorporated in the ANOVA test. Each group of quinoa producers was named according to their main characteristics. Thus, group two is “good performance” (GP) which exhibited better indicators in quinoa production (t), total area of all crops (ha), and net economic benefit (soles). It also had higher percentages in two other cultural activities. Group one was called “moderate performance with weeding” (MPwW) to differentiate it from the group three “moderate performance without weeding” (MPwoW). In the latter, the continuous classification variables were below the general average.

In group one (MPwW), 100% of producers do not use chemical fertilizers or carry out weed control, and they have fewer hours/ha of use of machinery. This group is ethnically composed of Quechua (52%) and Aymara (48%) farmers, about 65 % of producers do not sell quinoa and 71% allocate most of their production for self-consumption. In group two (GP), 100% of producers use fertilizers, 74% do weed control, have a higher-than-average yield of quinoa (0.18 t) and, total area of crops (1.90 ha). GP has a greater net economic turnaround, makes greater use of labor (441 h/ha), does better in quinoa sales (0.068 t), performs more harrowing (92%), uses more machinery (26.2 h/ha) and seed (24.0 kg/ha).
This group mostly includes Quechua farmers (67%) and allocates a higher proportion of their production for sale (38%). In group three (MPwoW), 100% of producers use fertilizers, but do not confirm if they do weed control, more than 95% do not use organic fertilizers or apply fungicides or insecticides, they are younger (average age of 48.5), they carry out more furrowing (80%), they are mostly Aymara (57%) and have lower yields (Table 4).

Based on the classification of the three groups recognized by the Two-Stage Cluster (Table 4), and the factorial analysis for mixed data shown in Figure 1, the variables that have the greatest influence on the classification of each group were identified, as well as those that differentiate among the groups formed (See Supplementary Material 3a and 3b).

Figure 1 shows, for example, that the benefit variable is more important for the classification of group 1 (MPwW), it is less important for the classification of group two (GP), and it is not very relevant for the classification of group three (MPwoW). In that context, although all the groups of producers work for self-consumption, the producers of group three (MPwoW) are the ones who cultivate the most quinoa for self-consumption. Therefore, this variable is not significant for that group of producers. The variable sem (average use of seeds by quinoa producers) is more significant for classifications in groups 1 and 3, but less significant in group 2. The variable producX (average production of quinoa) is important for all the three groups of producers.

### Table 3
Classification according to III CENAGRO 1994 and according to MINAGRI (2015), Total area of Agrarian Unit (A.U.) of the quinoa producer of Puno

<table>
<thead>
<tr>
<th>Extent of the complete A. U. (ha)</th>
<th>Used for Quinoa Cultivation ha</th>
<th>Economic Benefit (Peruvian Soles)</th>
<th>Economic Benefit (US Dollars)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Classification according to III CENAGRO 1994</td>
<td>Classification according to Family Farming (FF) MINAGRI (2015)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Smallholder 0 - 2.99 ha</td>
<td>323</td>
<td>79.0%</td>
<td>1.0</td>
</tr>
<tr>
<td>Small 3 - 9.99 ha</td>
<td>78</td>
<td>19.1%</td>
<td>4.7</td>
</tr>
<tr>
<td>Medium 10 - 29.9 ha</td>
<td>8</td>
<td>2.0%</td>
<td>17.4</td>
</tr>
<tr>
<td>Total</td>
<td>409</td>
<td>100.0%</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Source: Based on 409 surveys carried out in October 2017. The reference to the classification of producers is from III CENAGRO (1994) and MINAGRI (2015).

### Table 4
Results of the three groups identified including variables of typification of groups, size of the groups and other variables

