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Estimate of the Carbon Footprint in Organic Quinoa Plots in the South of Bolivia – Case Study

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Estimate of the Carbon Footprint in Organic Quinoa Plots in the South of Bolivia – Case Study*

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Abstract

This case study is part of the research project "Creating Indigenous Women's Green Jobs under Low-Carbon COVID-19 Response and Recovery in the Bolivian Quinoa Sector). I estimate the carbon footprint associated with the quinoa production in southern Bolivia based on primary information of 19 plots. Using a cradle-to-gate life cycle analysis approach, under the ISO 14067 standard, and analyzing various emission sources through the Cool Farm Tool, I determine that the carbon footprint generates an average of 741 .7 kg CO2e per plot; and an average of 267.4 kg CO2e per hectare. The main emission sources identified are the use of organic fertilizer (54%), the consumption of fossil fuels (35%) and the use of protection inputs (8%). Considering the declared unit of 1 kg of harvested quinoa, I obtain the carbon footprint results per product, with values ranging between 0.3 and 2.3 kg CO2e/kg of quinoa and an average of 0.98 kg CO2e/ kg of quinoa.

Key words: climate change, carbon footprint, quinoa crops.
JEL Codes: Q16, Q29, Q54, Y8

Resumen

En el marco del proyecto de investigación *Creación de empleos verdes para mujeres indígenas en el sector de la quinua boliviana para una respuesta y recuperación al COVID-19 baja en emisiones de carbono,* el presente estudio de caso estimó la huella de carbono asociada a la producción de la quinua en el sur de Bolivia considerando 19 parcelas. Utilizando un enfoque de *análisis de ciclo de vida* de la cuna a la puerta, bajo el estándar ISO 14067 y analizando diversas fuentes de emisión a través de la herramienta *Cool Farm Tool*, se determinó que la huella de carbono genera un promedio por parcela de 741,7 kg CO_2e; y por hectárea, un promedio de 267,4 kg CO_2e. Las principales fuentes de emisión identificadas son el uso de abono orgánico (54%), el consumo de combustibles fósiles (35%) y el uso de insumos de protección (8%). Considerando la *unidad declarada* de 1 kg de quinua cosechada, se obtuvieron resultados de la huella de carbono por producto, con valores que oscilan entre 0,3 y 2,3 kg CO_2e/kg de quinua y un promedio de 0,98 kg CO_2e/kg de quinua.

Palabras clave: cambio climático, huella de carbono, cultivos de quinua.
Código JEL: Q16, Q29, Q54, Y8

* This research is part of the project titled *Creating Indigenous Women's Green Jobs Under Low-Carbon COVID-19 Responses and Recovery in the Bolivian Quinoa Sector*, presently being developed by Fundación INESAD, under the auspices of International Development Research Centre (IDRC) of Canada. The author wishes to thank Noemí Martínez for the compilation of information, the producers of RED Quinua and other key actors of the sector for the primary information provided, and also the INESAD team, which supported in developing this document. Possible errors are the entire responsibility of the author.

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I. Introduction

Quinoa is renowned as an important nutritional crop at the global level. Its grains are highly nutritious and contain a considerable amount of protein and bioactive compounds that surpass traditional cereal grains in terms of biological value. Quinoa has many functional properties that serve to reduce risk factors related to chronic diseases; this is a result of its antioxidant, anti-inflammatory, immunomodulator, and anti-carcinogenic properties, among others (FAO, 2024).

In Bolivia, quinoa is one of the seven priority crops, given its potential for contributing to rural development. In 2011 a law was enacted for fostering quinoa production, industrialization, and sales in the domestic and international markets (Plurinational Legislative Assembly, 2011). In addition, Bolivia is the second largest quinoa producer after Peru, with production of 44,707 tons in 2022 (FAO, 2023). In the Altiplano (High Plateau), where quinoa grows, it is the main commercial and export crop, and the grain is thus of great importance for the 70,000 small farmers that cultivate it in small parcels from one to six hectares in size (Stockholm Environment Institute, 2020).

