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Assessment of Water Footprint Profiles: Analysis of the Quinoa Life Cycle in Bolivia[*]

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Abstract

This study analyzes the water footprint profiles of quinoa production in Bolivia, an emblematic crop that faces significant challenges in terms of yield and sustainability. The Total Water Footprint (WH) of quinoa estimated for the Southern Altiplano region of Bolivia is approximately 1,728 liters per kilogram, with average yields of 1.15 tons per hectare. This result shows a worrying level of inefficiency in the relationship of HH and crop yield, especially in comparison with countries such as Peru and Ecuador.

The results show high HH and low yields; therefore, quinoa production in Bolivia in the study area is not optimizing water use. This situation can be explained to a large extent by the low level of organic matter in the soil of the area (verified by soil studies). Thus, a soil with low organic matter content lacks essential nutrients, which impairs quinoa growth and negatively affects its root development due to soil compaction. In addition, the lack of organic matter decreases water retention capacity, which is critical in periods of drought as a result of the increased frequency and intensity of climatic events in the area. Likewise, the lack of organic matter makes plants more vulnerable to pests and diseases, but also reduces microbial biodiversity, which affects key processes such as decomposition and nutrient cycling, compromising soil fertility.

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In summary, this type of soil is less efficient in water use, which can increase the water footprint of the crop by requiring more frequent irrigation. Based on these conclusions, several recommendations are proposed. First, it is crucial to optimize yield and reduce WH by implementing efficient irrigation systems. This includes training farmers in these technologies. The use of vegetative covers that improve moisture retention is also suggested. In addition, advanced irrigation technologies -such as soil moisture sensors- should be adopted and rainwater harvesting systems should be promoted. Training in integrated water resources management is essential, as well as the development of climate adaptation strategies.

Key words: WH, life cycle, water productivity, econometric analysis, agricultural sustainability.

JEL codes: Q57, Q56, Q15, Q25, C21.

Resumen

Este estudio analiza los perfiles de huellas hídricas en la producción de la quinua en Bolivia, un cultivo emblemático que enfrenta desafíos significativos en términos de rendimiento y sostenibilidad. La Huella Hídrica Total (HH) de la quinua estimada para la región del Altiplano Sur de Bolivia es de aproximadamente 1.728 litros por kilogramo, con rendimientos promedio de 1,15 toneladas por hectárea. Este resultado muestra un nivel preocupante de ineficiencia en la relación de la HH y el rendimiento del cultivo, especialmente en comparación con países como Perú y Ecuador.

Los resultados muestran una alta HH y bajos rendimientos; por lo tanto, la producción de quinua en Bolivia en la zona de estudio no está optimizando el uso del agua. Esta situación puede ser explicada en gran medida por el bajo nivel de materia orgánica en el suelo de la zona (verificado mediante estudios de suelo). Así, un suelo con bajo contenido de materia orgánica carece de nutrientes esenciales, lo que perjudica el crecimiento de la quinua y afecta negativamente su desarrollo radicular debido a la compactación del suelo. Además, la falta de materia orgánica disminuye la capacidad de retención del agua, lo que es crítico en períodos de sequía como resultado del aumento en la frecuencia e intensidad de eventos climáticos en la zona. Asimismo, la falta de materia orgánica hace que las plantas sean más vulnerables a plagas y enfermedades, pero también reduce la biodiversidad microbiana, lo que afecta a procesos clave como la descomposición y los ciclos de nutrientes, que comprometen la fertilidad del suelo.

En resumen, este tipo de suelos son menos eficientes en el uso del agua, lo que puede incrementar la huella hídrica del cultivo al requerirse riegos más frecuentes. A partir de estas conclusiones, se proponen varias recomendaciones. Primero, es crucial optimizar el rendimiento y reducir la HH mediante la implementación de sistemas de riego eficientes. Esto incluye capacitar a los agricultores en estas tecnologías. También se sugiere el uso de coberturas vegetales que mejoren la retención de humedad. Además, se deben adoptar tecnologías avanzadas de riego -como sensores de humedad del suelo- y promover sistemas de captación de agua de lluvia. La formación en manejo integrado de recursos hídricos es esencial, así como el desarrollo de estrategias de adaptación climática.

Palabras clave: HH, ciclo de vida, productividad del agua, análisis econométrico, sostenibilidad agrícola.
Códigos JEL: Q57, Q56, Q15, Q25, C21.

Introduction

Quinoa has gained global recognition in recent decades due its nutritional properties and its adaptability to diverse climate conditions. In Bolivia, this crop is of vital importance in cultural and economic terms, particularly for the indigenous communities that have been growing it for centuries (Jacobsen, 2012). However, the increase in quinoa demand in international markets has led to an increase in production that poses considerable challenges in terms of sustainability and efficient resource use, particularly in the use of water and soil.

Total water footprint (TWF) – defined as the volume of freshwater employed for producing goods and services – has become an essential indicator for evaluating the environmental impact of agricultural systems (Hoekstra, 2017). In the context of quinoa production, it is essential to understand how farming practices affect the water footprint (WF) and hence crop sustainability. This analysis becomes even more relevant in regions such as Bolivia, where access to water is limited and where climate variability can affect access to the water resource.

The WF is also influenced by consumption decisions, as consumers can choose food that requires less water to produce, thus fostering sustainable diets and reducing food waste, which would contribute to reduce the WF at the global level (Mason *et al.*, 2020). Besides, international cooperation is essential for sustainable water management, given that water resources are shared between countries and regions. This necessitates cooperation agreements for research and development of technologies that improve efficiency in the use of water in agriculture (Schwarz *et al.*, 2021). It is important to highlight that the WF is a dynamic indicator that can change in time due to factors such as agricultural practices, climate change and water management policies. Given this, periodical evaluations must be done to adapt strategies and ensure sustainable water use (Rosa *et al.*, 2021).

Life cycle assessment (LCA) tends to be used for measuring the WF; it is a robust methodology that allows assessing the environmental impacts of a product from its production to its final disposal. In this study, the Cool Farm Tool (CFT)[1] will be used. This is a tool that facilitates WF assessment throughout the quinoa life cycle, given that it identifies the phases of the production cycle which most contribute to the WF.

The objective of the present working document is to contribute to understanding the WF in quinoa production in the area of the Southern Altiplano (High Plateau) of Bolivia and to provide practical tools for sustainable water management in this sector. Through an exhaustive analysis and an approach based on the life cycle, the findings of this study can make possible the construction of WF profiles at the aggregate level and by clusters.

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[1] CFT is an on-line tool designed to help measure and manage the carbon footprint and the WF of agricultural crops. For measuring the WF, the tool is based on a model that gauges water consumption in each phase of agricultural processes, from sowing to harvest. Included is the amount of water used in irrigation, as well as rain that contributes to crop growth. By providing precise information on the environmental impact, CFT allows making informed decisions for improving the sustainability of agricultural practices.

In turn, this information can be very useful for providing specific recommendations to producers and to those responsible for determining policies in the agriculture field.

The literature review in Section 2 deals with prior studies that analyzed the WF in different agricultural contexts and methodologies, as well as specific research on quinoa. The methodology is described in Section 3, where details are provided on the criteria for the selection of quinoa producer communities. The section also presents the data collection process and the application of CFT. The results of this analysis are presented in Section 4, where the different profiles of the WF are provided, based on agricultural practices, climate conditions and other contextual factors. Section 5 offers conclusions based on the results obtained, highlighting the importance of the WF in water management for quinoa production. Reflections are made on how the findings can contribute to determining policies and strategies that promote a more sustainable use of water in Bolivian agriculture. Finally, in Section 6, practical recommendations are made for the farmers and those responsible for policies.

I. Literature review

Measuring the WF has become a key tool for assessing the use of water in agriculture, a sector that consumes approximately 70% of the world's fresh water (Mekonnen and Hoekstra, 2016). This concept, which comprises both water consumed and water contaminated in the production of goods, is essential for understanding the environmental impact of agricultural practices and the sustainability of water resources (Hoekstra, 2017).

One of the main concerns relating to the WF is the growing demand for food as a result of the increase in global population. It is estimated that the world's population will reach 9.7 billion by 2050, demanding a considerable increase in agricultural production (FAO, 2017). This increased food requirement poses critical challenges for water management, particularly in regions where water resources are limited or more vulnerable to climate change.