<table>
<thead>
<tr>
<th>Identified Groups</th>
<th>Group 1, Moderate Performance with Weeding</th>
<th>Group 2, Good Performance</th>
<th>Group 3, Moderate Performance without Weeding</th>
<th>General Average (Three Groups)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typtification Variables</td>
<td>Uses chemical fertilizers</td>
<td>No (100%)</td>
<td>Yes (100%)</td>
<td>No (100%)</td>
</tr>
<tr>
<td></td>
<td>Make weed control (weeding)</td>
<td>Yes (100%)</td>
<td>Yes (74.4%)</td>
<td>No (100%)</td>
</tr>
<tr>
<td></td>
<td>Use organic manure</td>
<td>No (67.9%)</td>
<td>No (72.7%)</td>
<td>No (96.4%)</td>
</tr>
<tr>
<td></td>
<td>Apply fungicide or insecticide</td>
<td>No (81.1%)</td>
<td>No (73.8%)</td>
<td>No (97.6%)</td>
</tr>
<tr>
<td></td>
<td>Average of Quinoa Production (t)</td>
<td>0.13</td>
<td>0.18</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>Average total area of all crops (ha)</td>
<td>3.48</td>
<td>1.90</td>
<td>1.28</td>
</tr>
<tr>
<td></td>
<td>Average Net Economic Benefit (soles)</td>
<td>76.79</td>
<td>95.17</td>
<td>38.35</td>
</tr>
<tr>
<td>Size</td>
<td>Number of Producers Surveyed</td>
<td>106.00</td>
<td>172.00</td>
<td>83.00</td>
</tr>
<tr>
<td></td>
<td>Percentage size (Surveyed)</td>
<td>29.4%</td>
<td>47.6%</td>
<td>23.0%</td>
</tr>
<tr>
<td>Significant Variables from ANOVA</td>
<td>Average Labor (hours/ha)</td>
<td>320.56</td>
<td>441.20</td>
<td>249.84</td>
</tr>
<tr>
<td></td>
<td>Average Quinoa Sales (t)</td>
<td>0.043</td>
<td>0.068</td>
<td>0.036</td>
</tr>
<tr>
<td></td>
<td>Average Age (years)</td>
<td>55.13</td>
<td>55.26</td>
<td>48.53</td>
</tr>
<tr>
<td>Others</td>
<td>Do Plowing</td>
<td>Yes (80.1%)</td>
<td>Yes (91.8%)</td>
<td>Yes (83.1%)</td>
</tr>
<tr>
<td></td>
<td>Make Rows</td>
<td>Yes (51.1%)</td>
<td>Yes (64.1%)</td>
<td>Yes (79.5%)</td>
</tr>
<tr>
<td></td>
<td>Average use of machinery (hours/ha)</td>
<td>23.75</td>
<td>26.24</td>
<td>23.86</td>
</tr>
<tr>
<td></td>
<td>Average Seed (kg/ha)</td>
<td>22.84</td>
<td>23.87</td>
<td>19.02</td>
</tr>
<tr>
<td></td>
<td>Sale of Quinoa Production</td>
<td>No (65.1%)</td>
<td>No (50.6%)</td>
<td>No (63.9%)</td>
</tr>
<tr>
<td></td>
<td>Farmer’s Language (percentage)</td>
<td>quechua</td>
<td>quechua</td>
<td>aymara</td>
</tr>
<tr>
<td></td>
<td>Average Quinoa Yield (t/ha)</td>
<td>0.092</td>
<td>1.02</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td>Average Sale/Production (%)</td>
<td>33%</td>
<td>38%</td>
<td>30%</td>
</tr>
<tr>
<td></td>
<td>Average Self-Consumption/Production (%)</td>
<td>71%</td>
<td>67%</td>
<td>70%</td>
</tr>
</tbody>
</table>

Source: from 361 surveys conducted in quinoa producers in Puno in October 2017.
Figure 2. Classification of Quinoa Producers in Puno based on the Two-Stage Method. Source: from 361 surveys conducted in quinoa producers in Puno in October 2017.

The groups identified exhibited geographic diversity (Figure 2). The southern area (Aymara area) is more diverse compared to the northern area (Quechua) where the Good Performance (GP) group is predominant. In the provinces of Lampa (79%), Azángaro (74%), San Román (56%) and Huancané (54%), the group two (GP) is prevalent. Groups one (MPwW) and three (MPwoW), with moderate performance, are predominant in the provinces of Chucuito (83%), Collao (62%), Melgar (65%) and Puno (60%). Group one MPwW is more prevalent in Collao (49%) while group three MPwoW in Chucuito (60%).