The Bolivian Altiplano has arid and semiarid climatic conditions, an altitude of approximately 4,000 m.a.s.l., annual precipitation of 200 mm, a temperature range of -11°C to 30°C, 200 days annually of frost, and very poor and salty soil conditions (Jacobsen, 2011). This is the challenging context in which quinoa is grown, a crop recognized for its resistance to adverse climate conditions. However, the Altiplano has been seriously affected by climate change in recent years, with greater risks of drought, frost and higher temperatures. The projections for the region indicate an increase in temperature of at least 3°C and a fall in precipitation of between 10% and 30% by the end of this century, which would make quinoa production more vulnerable (Boulanger *et al*., 2014).

Agriculture is a sector that contributes to climate change due to its greenhouse gas (GHG) emissions. Bolivia reported that the agriculture, forestry, and other land use sectors (AFOLU) contributed, by 2008, to 61.6% of emissions (51,096.20 Gg of CO_2eq), making this sector the main generator of greenhouse gases (Ministry of the Environment and Water – Plurinational Authority of Mother Earth, 2020).

Given the properties of the quinoa grain, demand for this product increased at both the national and international levels at an average annual rate of approximately 12% in the 2005-2015 period (Pizarro and Martínez, 2015). This increase prompted the adoption of unsustainable agricultural practices which led to more soil erosion and degradation, as well as greater exposure and higher risks for the crops in the face of climate change (Liuhto *et al*., 2016). Despite this, some studies show that the carbon footprint associated to the production and distribution of quinoa is 1.03 kg of CO_2 eq per kg of quinoa, and in comparison, other products such as beef reach 28.6 kg of CO_2eq per kg of boneless products (Vázques-Rowe *et al*., 2017).

In such a context, the present endeavor, *Estimate of the Carbon Footprint in Organic Quinoa Plots in the South of Bolivia – Case Study*, seeks to estimate the carbon footprint generated by a group of plots of quinoa cultivation under present agricultural practices, comparing it with the adoption of best agricultural practices for improving the soil's organic matter.

The study is part of the research project titled *Creating Indigenous Women's Green Jobs Under Low-Carbon COVID-19 Responses and Recovery in the Bolivian Quinoa Sector*, performed by Instituto de Estudios Avanzados en Desarrollo (INESAD Foundation), with the support of International Development Research Centre (IDRC) of the Canadian government.

The main research objective of this project is "Building ample evidence of the social protection system from a perspective of generating green jobs for quinoa producers, focusing on indigenous women, in response to COVID-19 recovery low in carbon in the Bolivian quinoa production sector".

This work is related to the development of Product 2.1, *Agroclimatic diagnosis of the quinoa value chain*, which corresponds to the second specific objective of the project: "Providing scientific evidence for constituting fair labor income that is stable and sustainable (as components of green jobs), allowing small quinoa producers to increase their resilience in the face of negative climate, economy and health impacts".

II. Methodology

The present case study has the objective of estimating the baseline of the carbon footprint generated by traditional agricultural activities performed in the agricultural cycle of the quinoa crop (in a group of 19 selected plots in the Southern Altiplano of Bolivia). In future, the case study will also allow assessing the change in emissions that would occur by applying best agricultural practices.

The carbon footprint is defined as the total amount of CO_2 and other GHGs discharged into the atmosphere, and which are the responsibility of individuals, organizations, or products (Carbon Trust, 2007).

The estimate of the carbon footprint was done taking as a reference the technical specifications described in ISO 14067:2018 of greenhouse gases – Carbon Footprint of Products – which has a life cycle assessment (LCA) approach. LCA is a methodology that allows estimating the potential environmental impacts associated with the phases of a product. In the present case they are the impacts in the category of environmental impact: climate change (Asociación Española de Normalización UNE, 2006). LCA considers four phases: the first is the definition of the objective and scope; the second is the life cycle inventory; the third is the life cycle assessment; and the fourth is the interpretation of the life cycle. LCA has the characteristic of being an iterative process. Additionally, 2006 and 2019 IPCC Guidelines were followed. The GHGs included in the assessment are carbon dioxide (CO_2) with a global warming potential (GWP[1]) of 1 kg of CO_2eq/kg; methane (CH_4) with a GWP of 27.9 kg of CO_2eq/kg; and nitrous oxide (N_2O) with a value of 273 kg of CO_2eq/kg.