One of the relevant studies on the WF in quinoa cultivation is in the work done in 2012 by the National Water Authority (ANA) of Peru. This study assessed the amount of water employed in quinoa cultivation performed mainly in conditions of no irrigation in the Peruvian highlands. The research revealed that the average national water footprint of the crop in the 2001-2012 period was 3,841.47 m^3 per ton, with an average yield of 1.19 tons per hectare. Among the components of the water footprint, the green component represents rainwater, and made up 80%; the grey footprint, which measures the water needed for diluting contaminants, 14%; and the blue footprint, which corresponds to water from surface and subsurface sources, 6%. These results highlight the importance of the rainwater stored in the ground for satisfying the water requirements of quinoa cultivation, particularly at altitudes of between 2,500 and 4,100 m.a.s.l. The study underscores the vulnerability of the quinoa crop to variations in precipitation, which could affect production in the context of climate change (Schneir, 2015).

Efficiency in the use of water is a crucial factor for reducing the WF in agriculture. Irrigation technologies have demonstrated to be more effective than traditional methods such as flood irrigation (Keller and Bliesner, 1990). These technologies not only improve irrigation efficiency, but also minimize evaporation and runoff, thus contributing to a lower WF. Besides, for optimizing quinoa cultivation in strictly rainfed conditions, specific practices may be implemented that maximize the use of available water. This includes planting at the beginning of the rainy season, adjusting the sowing density to minimize competition between plants, and having an adequate number of plants to ensure that an optimal percentage is harvested in relation to the initial density, such as 60%, 70% or 80%. It is also important to select varieties that are more tolerant to drought, to perform weed control to reduce competition for water and nutrients, and to apply techniques such as the use of furrows or ditches to guide the water to the roots, thus favoring more sustainable and efficient crops.

Fundamental besides irrigation technologies is the implementation of water conservation practices. Conservation agriculture, which includes techniques such as direct sowing and crop rotation, can help improve water retention in the soil and reduce the need for irrigation (González *et al.*, 2019). These practices not only benefit the WF, but also promote soil health and biodiversity.

Climate change is another critical aspect that affects the WF in agriculture. Variations in precipitation patterns and the increase in temperatures can affect water availability and thus agricultural production (Bates *et al.*, 2008). Adapting agricultural practices to these new climate realities is essential for ensuring sustainability in water use in the Southern Altiplano.

Education and sensitization of farmers are key components for efficient water management. Some training programs that teach efficient irrigation techniques and sustainable management of water resources have had positive results in different regions (Mastrorillo *et al.*, 2016). Thus, knowledge transfer is fundamental for fostering agricultural practices that reduce the WF.

Public policies also play a crucial role in managing the WF in agriculture. Creating regulatory frameworks that foster sustainable use of water can provide farmers with incentives to adopt more responsible practices (Pérez *et al.*, 2019). Such policies must go hand in hand with economic incentives that facilitate the transition towards more sustainable methods.

The implications of the WF are not only environmental, but also social and economic. Competition for water resources can generate conflicts between sectors such as agriculture, industry and urban consumption (García *et al.*, 2020). It is therefore essential to deal with the WF from a comprehensive approach that considers the needs of all water users.

Similarly, ongoing research is indispensable for improving our understanding of the WF in agriculture. Compiling precise data and carrying out case studies help to develop best practices and policies that deal with the challenges related to the use of water in agricultural production (Rosa *et al.*, 2021). Cooperation between researchers, governments and farmers will be key to achieving more efficient water use.

Applying technological tools such as simulation models and geographic information systems (GIS) can facilitate assessment of the WF in different agricultural contexts. In the present study, the CFT methodology was specifically used for analyzing the availability of water resources and optimizing water management practices (López *et al.*, 2022). Integrating these technologies into decision-making is fundamental for improving water management.

Mejía *et al.* (2020) underscore that there are two main methods of calculating the WF: life cycle assessment (LCA) and water footprint assessment (WFA). While LCA evaluates the environmental impacts associated with production throughout a product's life cycle, WFA centers on quantifying the volume of water used directly or indirectly in the supply chains. The main difference between the two methods lies in that WFA specifically measures water use, while LCA considers the broader impacts of its use. These methods are complementary and are subject to ISO Standards 14046 and 14044, which provide guidelines for ensuring coherence and comparability in analyses. The distinction is essential for understanding how water sustainability is measured in different agricultural contexts and how these methodologies can be applied for improving management of the water resource.

The water footprint varies considerably between agricultural crops. For quinoa, the total WF ranges from 1,200 to 2,500 m^3 per kg, which reflects moderate use of water compared to other crops (Hoekstra *et al.*, 2012). Alfalfa, on the other hand, has a considerably higher WF, of between 3,000 and 4,000 m^3 per kg, (Allen *et al.*, 1998). Potatoes have a WF of 1,500 to 2,000 m^3 per kg, suggesting water consumption similar to that of quinoa, though slightly higher (Castañeda and Cañizares, 2018). On its part, corn has a WF of 1,200 to 1,800 m^3 per kg, indicating efficient use of water compared to crops like alfalfa (Gutiérrez and Rojas, 2017). Finally, barley has a WF of 1,500 to 2,200 m^3 per kg, making it stand out as a crop with an intermediate level of water consumption (Tovar and García, 2019). (see Table 1).

Table 1. Normalized Water Footprint (WF) among quinoa-producing countries

Crop	Total Water Footprint (m^3 per kg)
Quinoa	1,200 – 2,500
Alfalfa	3,000 – 4,000
Potato	1,500 – 2,000
Corn	1,200 – 1,800
Barley	1,500 – 2,200

Source: Own elaboration based on bibliographic consultations.

II. Methodology

This section describes the methodology used for measuring the WF with a life cycle approach, from data collection up to the analysis of the water consumption profiles of quinoa producers of the Southern Altiplano of Bolivia. The methods section explains in detail the specific procedures applied for analyzing this information (*i.e.*, measuring the WF and econometric methods).

III.1. Data collection

The data collection was performed by means of a survey done in the first quarter of 2024 in three quinoa producer communities of the Bolivian Altiplano (*i.e.*, Capura, Vintuta and Bella Vista). Given that in these locations climate conditions, extreme temperatures and lack of water affect agricultural practices and the use of water resources, the survey's approach was towards identifying consumption patterns and the need for water in quinoa production. The population parameter is linked to the farmers' water consumption and includes the following specific dimensions:

- **Quantity of water used for irrigation.** This is measured in liters per hectare and by cultivation cycle.
- **Available water sources.** These include mainly rainwater and other sources, if they exist (*i.e.*, surface and subsurface sources, as well as irrigation systems).
- **Impact perceived in agricultural production.** This is assessed by questions on how water use affects quinoa yield, and on the sustainability of the agricultural practices.

In this context, a random sample was designed in the communities that showed similar characteristics in terms of quinoa production and socioeconomic conditions. By choosing the producers at random, the risk of selection biases was minimized, allowing each producer to have the same likelihood of being chosen. This also ensured representativity, increasing the chances for the sample to reflect the population's diversity. This in turn makes the findings more general for other quinoa producer communities of the Altiplano.

The decision was made to perform surveys with a total of 137 producers chosen based on their availability for participating in the study. Although this introduces a component of convenience, the random nature of selection within homogenous communities ensured the sample's representativity. In other words, a systematic sampling was employed, selecting population units in a regular and predefined way. In general, this approach is used for obtaining a representative sample without the need for performing a complete random sample.

The choice of a systematic design within homogenous communities was the most adequate one for several reasons. Firstly, homogeneity of the characteristics ensured that the variations observed in water consumption would be attributable to relevant factors and not to structural differences between communities. Besides, this approach provided flexibility and timeliness in data collection, allowing for a more efficient compilation, facilitating access to the producers, and optimizing the data collection time. Finally, the sample's representativity ensures external validity of results, as it makes them applicable to other quinoa producer communities of the Southern Altiplano, thus contributing towards a broader understanding of the water consumption patterns.