Following the CENAGRO III classification (1994), group two (GP) showed a lower percentage of smallholders compared to groups one (MPwW) and three (MPwoW) (Table 5). In the circumlacustre (bordering the lake) zone, smallholders predominate but in the continental zone, they are more diverse. In the south, smallholders are the majority, and, in the north, they are more diverse. According to MINAGRI (2015), group two (GP) has the highest percentage of intermediate FF and the lowest percentage of subsistence FF. While groups one (MPwW) and three (MPwoW) do not have consolidated FF but have higher subsistence FF. In the circumlacustre zone, subsistence FF predominates. Subsistence FF is prevalent to the south and Intermediate FF to the north. In the Aymara zone, they are mostly subsistence FF while the Quechua zone is more diverse.
3.3 Technical efficiency by types of quinoa producers

The general technical efficiency of the producers was found to be significant and differed among the groups identified. The corresponding results are shown using equation 5 of the stochastic frontier analysis (see Supplementary Material 4).

The Prob > chi² = 0.000 indicates that all the coefficients (β) are different from zero, it rejects the hypothesis that all the estimated parameters are equal to zero (β = 0). Individually, p = 0.000 in the total area of the crops in ha (log total area) and, p = 0.00 in the number of seeds in kg/ha (log_sem) are significant. Thus, a reduction in the total area of crops in ha (log_total_area) by 1% would increase the quinoa yield in t/ha (log_prod) by 0.4279%. An increase in the number of seed in kg/ha (log_sem) by 1% would increase quinoa yield by 0.113% calculated in t/ha (log_prod). Previous literature has indicated that the use of the optimum number of seeds can enhance yield and technical efficiency (Mercado et al., 2020), as well as the use of agricultural inputs and the access to markets.

The average technical efficiency found among quinoa producers evaluated in Puno was 0.474 within an interval of 0.0076 and 0.8107. Group two (GP) was the most technical efficient (average = 0.5025), while groups one (MPwW) and three (MPwoW) had similar values of technical efficiency (0.4464 and 0.4504, respectively). These assessments revealed low technical efficiency in group and at individual levels which were validated by the variables: use of seeds, yield, fertilizer, and sale. Hence, an increase in the total area of quinoa and a higher quantity of seeds would increase yield.

By establishing a possible baseline of efficiency in the study area, the individual efficiency of producers can be compared which evidenced that there were low levels of individual technical efficiency because producers with technical efficiency greater than 0.70 only represented 13.3% of the interviewed (see Supplementary Material 5).

At the national level, Coras (2014) indicated that the technical efficiency found among quinoa producers in Junín was positively correlated to the levels of education, access to irrigation systems, and the lease of agricultural land. The total average for efficiency was 80%, with 84%, 76% and 75% for the four classified groups. Mercado et al. (2020) also estimated the technical efficiency for groups of quinoa producers in Junín which were: 77%, 66%, 67% and 65% (with an averaged efficiency of 67% for the total of producers).

Both studies showed technical efficiency values that were higher than those estimated for Puno (47.4% efficiency on average). Even if the efficiency of each group was considered, these assessments suggested that the results of technical efficiency in rural economies, where self-consumption is important, would not be sufficient to conclude on a rational pro-market behavior because the primary orientation of production is not the market but food security.

Similarly, according to Liceaga (2021) and Landini (2011), family economy is characterized as a small-scale economy and structured on a family basis. In Puno, 80% of quinoa producers are smallholders and that 85% get their income from their own productive unit. Their technical efficiency is characterized for limited availability of resources (water, fertile soils, and biodiversity) compared to other producing areas with more favorable conditions. This region is exposed to extreme environmental variations since cultivation is done over 3800 masl.

On the other hand, technical efficiencies in relation to the dichotomous variables revealed an R-squared of 89.4%. All the coefficients (γ) were different from zero (Prob > F = 0.000). Individually, only some of the variables were significant. Thus, those who use fertilizers (p = 0.022) have 0.04809 points of greater technical efficiency than those who do not, and those who use quinoa for sale (p = 0.000) have 0.0900 points of greater technical efficiency than those who do not (See Supplementary Material 6).