The study considered, as a system, the life cycle of quinoa crops and employed a cradle-to-gate approach; that is, it considered everything from preparation of the soil up to the management of agricultural waste, and from transportation to the storage of the product prior to milling (Figure 1). The research is based on the inventory of the agricultural production system. A crop season identified by three major phases of tasks (Gómez-Pando *et*

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[1] This is a useful measure for comparing the potential climate impact from the emissions of the different GHGs. It defines the effect of warming integrated across time which is caused presently by an instantaneous release of 1 kg of a GHG, compared to the one caused by CO2 (IPCC, 2018).

al., 2013) was considered. The phases are: i) transportation of inputs, and soil preparation (diesel consumption in cultivation work is included in this phase); ii) sowing (occuring between May and June) and the tasks during this process, which takes place between September and November (and includes fertilizing, sowing, cutting undesired quinoa plants, soil accumulation at the base of the plants, applying protection inputs, and irrigation); iii) harvest and post-harvest, done in the months of February and April (Mollisaca, 2021), which includes cutting, grain separation, transportation of the harvested product, and waste management. The unit established was kilogram of harvested quinoa, but the results were also expressed in terms of totals and by hectare.

GHG emissions were estimated with the help of Cool Farm Tool, a calculator of net emissions generated by specific crop. The tool is continuously updated and employs empirical research as well as a broad range of published databases and IPCC 2006 and 2019 methodologies, in addition to the GHG Protocol guidelines (Cool Farm Alliance, 2022; Cool Farm Alliance, 2024). At the farm level, the tool identifies specific context factors such as climate characteristics, production inputs and other management activities that affect GHG emissions. Cool Farm Tool (CFT) calculates total GHG emissions in terms of "per unit of area" and "by unit of product" (Kumar *et al.*, 2021). The tool has seven sections: crop, soil, inputs, fuel and energy, irrigation, carbon, and transportation, each of which has questions and a request for information that the farmers possess (Cool Farm Alliance, 2023). Also, at the beginning of the assessment, the climate zone of the study is selected, according to the climate zone map published in the most recent IPCC guide (2019) to determine which climate zones must be used to calculate GHG emissions arising from agricultural practices. It should be noted that the climate zones are necessary for several calculations within the CFT, including N_2O and waste management.

In general, and for all cases, the quantification mechanisms are based on multiplying the emission factors (FE) which apply to each emission source by the activity data:

$$L = \sum_i L_i = \sum_i Da_i \, FE_i \tag{1}$$

where:

$L =$	GHG emissions (kg of CO_2eq)
$Da_i =$	Activity data (m^3, liters, kWh, etc.)
$FE_i =$	Emission factor

In this tool, total carbon emissions from crops are based on equation (2) and include fertilizer production, fertilizer use, energy use (and land use), change of land use, agricultural waste, wastewater, and emissions from pesticides and protection inputs (Cool Farm Alliance, 2024):

$$L_i = L_{residue} + L_{\text{fert.use}} + L_{\text{fert.prod}} + L_{\text{pest.}} + L_{\text{fuel\&energy}} + L_{irrigation} + L_{Cstocks} + L_{\text{n-mineralised}} + L_{\text{transp.}} \tag{2}$$

where:

$L_{\text{i}} =$	Total crop emission (kg of CO_2eq)
$L_{\text{residue}} =$	Methane and nitrous oxide emissions from crop waste management (kg of CO_2eq)
$L_{\text{fert. prod.}} =$	Emissions associated with fertilizer production (kg of CO_2eq)
$L_{\text{fert. use}} =$	Soil emissions from the application of fertilizers (kg of CO_2eq)
$L_{\text{pest.}} =$	Emissions from the use of pesticides (kg of CO_2eq)