Within each community, inclusion criteria were established for selecting the quinoa farmers. Priority was given to those who had at least three years' experience in production and who used irrigation water as their main source. However, it is also important to mention that there are many producers who do not irrigate their land, and this affected the comparability of data. In any case, this criterion ensured that those surveyed possessed relevant knowledge on water consumption and its impact on agricultural production, which allowed obtaining more precise and significant data.

The structured questionnaire dealt with several dimensions of water consumption, including the amount of water used, available water sources and the farmers' perception of environmental effects. The questionnaire was validated in a pilot group of farmers prior to its implementation in the field, allowing to fine-tune the questions and ensuring clarity and relevance.

The collection of data was performed between January and March 2024. A team of surveyors who were also farmers of the zone was trained and then visited each community for performing in-person interviews with the selected producers. This method facilitated obtaining detailed information and allowed clarifying doubts in real time, thus improving the quality of the compiled data. The answers were recorded in mobile devices for ensuring quick digitalization and posterior analysis.

In the 137 initial surveys, atypical observations that could have distorted the results were identified and eliminated, as there were answers that deviated considerably from the mean in key variables, such as water consumption. An approach based on statistical analysis was employed for identifying atypical observations: the means and standard deviations were calculated for the key variables (such as amount of water used); then a threshold was defined for considering an observation as an outlier, generally with a limit of more than two standard deviations above or below the mean.

The study was performed respecting ethical principles, including the informed consent of participants. An explanation of the study's objective was given to the participants and confidentiality of the information provided was ensured. The persons surveyed were at liberty to withdraw from the study at any time and with no consequences. Transparent and respectful practices were ensured throughout the data collection process.

III.2. Method

For evaluating the WF, the methodology of The Water Footprint Assessment Manual of Hoekstra *et al.* (2011) was employed, as well as the methods proposed by Garrido *et al.* (2010), adapted to the assessment criteria of the Cool Farm Tool software (Kayatz *et al.*, 2019). We began by defining the need for water as the amount of water necessary for satisfying evapotranspiration (ETc) of the crops following equation (1) of Allen *et al.* (2006):

$$ET_c = ET_0 * k_C \ (1)$$

where:

ETc (mm/month): water necessary for evapotranspiration during crop growth

ETo (mm/month): reference evapotranspiration based on climate data of each crop's zone

Kc: crop coefficient in different phases of the vegetative period

Another parameter for the water requirements of the crops is effective precipitation (PrEfec), which is the precipitation accumulated in the soil.

According to various authors (Angulo *et al.*, 2024; Benique, 2021; Chavarría-Solera *et al.*, 2020; Becerra *et al.*, 2013), equation (2), adapted for our study, is expressed as:

$$HH = HH_{\text{azul}} + HH_{\text{verde}} \ (2)$$

where:

HH: TWF

HH_{azul} (blue WF): defined as the volume of surface and subsurface water evaporated, incorporated in the product or returned to another basin or to the sea as a result of production

HH_{verde} (green WF): defined as the volume of rainwater evaporated or incorporated into the product during the production process

Measuring the WF implies quantifying the total volume of freshwater used in the production process of a good, considering both rainwater and irrigation water. This includes water consumed by plants and water which evaporates or is lost in the process. Calculating the WF and associating it with crop yield allows obtaining a clear picture of efficiency in water use.

Once the WF is calculated, water productivity is derived, measured as the amount of agricultural production obtained per unit of water used. This metric is essential for assessing efficiency in water use and for identifying opportunities for improvement in the management of water resources. The equation for calculating water productivity, based on González *et al.* (2014), is:

$$\text{Prod. Agua} = \frac{\text{Rendimiento}\left(\frac{kg}{ha}\right)}{HH\left(\frac{m^3}{ha}\right)} \quad (3)$$

For the present research we applied a life cycle assessment (LCA) using the CFT platform in the communities which were the object of the study. The data entered in the tool contains information on crop size, quantity of product sown, quantity harvested, volume destined for sale, and the sowing and harvesting dates. Besides this, records were made of soil characteristics, classified into two categories. The first category is the type of soil (fine: clayey-sandy, clayey, clayey-loamy, silty-clayey-loamy, sandy, medium silty-clayey, silty-clayey-loamy; and thick: sandy-silty, silty, silty-loamy, and loamy). The second category is soil moisture, categorized under three levels: moist, wet and dry.

As to use of water, the information included irrigation period, technology employed (solely rainwater), water source for irrigation (if applicable), crop irrigation area, maximum rate of precipitation infiltration (mm/day), initial exhaustion of soil moisture (%), and ETo, represented by equation (4) according to Mejía *et al.* (2020):

$$ET_c * ST \quad (4)$$

where:

ETc (mm/month): water needed for evapotranspiration during crop growth

ST (m^3/ha): crop size

Also included were the crop water requirements: RACverde (green crop water requirements) (m/ton), and RACazul (blue crop water requirements) (m/ton). Crop water requirements are necessary for determining water footprints. The following are equations (5) and (6) based on Renderos (2016):

$$HHA = \frac{RAC_{\text{azul}}}{Y} \quad (5)$$

$$HHV = \frac{RAC_{\text{verde}}}{Y} \quad (6)$$

where:

RAC_{azul}: blue crop water requirements

RAC_{verde}: green crop water requirements

Y (m^3/ton): crop water volume

Finally, information was included on the price of quinoa and its types of production for estimating the crop's value (Ej) with equation (7) (Mejía *et al.*, 2020):

$$E_j = f \quad (7)$$

where:

E_j: crop value

f (kg): sale of agricultural products to a determined zone

Figure 1 presents the application of LCA for the quinoa crop. Five parameters of the WF were assessed: total, green and blue, as well as water yield and productivity, both at the community level and as a whole. Following this, statistical analyses were done of central tendency and dispersion. Based on the metrics obtained, clusters (*i.e.*, A, B, C) were identified, which were adjusted by means of regressions (Carrasquilla-Batista *et al.*, 2016). Afterwards, the elasticities and diverse regressions[2] were estimated for analyzing robustness of the results (Gallego *et al.*, 2011; Cedeño Plaza, 2020).

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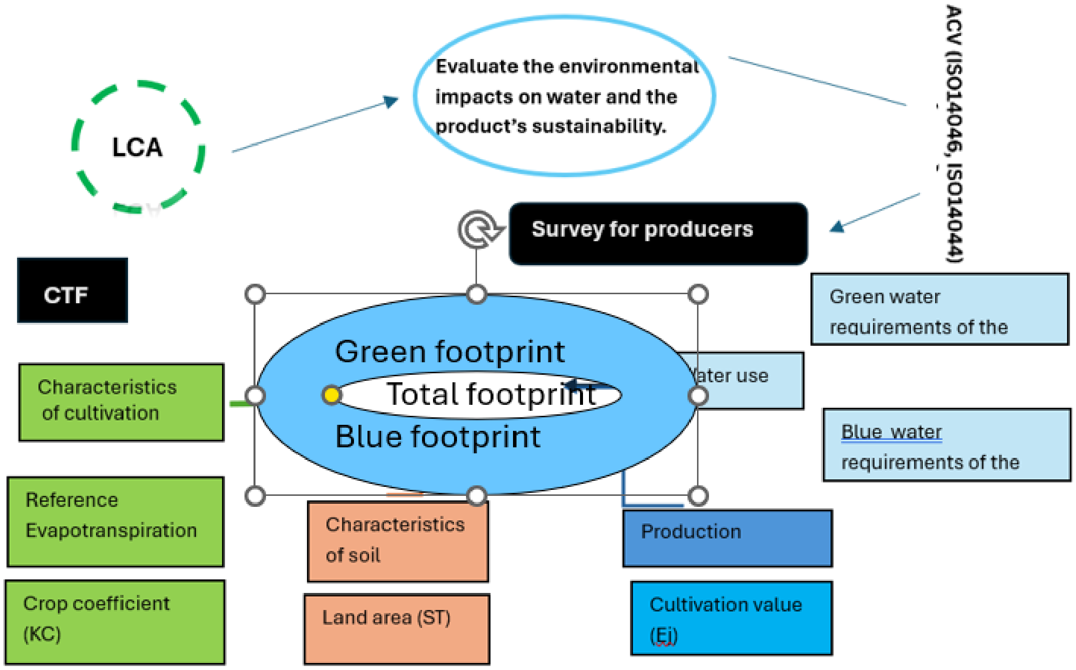
[2] Ordinary least squares (OLS), robust ordinary least squares for assessing the impact of outliers of the sample, generalized linear model (GLM), and a regression of quartile 50 (Q50)

Figure 1. Application of LCA-CFT for the cultivation of quinoa



Source: Own elaboration based on CFT guide.