On the other hand, Soares & Spolador (2019), Khanal et al. (2018), and Melo-Becerra & Orozco-Gallo (2015) indicated that if different production technologies coexist, technical efficiency cannot be directly compared to the same production frontier that holds all production units because decisions are taken with different combinations of inputs - outputs. In those cases, Hayami, (1969) and Hayami & Ruttan (1970) assumed that producers have potential access to several production technologies and choose some. It allows the estimation of technical efficiency within each production system or group of producers, but not for all of them since they all are not homogenous in the use of production technologies.

<table>
<thead>
<tr>
<th>Identified Groups</th>
<th>Group 2 - GP</th>
<th>Group 1 - MPwW</th>
<th>Group 3 - MPwoW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Classification MINAGRI 2015: Family Farming</td>
<td>6.4% Consolidated</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>43.0% Intermediate</td>
<td>34.9% Intermediate</td>
<td>36.1% Intermediate</td>
</tr>
<tr>
<td></td>
<td>50.6% Subsistence</td>
<td>65.1% Subsistence</td>
<td>63.9% Subsistence</td>
</tr>
<tr>
<td>Classification III CENAGRO 1994</td>
<td>75.0% Smallholder</td>
<td>84.9% Smallholder</td>
<td>94.0% Smallholder</td>
</tr>
<tr>
<td></td>
<td>25.0% Small</td>
<td>15.1% Small</td>
<td>6.0% Small</td>
</tr>
<tr>
<td>Size in % (Surveyed)</td>
<td>47.6%</td>
<td>29.4%</td>
<td>23.0%</td>
</tr>
</tbody>
</table>

Group 1: Moderate Weeding Performance (MPwW). Group 2: Good Performance (GP). Group 3: Moderate No Weeding Performance (MPwoW)

Source: From 361 surveys conducted in quinoa producers in Puno in October 2017.
Finally, the averages of net benefits (Peruvian Soles) differed statistically between the groups as identified with the ANOVA test ($p = 0.034$) at a significance level of 0.05. The highest was found in group two (GP) at USD 29 or S/ 96, followed by group one (MwWP) at USD 24 or S/ 78 and the lowest in group three (MwoWP) with USD 12 or S/ 39. Thus, the groups show differentiating variables in the use of fertilizers, weed control, organic fertilizer, the application of fungicides or insecticides, the production of quinoa (t), total area of all crops in ha, and, the net economic benefits (in Peruvian Soles). Group two (GP) differs from the other groups in technical efficiency, sale, quinoa production, and total crop area. Group one (MwWP) and group three (MwoWP) have similar values of technical efficiency, they do not use fertilizers, and have lower values in the sale of quinoa, the production of quinoa, and the total area for all crops. Based on the above, in the case of Puno, it is evident that the economic performance of the producers in that region is not relevant for defining their classification because, although it is true that sales are important for technical efficiency (i.e., the groups that interact more in the markets would yield better indicators), all the producers in rural areas devote a large part of their production to self-consumption. Therefore, this productive activity is the main driver of local food security.

4. Conclusions

The Peruvian Altiplano is the main center of origin and diversity of quinoa, even though cultivation is done under adverse climatic and agroecological conditions. Cultivation is carried out by small and diverse producers who apply traditional practices with limited use of inputs, and with the main purpose of promoting local food security.

The discriminating variables for the classification of producers in Puno were: use of external inputs, total area of cultivation, productive practices, and economic benefit. The group performing the best were mostly Quechua farmers who showed to allocate a relatively high proportion of quinoa for sale. In the other groups, the use of external inputs was found to be incomplete and was mostly composed of Aymara farmers who largely use quinoa for self-consumption. The identified groups showed geographic diversity, the southern zone (Aymara) is more traditional and diverse, with predominant agriculture for subsistence and small areas for farming. In the northern zone (Quechua) the percentage of smallholders is lower.

The general technical efficiency found in the producers was low (0.474) and between groups, the distance was not substantial (0.5025, 0.4464 and 0.4504, respectively). This revealed low technical efficiency in group and at individual levels which were validated by the variables: use of seeds, yield, fertilizer, and sale. Thus, an increase in the total area of quinoa and a higher quantity of seeds would increase yield.

Although it is possible to increase yield and technical efficiency through better allocation of inputs, this has a realistic regional limit. From that perspective, public policies enabling better access to technical services such as financing, training, technical assistance, quality seeds, irrigation, among others, should be considered.

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