$L_{fuel\&energy}$ = Emissions from energy and fuel used in machinery (kg of CO_2eq)
$L_{irrigation}$ = Irrigation emissions (kg of CO_2eq)
$L_{CStocks}$ = Emissions associated with changes in carbon reserves (kg of CO_2eq)
$L_{\text{n-mineralised}}$ = Emissions from N mineralized in the soil because of soil carbon loss (kg of CO_2eq)
L_{transp} = Transportation emissions (kg of CO_2eq)

The tool is aligned with different carbon footprint estimation standards, including ISO 14067:2018, thus providing results based on the defined unit declared; however, we do not expect the tool to strictly comply with all specifications. The methods employed are based mainly on the guidelines published in IPCC 2006 and the updates done in 2019 for the AFOLU sector. Specifically, use is made of *Volume 4: Agriculture, Forestry and Other Land Use; Chapter 5: Crops; Chapter 11: N_2O Emissions from Managed Soils, and CO_2 Emissions from Lime and Urea Application*. In addition, use is made of information generated by researchers who have published scientific articles. The following is a summary table of the emissions methods and factors employed by the tool:

Table 1. Summary of methods and emission factors used by *Cool Farm Tool*.

Section	Method	Emission factors
Global warming potentials	IPCC 2019	AR6
Crop residues	IPCC 2019 tier 1	IPCC 2019. Default values for crops not in IPCC by papers
Fertiliser application	IPCC 2019 tier 1 & 2, with some refinements for wet/dry factor use	IPCC 2019 tiers 1 y 2
Compost production (fertiliser)	N/A	S. Brown, M. Cotton, S. Messner, F. Berry, y D. Norem. "*Methane Avoidance from Composting*". *Climate Action Reserve*, 2009.
Pesticide use	N/A	WFLDB- pesticide factors
Energy use	N/A	DEFRA 2021
Carbon stock change	IPCC 2019 tier 1	IPCC 2019
Irrigation emissions	Depth and distance: J. Hillier, C. Walter, D. Malin, T. Garcia-Suarez, L. Mila-i-Canals, y P. Smith. "*A Farm-focused Calculator for Emissions from Crop and Livestock Production*". *Environmental Modelling & Software*, 26(9):1070–1078, 2011.	WFLDB-electricity factors

Source: *Cool Farm Alliance* (2024).

The considerations for verifying and validating the estimate of the carbon footprint are provided in ISO 14064-3, which describes the process for such validation or verification, including planning of the validation or verification (strategic analysis, risk assessment, compilation of evidence, etc.), the procedures and activities of verification and validation, and assessment of the declarations of organizational, project and product GHG.