III. Results

The results normalized for the Bolivian Southern Altiplano indicate that the parameters of the WF, the green WF (GWF) and the blue WF (BWF) are higher in terms of water efficiency, and together with water yield and productivity, show better results compared to those for quinoa crops in Ecuador and Peru (Hoekstra and Chapagain, 2008; Vizcarra, 2022; Schneir, 2015). This finding is attributable to greater efficiency in the use of water in agriculture in these countries, which increases agricultural production and yield (FAO, 2017; Roncagliolo and Pierrend 2017; Geerts *et al.*, 2008, 2009). These countries show frequent implementation of practices such as use of fallow lands, crop rotation and complementary use of irrigation, which contribute to higher productivity with a lower water impact (Barco-Gamarra, 2019) (see Table 2).

Table 2. Normalized Water Footprint (WF) among quinoa-producing countries

Country	Total Water Footprint (m^3)	Green Water Footprint (m^3/kg)	Blue Water Footprint (m^3/kg)	Average Total Water Footprint (m^3/kg)
Bolivia	1,500-2,000	1,200-1,800	300-400	1.75
Peru	1,600-2,200	1,100-1,600	500-600	1.68
Ecuador	1,400-1,900	1,000-1,500	400-500	1.715

Source: Own elaboration based on FAO (2011), Mekonnen and Hoekstra (2011), and Paredes (2016).

As expected, the results confirm that higher crop yield is associated with a decrease in the total water footprint, particularly in the green water footprint. Higher yield implies more efficient use of water resources, which reduces the amount of water needed per unit of production (Cando *et al.* 2017). Similarly, an increase in water productivity is associated with better quinoa crop yield, as higher water productivity results in greater yield per liter of water used.

The average TWF of the entire sample studied in the Southern Altiplano is 1,727 l/kg. This is the total amount of water used in the entire production process, including both green water (precipitation) and blue water (irrigation), which is very low (Aldaya and Hoekstra 2010; Lovarelli *et al.*, 2016). A GWF of 1,457.59 l/kg was estimated, and a BWF of 270.69 l/kg was estimated, which is consistent with the strictly rainwater technology applied in the Bolivian Altiplano. These differences, as well as the technology employed, could be attributable to factors such as the type of crop, water management practices, and the climate conditions of the study zone (Figueroa and Rodríguez, 2020; World Bank, 2020; IPCC, 2019). Table 3 presents the statistical description of the sample studied. This information may be useful for water resource planning and sustainable use (Canavire-Bacarreza *et al.*, 2021).

Table 3. Measures of Central Tendency and Dispersion (Yield, TWF, GWF, BWF, Prod.)

Trend	**Yield (ton/ha)**	**TWF (l/kg)**	**GWF (l/kg)**	**BWF (l/kg)**	**Prod (kg/m^3)**
Average	**1.15**	**1,728.28**	**1,457.59**	**270.69**	**0.13**
Deviation	**0.91**	**292.63**	**246.79**	**45.83**	**0.06**

Source: Own elaboration based on the INESAD-2024 survey and estimates using the Cool Farm Tool.

IV.1. Total water footprint by community

Table 4 presents the statistical description of the sample divided at the community level. The lowest median TWF was in the community of Vintuta, with 1,584.82 l/kg; and the highest one was in Capura, with 1,833.66 l/kg. This means that Vintuta and Capura need 1,584.82 and 1,833.66 liters of water, respectively, for producing 1 kilogram of quinoa.

The TWF of Vintuta was 1,336.59 l/kg; that is, the lowest one of all. Capura had the highest TWF, at 1,546.46 l/kg. As to the BWF, Vintuta also had the lowest value, of 248.22 l/kg; and Capura had the highest value, of 287.20 l/kg. The GWF indicates that quinoa production in Vintuta is less dependent on precipitation than in Capura.

Both these values are below the minimum range reported for quinoa production (Schneir, 2015; Roncagliolo and Pierrend, 2017). This suggests that the environmental factors, such as climate change (Liuhto *et al.*, 2016) or they type of production (Jacobsen, 2012) could be influencing factors. The BWF shows low dependence on external water sources (Liuhto *et al.*, 2016), mainly due to the high costs associated with irrigation in the Bolivian Altiplano. Between 248.22 and 287.20 liters of water come from surface or subsurface sources for producing 1 kilogram of quinoa, which could pose a serious problem in a drought scenario (when water stress increases).

Table 4. Descriptive Statistics by Community

Community	Trend	Yield (ton/ha)	TWF (l/kg)	GWF (l/kg)	BWF (l/kg)	Prod (kg/m³)
Capura	Average	0.79	1,833.66	1,546.46	287.2	0.13
	Deviation	0.36	377.33	318.23	59.1	0.04
Bella Vista	Average	0.43	2,451.25	2,067.32	383.93	0.11
	Deviation	1.27	1,815.11	1,530.82	284.29	0.16
Vintuta	Average	1.22	1,584.82	1,336.59	248.22	0.1
	Deviation	0.95	227.02	191.46	35.56	0.08

Source: Own preparation based on the INESAD-2024 survey and Cool Farm Tool.

Maximum quinoa yield goes from 1.44 to 3.23 tons per hectare (t/ha), while the TWF goes from 1,958.01 to 2,614.16 l/kg. As to the GWF, the values range from 1,651.33 to 2,067.32 l/kg, and the BWF goes from 306.68 to 409.45 l/kg. Additionally, the minimum yield values go from 0.36 to 0.43 t/ha, with a TWF of between 1,120.50 and 1,400.68 l/kg, a GWF between 945.00 and 1,181.30 l/kg, and a BWF between 175.50 and 219.38 l/kg. This analysis of variability leads us to believe that there are groups or clusters of producers within each community that use the water resource differently (see Table 5).

Table 5. Comparative table of the maximum and minimum values of the evaluated variables.

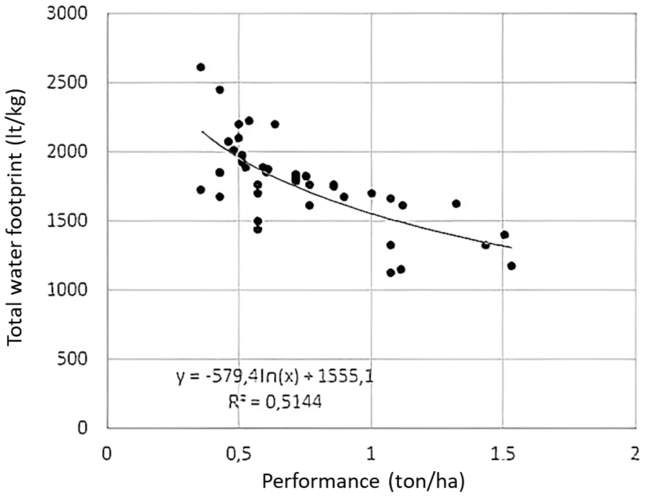
Community	Max Yield (ton/ha)	Min Yield (ton/ha)	Max TWF (l/kg)	Min TWF (l/kg)	Max GWF (l/kg)	Min GWF (l/kg)	Max BWF (l/kg)	Min BWF (l/kg)
Capura	1.44	0.36	2,614.16	1,321.78	2,067.32	1,181.30	409.45	207.03
Vintuta	3.23	0.36	1,958.01	1,120.50	1,651.33	945.00	306.68	175.50
Bella Vista	3.23	0.43	2,451.25	1,400.68	2,067.32	1,181.30	383.93	219.38
Aggregate	3.23	0.36	2,204.72	1,120.50	2,204.71	945.00	409.45	175.50

Source: Own preparation based on the INESAD-2024 survey and estimates using Cool Farm Tool.

As expected, as yield increases, the TWF tends to decrease. This inverse relationship is observed in two clusters identified in the complete sample studied, called Group A and Group B for the purposes of analysis.

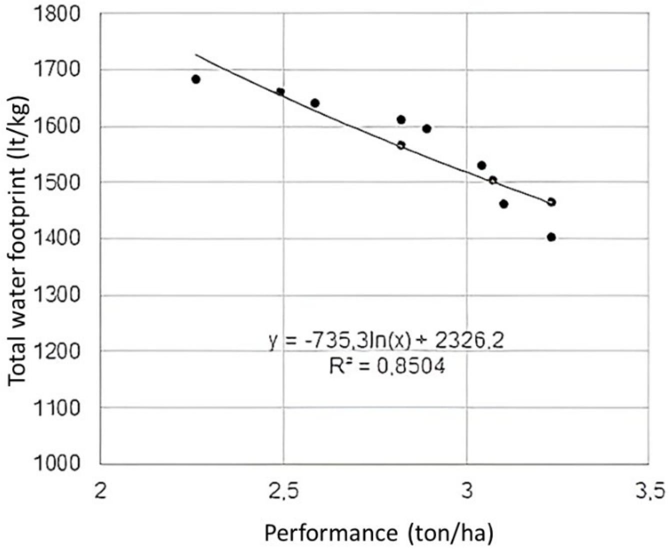
For Group A, it is estimated that a 1% increase in yield results in a decrease of 1.12% in the TWF. For Group B, a 1% increase in yield results in a decrease of 0.84% in the TWF. Group A has a more efficient production profile in the use of water (which is nonetheless not optimal) in quinoa production. This is crucial in a context where water scarcity is a growing concern for small producers, as a result of an increase in the frequency and intensity of drought (see Figures 2 and 3).

Fig. 2. WF-Yield for Group A



Source: Own preparation based on cluster identification and Cool Farm Tool.

Fig. 3. WF-Yield for Group B

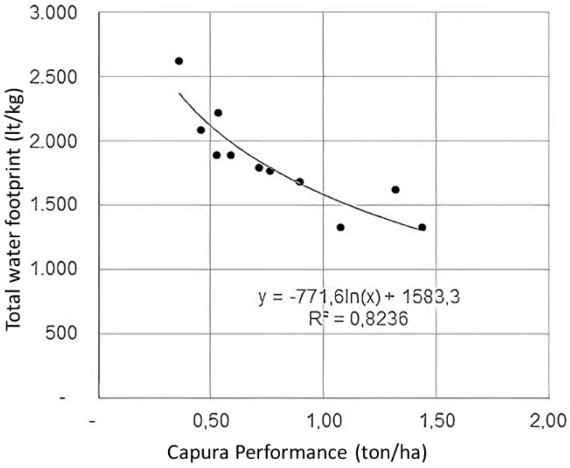


Source: Own preparation based on cluster identification and Cool Farm Tool

IV.3. Water footprint and yield in each community

In the community of Capura it is observed that as yield increases, the TWF tends to decrease, showing an inverse relationship. There, a 1% increase in yield leads to a 0.02% decrease in the TWF (see Figure 4).

Fig. 4. TWF and performance in the Capura community

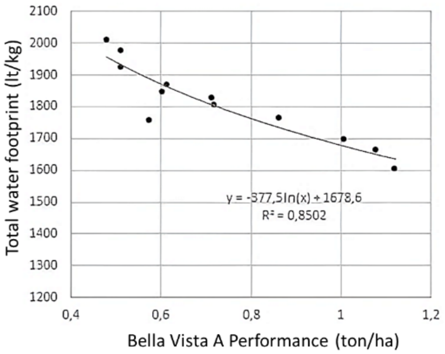


Source: Own preparation based on cluster identification and Cool Farm Tool.

In the community of Bella Vista, two groups[3] were formed; the community was divided into two groups called Bella Vista A and Bella Vista B.

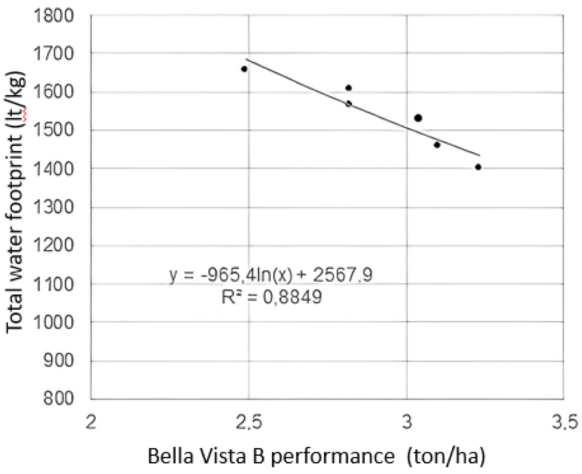
In Bella Vista A it is observed that as yield increases, the TWF tends to decrease. In Bella Vista B there is also an inverse relationship between yield and the TWF. In Bella Vista A, a 1% increase in yield leads to a reduction of the TWF of between 0.12% and 0.34%. In Bella Vista B, a 1% increase in yield reduces the TWF between 1.48% and 3.44% (see Figures 5 and 6).

Fig. 5. TWF and yield in the Bella Vista A community



Source: Own preparation based on cluster identification and Cool Farm Tool

Fig. 6. TWF and yield for the Bella Vista B community



Source: Own preparation based on cluster identification and Cool Farm Tool**.**

For the community of Vintuta, two clusters were also identified by dividing the sample into two groups, called Vintuta A and B. In both groups it is observed that as yield

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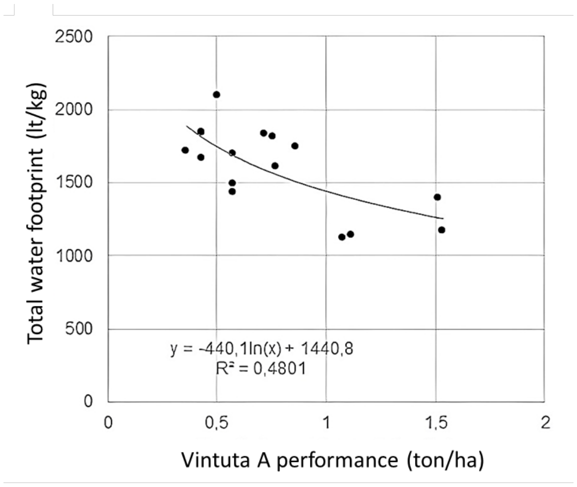
[3] The identification of the clusters was done using the K-means Clustering method, which is based on dividing data into K groups, where K is a predefined number. The algorithm assigns each data point to the nearest cluster, calculating the median of points in each cluster to update its position.

increases, the TWF tends to decrease. In Vintuta A, a 1% increase in yield reduces the TWF between 0.10% and 0.67% (see Figure 7).

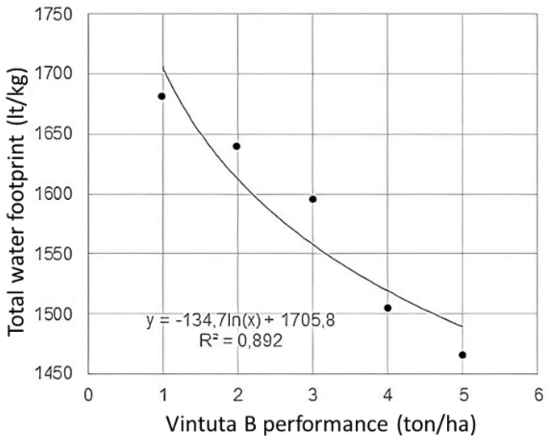
Fig. 7. WF and crop yield for Vintuta A



Source: Own preparation based on cluster identification and Cool Farm Tool.

In the case of Vintuta B, a 1% increase in yield reduces the TWF between 0.07% and 0.10%. The crop varieties and their resistance to drought (IPCC, 2019) may explain this behavior (see Figure 8).