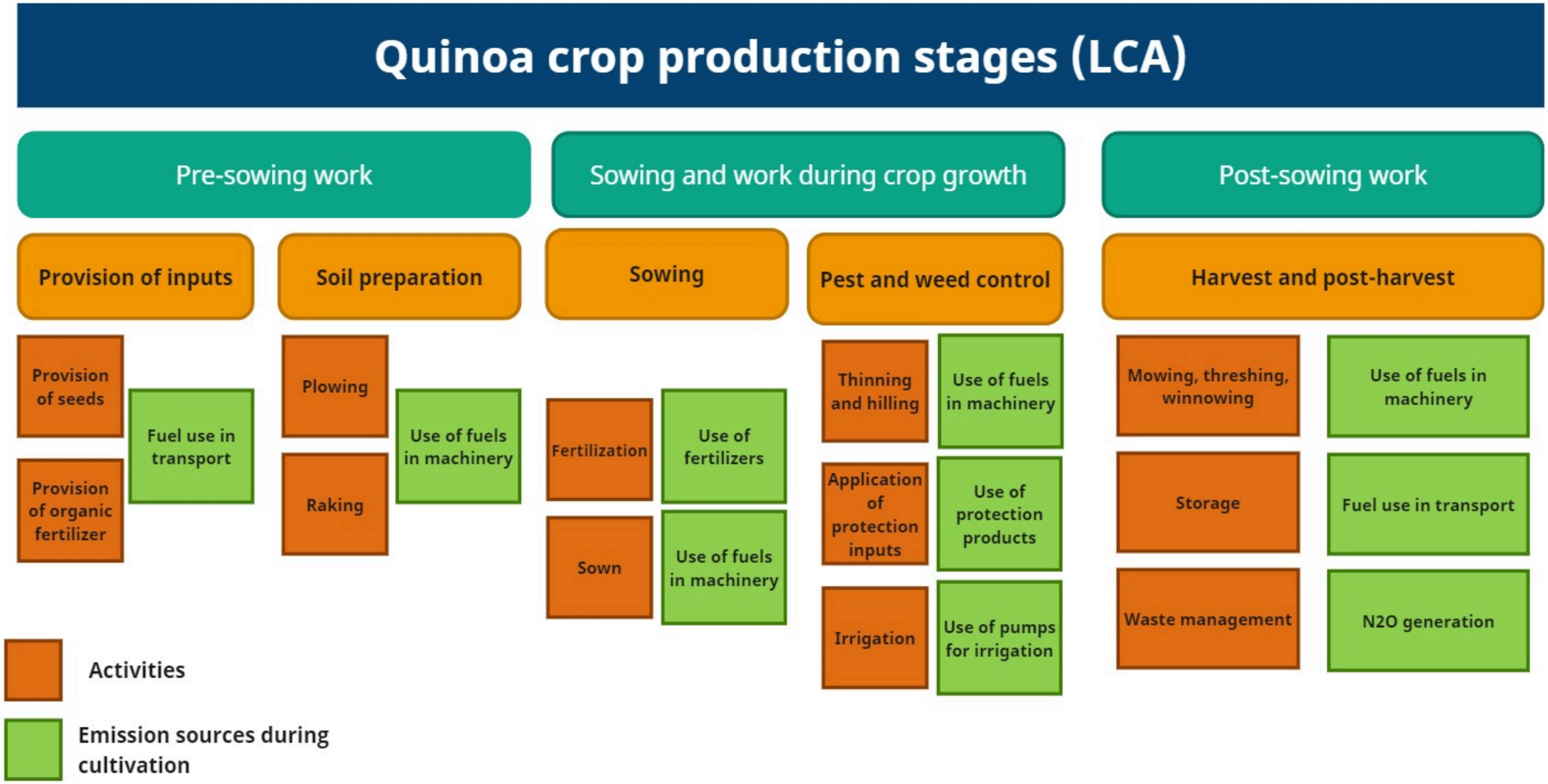
All information and data entry used for the carbon footprint estimate are provided in the present report under *Annex 1. The information employed in the study*. The aim of this is to facilitate reproduction and replication of the study in future.

Geographic scope of the study

Most quinoa production occurs in the Southern Altiplano zone, made up of the Departments of Oruro and Potosí (in the inter-salt lake area). For the present study, analysis was done of 19 plots, listed in Figure 2 below.

- Department of Oruro: Municipality of Salinas de Garci Mendoza, including the communities of Capura (2 plots), Rodeo (3), Sighualaca (1), and Florida (4); Municipality of Pampa Ullagas, at the community of Bengal Vinto (1)
- Department of Potosí: Municipality of Uyuni, including the communities of Vintuta (3), Bella Vista (4) and Tusqui (1)

Figure 1. Quinoa production stages included in the Life Cycle Assessment (LCA).