Fig. 8. TWF and crop yield for Vintuta B



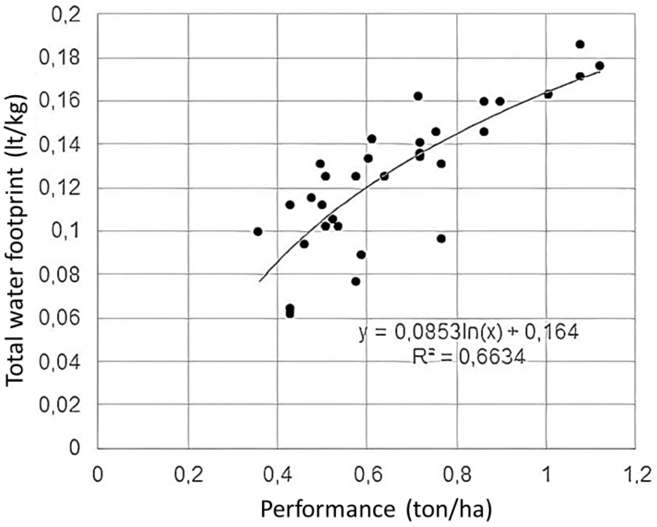
Source: Own preparation based on cluster identification and Cool Farm Tool

IV.4. The water footprint and water productivity in each community

In the analysis of the water productivity profile we identified three clusters, called Panels A, B and C, where it is observed that as yield increases, so does water productivity (Hoekstra and Hung 2005; Geerts *et al.*, 2008, 2009).

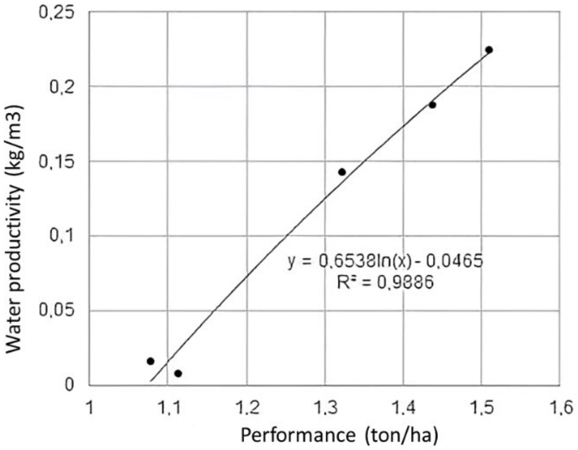
In Panel A, a 1% increase in yield increases water productivity by 8.21% (see Figure 9). In Panel B, a 1% increase in yield increases water productivity by 3.48%. Efficiency in the use of water, which improves crop resistance to drought, reinforces the positive relationship between yield and water productivity (see Figure 10).

Fig. 9. Water productivity and yield for panel A



Source: Own preparation based on cluster identification and Cool Farm Tool**.**

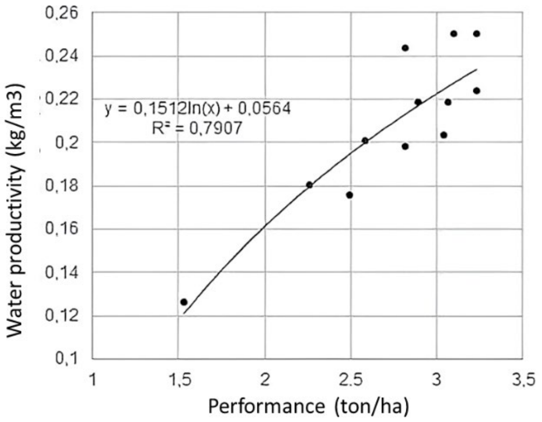
Fig. 10. Water productivity and yield for panel B



Source: Own preparation based on cluster identification and Cool Farm Tool**.**

In Panel C, a 1% increase in yield increases water productivity in the range of 0.82% to 0.91% (see Figure 11).

Fig. 11. Water productivity and yield for panel C

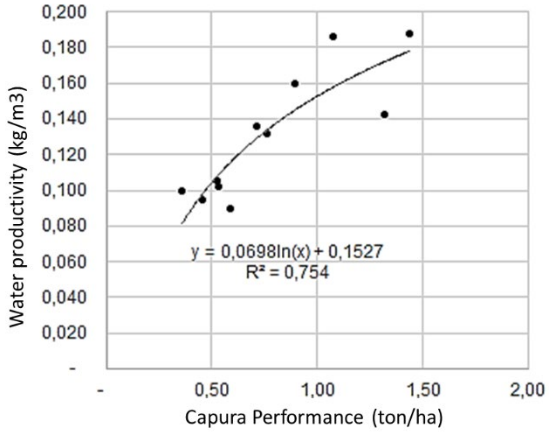


Source: Own preparation based on cluster identification and Cool Farm Tool.

IV.5. The water footprint and water productivity in each community

In Capura a positive relationship was also observed between yield and water productivity (Geerts *et al.*, 2008, 2009). In this community, it was estimated that a 1% increase in yield increases water productivity between 0.41% and 0.73% (see Figure 12).

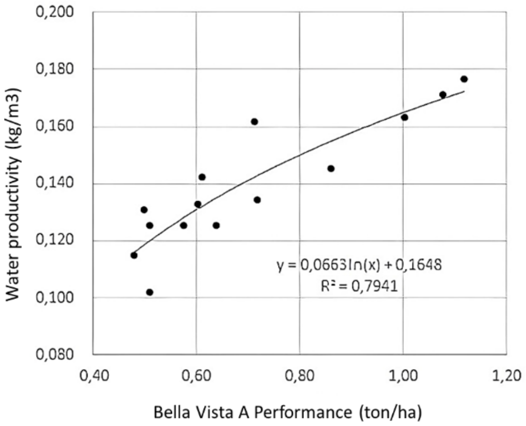
Fig. 12. Water productivity and yield for the Capura community



Source: Own preparation based on cluster identification and Cool Farm Tool.

In the community of Bella Vista, two clusters were identified (*i.e.*, Bella Vista A and Bella Vista B). As expected, in both groups a positive relationship was observed between yield and water productivity. In Bella Vista A, a 1% increase in yield increases water productivity between 0.21 and -0.338% (see Figure 13).

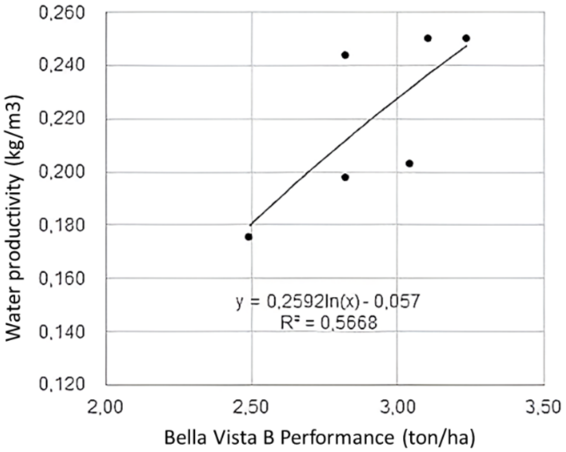
Fig. 13. Water productivity and yield for Bella Vista A



Source: Own preparation based on cluster identification and Cool Farm Tool.

In Bella Vista B it was estimated that a 1% increase in yield increases water productivity between 1.20% and 1.28% (see Figure 14).

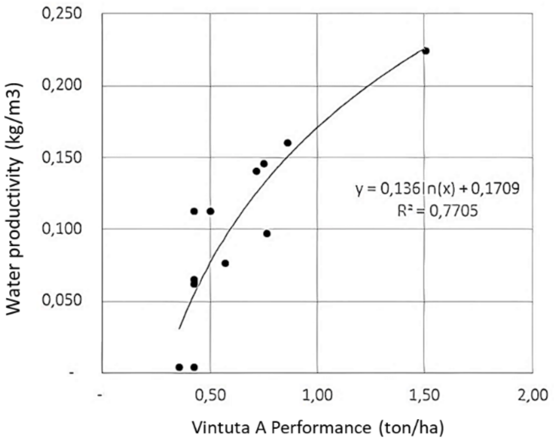
Fig. 14. Water productivity and yield for Bella Vista B



Source: Own preparation based on cluster identification and Cool Farm Tool

For the community of Vintuta, two groups were also identified (*i.e.*, Vintuta A and B), where there is a positive relationship between yield and productivity. In Vintuta A a 1% increase in yield increases water productivity in the range of 0.93 to 1.10% (see Figure 15).

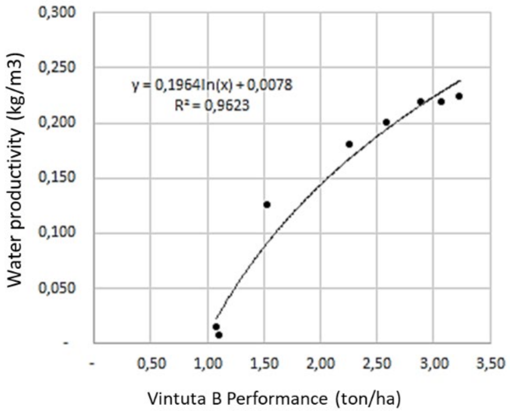
Fig. 15. Water productivity and yield for Vintuta A



Source: Own preparation based on cluster identification and Cool Farm Tool.

In Vintuta B a 1% increase in yield increases water productivity between 4.7% and 13.54% (see Figure 16).

Fig. 16. Water productivity and yield for Vintuta B



Source: Own preparation based on cluster identification and Cool Farm Tool.

IV.6. Adaptation to climate change and best agricultural practices

In this section an analysis is done of the different econometric models for assessing quinoa yield in relation to the GWF and the implementation of best agricultural practices (BAP). For this purpose, four methodological approaches were employed: ordinary least squares (OLS), robust least squares (RLS), generalized linear models (GLM), and quantile regression (see Table 6). Also, equation (8) is used:

$$\text{Rend} = \propto_0 + \propto_1 HV + \propto_2 BPA_{\text{soil}} + \propto_3 BPA_{\text{mix}} \quad (8)$$

where:

HV: This variable represents the impact on the use of rainwater in quinoa yield (*Rend*).

BPA_{soil}: Refers to best agricultural practices that can help in improving soil fertility, such as the use of organic fertilizer.

BPA_{mix}: Represents a combination of best practices in both soil and water management.

Table 6. Climate Change Adaptation Models and Good Agricultural Practices (GAPs)

		-	-	-
Coefficient α_0	-0.0004	0.0036	0.0004	0.0031
Coefficient α_1	0.4781	0.4886	0.4781	0.4738
Coefficient α_2	1.0856	1.1194	1.0856	1.1194
p-value α_0	***	***	***	***
p-value α_1	***	***	***	***
p-value α_2	***	***	***	***
R^2	0.9619	0.7095	0.9101	0.7777
Adjusted R^2	0.9597	0.9695	0.9101	0.7494
tα_0	5.6822	5.6822	5.6822	4.2154
		-		-
tα_1	-2.691	2.6193	-2.691	2.6448
tα_2	29.802	29.802	29.802	17.024
z-statistic α_0	5.4521	5.6822	5.6822	3.7654
		-		-
z-statistic α_1	-2.6193	2.6193	-2.691	2.5432
z-statistic α_2	5.8645	5.6633	5.8645	5.4215
F-statistic	437.6437	29.802	29.802	***
Prob(F-statistic)	***	***	***	***
Prob (Quasi-LR stat)	***	***	***	***
Standard Error α_0	0.2151	0.2132	0.2151	0.2562
Standard Error α_1	0.0844	0.0838	0.0844	0.0847
Standard Error α_2	0.0364	0.0359	0.0364	0.0657

Source: Own elaboration based on estimates made with Stata.

***Note:** The coefficients represent the relationship between the independent variables and the Green Water Footprint (GV). A p-value < 0.05 is: ** and < 0.005 is: *** indicating statistical significance. For more details, see Appendix 2.*

The first method (OLS) is based on the estimate of the regression coefficients by minimizing the sum of the squares from the differences between the values observed and those predicted. This approach assumes that the errors are normally distributed and that they possess a constant variation, which ensures the validity of statistical inferences (Wooldridge 2016).

In contrast, RLS is presented as an alternative that is less sensitive to the presence of atypical values and to heteroscedasticity, characteristics which are particularly relevant in the agriculture field, where conditions may vary considerably between plots. This method allows obtaining estimates of the coefficients which reflect more precisely the relationship between variables, thus minimizing the impact of outliers (Holland and Welsch 1977).

The third approach (GLM) allows the dependent variable to follow different distributions. It employs linking functions to associate the measurement of the dependent variable with the independent ones. This is useful in situations in which it is assumed that yield does not follow a normal distribution (McCullagh and Nelder 1989).

Finally, quantile regression is applied for estimating the effects of the independent variables in quartile 50 (Q50), which provides a more complete picture of how the variables affect yield at different levels of the distribution (Koenker and Basset 1978).

The results obtained indicate that RLS and GLM are the models most adequate for explaining quinoa yield. RLS is the preferred option because of its lower sensitivity to atypical values and its capacity to handle data that does not comply with the assumptions of the classic linear model. Although both models have a similar adjusted R², RLS provides more dependable estimates, particularly in the presence of anomalies in data, which is fundamental in the analysis of agricultural yield (Rousseeuw and Leroy 1987).

The analysis of the coefficients estimated reveals that the intercept has a similar value in both OLS and GLM (1.22) and that it is slightly higher in RLS (1.157). This indicates that in the absence of other variables, yield has a positive base value. As to the GWF, the coefficients are negative with all methods, suggesting that an increase in the WF is associated with a decrease in yield.

On the other hand, coefficients BPA_{soil} and BPA_{mix} are positive with all methods. This indicates that applying best agricultural practices, such as the use of organic fertilizer and combined (mixed) practices is associated with an increase in yield. It is relevant to mention that the Q50 quantile coefficient for BPA_{soil} is lower than with other methods, suggesting that its effect may be less pronounced in the median quartile of the yield distribution.

Interpretation of the results suggests that the positive coefficients associated with best agricultural practices, specifically BPA_{soil} and BPA_{mix} reflect a significant improvement in quinoa yield. This may be explained because the implementation of BPA_{soil} could help improve soil fertility through the use of organic fertilizer. This type of practice could foster a more favorable environment for the development of roots, improve moisture retention and increase the availability of essential nutrients. As a result, the quinoa plants could have access to water and nutritional resources more efficiently, which could translate into an increase in yield (López *et al.*, 2020).

On the other hand, BPA_{mix} implies the use of combined agricultural practices (soil and water management together). This approach seeks to integrate diverse strategies which when applied together would improve the efficiency and sustainability of agricultural systems. As to water management, this approach could allow for a more efficient use of water, particularly during dry periods. The benefits of BPA_{mix} are numerous, as water productivity could improve when optimizing the use of resources, promoting sustainability by conserving natural resources, and increasing resilience by allowing farmers to better adapt to climate variations and other environmental challenges.

The negative and considerable relationship of the GWF is particularly intriguing when what is expected is an improvement in water productivity to be accompanied by an improvement in crop yield. This negative coefficient can be explained by the fact that most of the plots studied have very low water productivity, with only 18% of the plots applying some type of management of the water resource. This suggests that many plots may be operating with low levels of efficiency, where an increase in the WF does not necessarily translate into efficient use of water, which results in lower yields (Grafton *et al.*, 2018). Besides, an increase in the GWF may indicate greater demand for water, which could lead to competition for limited water resources between plots, resulting in a negative effect on yield, particularly in areas in which water is scarce or is poorly managed (Pérez *et al.*, 2019).

It is important to highlight that when isolating the plots in which best agricultural practices were applied, a clear relationship was observed between the increase in water productivity and yield. This suggests that these practices not only improve efficiency in water use, but also contribute towards maximizing yield, which contrasts with the plots that do not apply BAP. The combination of adequate water management techniques and sustainable agricultural practices is essential for optimizing production (Zhang *et al.*, 2020).

The elasticity results for the GWF, BPA_{soil} and BPA_{mix} variables show that elasticity for the GWF was approximately zero in all models, indicating that yield does not respond to changes in the GWF. For BPA_{soil} and BPA_{mix}, in all models the values were above zero but less than 1. This means that yield does not proportionately respond to changes in both variables.

According to our results, there may be other variables that may be affecting quinoa production yield and its relationship with the WF. Soil management, its best practices, and overuse of water could have an effect if other variables are considered for defining their impacts. This may be related to discovering the microbial communities associated with the soils under different treatments and combinations of organic matter (Mohammadi *et al.*, 2011). Work could be done with different types of fertilizers to observe the different responses of organic matter on the soil's nutrient cycle, which could improve plant growth. Having more healthy and productive plants could contribute to absorbing water more effectively, which would reduce the amount of water needed for reaching optimal yields (Tarafdar, 2022). Different treatments could also be done in terms of the availability of water and plant water stress, as well as considering additional variables that may be affecting the response of crops to environmental changes.