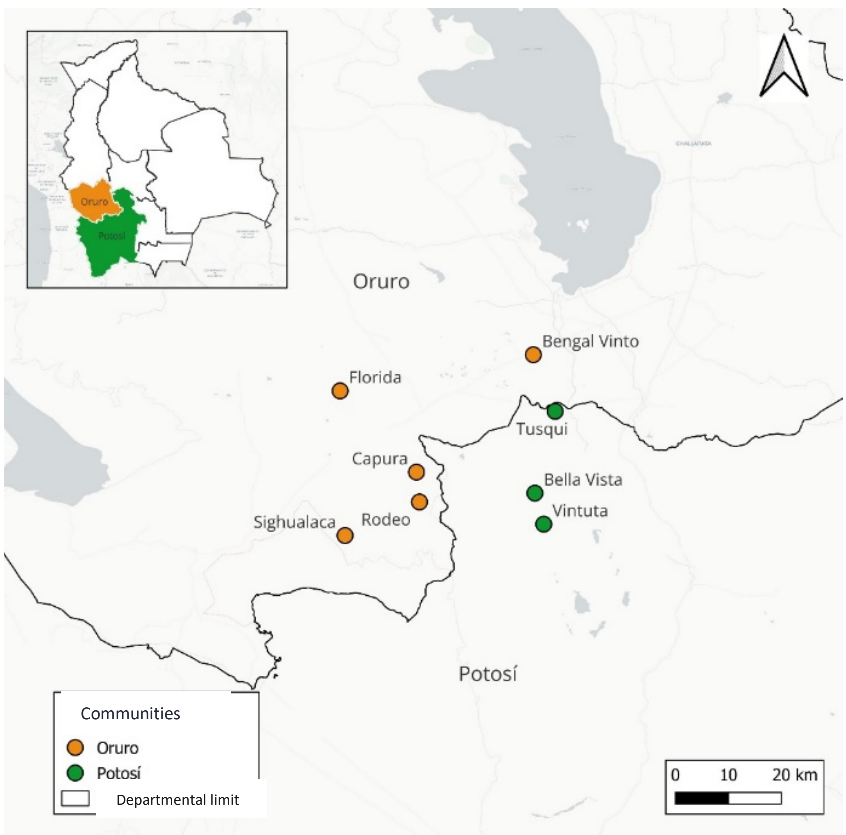
Source: Own elaboration based on ISO 14067 guidelines.

This region is located at an altitude of between 3,650 and 4,200 m.a.s.l. and is known for its extreme environment and climate characteristics.

The region has 160 to 257 days of frost per year, annual precipitation going from 150 mm in the south to 300 mm in the northeast, and a median annual temperature of 8.3°C, which can go as low as -17.8°C.; in the dry and warm months of September to December, temperatures can go up to 23.4°C. The area is continuously exposed to drought, soil erosion, strong winds, and intense solar radiation. The soil is rocky, and its texture is mostly silty-sandy; organic matter content is “low” and “very low” (Vargas and Sandy, 2017; Winkel *et al.*, 2014).

The laboratory analyses done reveal that the soil characteristics of the plots of the assessment have thick sandy loam texture, with average organic matter of 0.48% and 0,28% of C. Soil drainage is poor, and the pH value is 8.7, with a range of between 7.5 and 9.1.

Figure 2. Location of the communities included in the assessment.



Source: Own elaboration.

Data compilation

The data comes mainly from a survey done with the producers of the 19 plots[2] for obtaining information on: yield (100 kg or qq[3]/ha), plot size, agricultural practices applied, use and origin of organic fertilizer, use of protection inputs, quantity and types of fuel used in machinery such as tractors, use of fuel in transportation of harvested products, changes in use of soil, irrigation, and agricultural waste management. Compilation of data was done from September to October 2023.

As part of the project activities and in parallel to this study, another team took soil samples for characterizing its texture, organic matter content, moisture, and drainage. Information on yield was also compared with data compiled by this team. It was observed that the amount of organic matter present in these soils is low or very low, with values below 1.2%, except for P3, with 1.52%.

Table 2. Soil's characterization data by plot.

Plot	Soil texture	Soil organic matter (%)	C total (%)	Soil pH
Oruro				
P1	Sandy loam	0,37	0,21	9,02
P2	Sandy loam	0,58	0,33	8,93
P3	Sandy loam	1,52	0,88	8,7
P4	Sandy loam	0,71	0,41	8,97
P5	Sandy loam	0,63	0,37	8,89
P6	Sandy loam	0,52	0,30	8,91
P7	Sandy loam	0,40	0,23	7,99
P8	Sandy loam	0,42	0,24	8,76
P9	Loam sandy	0,15	0,09	8,18
P10	Sandy loam	0,59	0,34	8,94
Potosí				
P11	Sandy loam	0,39	0,22	8,90
P12	Sandy loam	0,68	0,40	8,89
P13	Sandy loam	0,47	0,27	8,76
P14	Sandy loam	0,43	0,25	8,7
P15	Sandy loam	0,41	0,24	8,82
P16	Sandy loam	0,42	0,25	9,06
P17	Loam sandy	0,15	0,09	9,02
P18	Sandy loam	0,30	0,18	8,29
P19	Sandy	0,18	0,11	8,33

Source: *Colque* (2023).

The production characteristics of each producer are standardized, though there are differences in terms of the amount of pesticide, organic fertilizer and fuels used. All producers of the participating communities reported having organic production certification. Sheep manure is used in all cases, and in some plots also camelid manure, from the communities themselves, and with applications of between 4,000 and 13,600 kg/ha with sowing done by scattering. The values were collated by technicians experienced in quinoa crops. As to protection inputs, use is made mostly of homemade insecticides in a preventive manner with applications of between 0.3 and 4 liters/ha; however, 8 of the 19 producers did not use any protection input.

[2] The plots were initially 20 in number; however, one of the producers did not provide information and was thus withdrawn from the analysis.
[3] Quintals.

There is fuel consumption in the production activities and in transportation during the cultivation phases. All producers reported using tractors for field work and diesel as fuel (on average, 60 liters of diesel were used). Pick-up trucks or motorcycles are used for transporting workers and the product, and they consume on average 25 liters of gasoline. Atypical values of certain cases were replaced by average values according to the values reported in plots with similar areas.

Given that quinoa can withstand extreme climate conditions, few producers irrigate their plots. Irrigation was done only in plots P3, P12, P13, and P14, employing between 10,000 and 50,000 liters of water, and fossil fuels for pumping.

Crop waste was estimated using a proportion of 0.73 (kg of harvested quinoa/kg of waste generated), and the waste considered was that generated during grain separation, and stems and leaves (Mollisaca, 2021; Secretariat of Food and Nutritional Safety, 2013). It is important to mention that in most plots, 50% to 70% of waste is used as livestock feed, and the remainder is left in the fields. On average, 323 kg/ha of waste is produced.

As to changes in carbon reserves, only the changes which took place in a period of less than 20 years were considered. Only plots P10 and P19 reported having performed changes in land use over this period.

In all cases, verification was done that the information was consistent with literature data and with the opinions of technicians experienced in quinoa cultivation.

A general description of the data obtained is presented in Table 3. The detailed information compiled is presented as an Annex in Excel format.

Table 3. Data collected by plot.

Plot	Community	Plot area (ha)	Yield (kg/ha)	Organic fertilizer use	Insecticides use	Irrigation
Oruro						
P1	Capura	1,0	207,0	No	No	No
P2	Capura	2,6	1.045,6	Yes	No	No
P3	Rodeo	1,9	625,6	Yes	Yes	Yes
P4	Rodeo	6,4	133,4	Yes	Yes	No
P5	Rodeo	1,3	410,7	Yes	No	No
P6	Sighualaca	1,6	400,2	Yes	Yes	No
P7	Florida	3,5	611,8	Yes	Yes	No
P8	Florida	0,6	197,8	Yes	Yes	No
P9	Florida	0,8	147,2	Yes	No	No
P10	Florida	1,6	414,0	Yes	No	No
P11	Bengal Vinto	2,0	216,2	No	No	No
Potosí						
P12	Vintuta	0,6	174,8	Yes	Yes	Yes
P13	Vintuta	2,6	970,6	Yes	No	Yes
P14	Vintuta	3,8	538,2	Yes	Yes	Yes
P15	Bella Vista	0,6	492,2	Yes	Yes	No
P16	Bella Vista	5,0	386,4	Yes	Yes	No
P17	Bella Vista	2,3	340,4	Yes	Yes	No
P18	Bella Vista	2,9	138,0	Yes	No	No
P19	Tusqui	8,0	179,4	Yes	Yes	No

Source: Own elaboration.

III. Results

Carbon footprint assessed in plots.

The total area of the study was 49 hectares, with an average plot size of 2.6 hectares. On average, reported yield was 402 kg/ha, with values of between 133 and 1,046 kg/ha. The total carbon footprint of the plots (without considering emissions due to change in land use) was 14,091 kg of CO_2eq, with an average of 742 kg of CO_2eq/plot. Emissions per hectare are in the range of 62 to 470 kg of CO_2eq, with an average of 267 kg of CO_2e/ha.