It is relevant to consider that soil quality and optimization of the nutrient cycle depends on the microbial communities present (Mohammadi *et al.*, 2011). It is well known that there are many symbiotic relationships of microbial communities with the roots of quinoa crops (Estrada *et al.*, 2023). Hence, the recommendation is made to do studies of microbial communities in the soil to discover their interactions with crops, all of this with the aim of implementing these communities as part of another best agricultural practice in soil management.

IV. Conclusion

High agricultural yield is associated with a low WF. In Bolivia, average quinoa yield is approximately 1.15 t/ha, while the TWF is high: 1,728 l/kg. This discrepancy indicates that the relationship between yield and the WF in Bolivia is inefficient compared to other countries such as Peru and Ecuador, where yields are above 2 t/ha. The high WF, combined with low yields suggest that production is not optimizing the use of water, which may be attributable to inadequate agricultural practices and lack of efficient irrigation technology. This problem is exacerbated by the effects of climate change, where drought tends to cause water stress in crops. It is thus essential to do life cycle analyses to better understand the impacts of each production phase on the WF and on yield. Besides, assessments of water productivity profiles could identify opportunities for improving efficiency and productivity in the use of water in quinoa agriculture. This emphasizes the need for improving cultivation techniques and water management for achieving more sustainable and productive use of resources.

Water productivity could be optimized with the adoption of advanced irrigation technology and agricultural management. In Bolivia, lack of access to such technology considerably limits water productivity, which is related to the amount of salts present in irrigation water. Besides, productivity is measured directly through the electrical conductivity of irrigation water, which in turn affects quinoa yield. This situation is made evident by the fact that yield in the communities of the Altiplano, like Vintuta – which has a relatively low footprint (1,584.82 l/kg) – are not able to maximize quinoa's productive potential. The absence of adequate irrigation technology and agricultural management, and irrigation systems and water conservation practices contribute to low efficiency in the use of water. Hence, low water productivity in Bolivia is a critical factor that contributes to low quinoa yield, a matter that underscores the need for technological innovation in agriculture.

Efficient use of water may result in higher yields and lower economic costs for farmers. In Bolivia, inefficiency in water use generates high economic costs and low yields in quinoa production. This translates into forcing producers to invest more in irrigation and in water management without obtaining a proportional return in production. Climate variability and lack of water resources in the Bolivian Altiplano exacerbates this situation, making water management even more critical. Thus, inefficiency in water management limits competitiveness between Bolivian producers in the international market, given that they face additional challenges that affect their capacity to produce in a profitable way.

Implementing best agricultural practices (BAP) could improve crop yield by optimizing resource management. In Bolivia, the limited adoption of BAPs is associated with low yields in quinoa production. Lack of training and resources for implementing these practices means that many farmers are not taking full advantage of their productive potential. BAPs, such as crop rotation, use of organic fertilizer, and techniques for conserving water complement each other significantly. Under the circumstances, lack of implementation of BAPs contributes to a reduction of quinoa yield in Bolivia. It is therefore essential to foster education and access to resources for producers to adopt BAPs and improve their production.

V. Recommendations

Soil characteristics in the Southern Altiplano of Bolivia limit efficiency in use of water, which contributes to a greater water footprint in quinoa production. These soils often have low levels of organic matter and are prone to compaction, which reduces their capacity to retain moisture and increases the need for frequent irrigation. This situation affects not only crop sustainability, but also places the economic viability of farmers at risk, as they must invest more resources in water management. It is thus imperative to implement strategies that improve soil quality and optimize the use of water in quinoa production.

One of the first recommendations is the implementation of programs aimed at recovering organic matter in the soil. Incorporating organic fertilizers and compost could significantly improve soil fertility and increase its capacity to retain water and nutrients. Also, the adoption of soil conservation practices, such as minimum tillage, is crucial for reducing erosion and enhancing soil health. These practices will not only benefit quinoa growth, but will also contribute towards the long-term sustainability of agricultural ecosystems in the Altiplano.

For optimizing crop yield and reducing the water footprint it is essential to implement efficient irrigation systems. This includes installing advanced technology – such as drip and micro-aspersion systems – which allows more precise water application. Also, use of moisture sensors in the soil could provide much needed data on the water requirements of crops, allowing the producers to modify their irrigation practices to more effective ones. Training in these technologies will be fundamental for ensuring that farmers make adequate use of them and maximize their benefits.

Periodical monitoring and measurement of the water footprint of crops are recommended practices for assessing efficiency in water use. Performing assessments regularly will allow identifying areas for improvement and changing management strategies in relation to climate and soil conditions. The information obtained could be valuable for developing an approach that is more sustainable and adapted to the particular characteristics of the Altiplano, where climate variation can be considerable.

Additionally, we suggest the use of vegetation cover with plants such as native legumes and *Lupinus* (a wild species) which improve the soil's moisture retention. Such cover could consist of cover crops or mulching, which help reduce evaporation and maintain the soil's temperature. Implementing these practices will not only contribute to water conservation, but will also improve the biodiversity of ecosystems, creating an environment more resilient to climate change.

Lastly, training in integrated management of water resources is indispensable for producers to grasp the importance of managing water sustainably. This includes developing climate adaptation strategies that consider climate change forecasts and possible impacts on quinoa production. Fostering cooperation between producers, research entities and government organizations could facilitate the dissemination of knowledge and the adoption of innovative practices. This could ensure a more sustainable future for quinoa production in the Bolivian Altiplano.

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Annex 1. Profile: HHV, water yield and productivity-yield

Panel A	y = -579.4 ln(x) + 1555.1	0.51	0.36	1.53	2147.04	130.86	-1.12	-0.84
Panel B	y = -735.8 ln(x) + 2326.2	0.54	2.26	2.36	1726.66	1464.07	-0.35	-0.58
Capura	y = -771.6 ln(x) + 1583.8	0.82	0.12	2.12	1699.29	1208.33	-0.4	-20.71
Bella Vista A	y = -377.5 ln(x) + 1678.6	0.48	0.48	1.12	1955.67	1635.82	-0.47	-0.44
Bella Vista B	y = -965.4 ln(x) + 2567.9	0.88	2.49	2.46	1936.58	1519.54	-0.48	-3.44
Vintuta A	y = -440.1 ln(x) + 1440.8	0.49	0.36	2.26	1959.47	1237.64	-0.34	-0.667
Vintuta B	y = -1347.7 ln(x) + 1705.8	0.82	2.26	2.26	1595.97	1547.87	-0.07	-0.01
Elasticity between water productivity and yield								
Community	**Profile**	**R^2**	**Max Yield (x1)**	**Min Yield (x2)**	**Max Water Productivity (ProdH$_2$O max x1)**	**Min Water Productivity (ProdH$_2$O min x2)**	**Elasticity x1**	**Elasticity x2**
Panel A	y = -0.853 ln(x) + 0.164	0.66	1.12	1.53	0.076	0.174	6.05	8.21
Panel B	y = 0.654 ln(x) + 0.046	0.59	1.15	1.51	0.063	0.142	135.63	3.48
Panel C	y = 0.512 ln(x) + 0.056	0.79	1.53	3.23	0.091	0.131	0.82	0.91
Capura	y = 0.698 ln(x) + 0.057	0.82	1.53	3.23	0.046	0.059	0.41	0.726
Bella Vista A	y = 0.663 ln(x) + 0.1648	0.79	1.33	3.23	0.051	0.091	0.21	0.338
Bella Vista B	y = 0.2592 ln(x) – 0.057	0.57	3.23	3.23	0.011	0.131	1.28	1.2
Vintuta A	y = 0.136 ln(x) – 0.1709	0.77	0.36	1.51	0.031	0.227	0.93	1.1
Vintuta A	y = 0.1964 ln(x) + 0.0078	0.96	1.08	3.23	0.023	0.238	4696	13542

Source: Own elaboration based on estimates made with Cool Farm Tool.