In terms of the declared unit defined (kg of harvested quinoa), emissions range from 0.3 to 2.3 kg of CO_2eq/kg of quinoa, with an average of 0.98 kg of CO_2eq/kg of quinoa. The range of variability depends on the activities and quantities reported for use of organic fertilizer, application or not of protection inputs, use of fuels, and irrigation, as well as the yield of each plot. Thus, for example, in the case of use of organic fertilizer, two plots reported applying 4,000 kg/ha of manure; three plots 6,400 kg/ha; ten plots 9,600 kg/ha; one plot 13,600 kg/ha; two reported not applying any organic fertilizer, and one reported a different form of applying it.

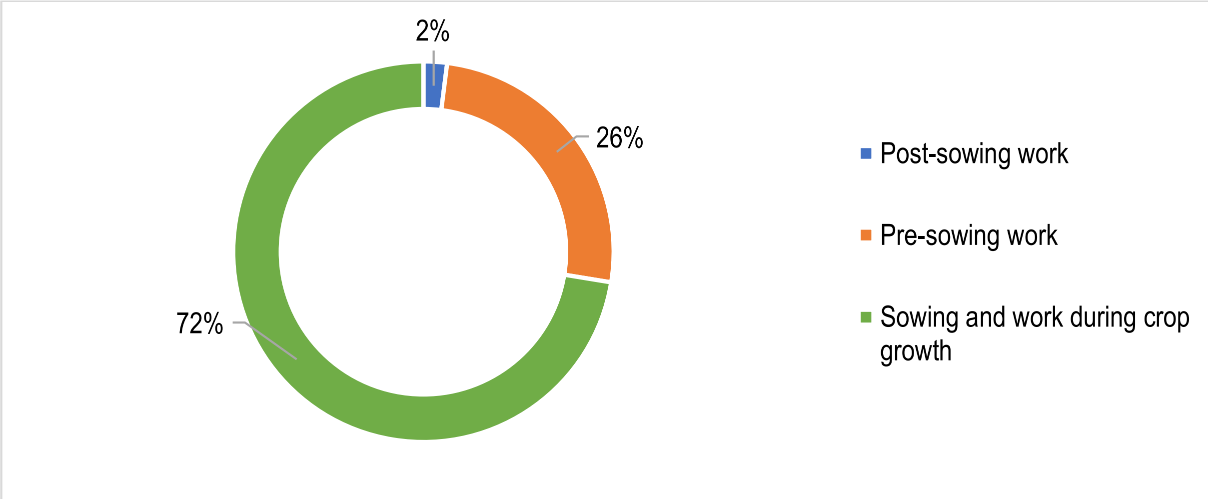
Table 4. Results: carbon footprint by plot.

Plot	Carbon Footprint		
	Total (kg CO_2e)	By hectare (kg CO_2e/ha)	By product (kg CO_2e/kg harvested quinoa)
P1	86,8	86,8	0,42
P2	732,6	286,2	0,27
P3	534,3	278,3	0,44
P4	1797,4	282,2	2,12
P5	80,9	62,2	0,15
P6	279,3	175,7	0,44
P7	1170,2	334,4	0,55
P8	136,5	239,4	1,21
P9	223,4	279,3	1,90
P10	737,6	472,8	1,14
P11	232,5	118,6	0,55
P12	249,8	390,3	2,23
P13	830,3	318,1	0,33
P14	1163,0	302,9	0,56
P15	152,0	237,5	0,48
P16	1306,7	261,3	0,68
P17	675,7	288,7	0,85
P18	944,7	321,3	2,33
P19	2757,8	344,7	1,92
Mean	**741,7**	**267,4**	**0,98**

Source: Own elaboration.

The life cycle phase which most considerably contributes to generating emissions is that of sowing and tasks during crop growth (72%). This includes the use of organic fertilizer, sowing, pest and weed control, and gasoline consumed in transporting persons. The next phase of the life cycle which most contributes to the carbon footprint is work prior to sowing, which includes the use of diesel in tractors for preparing the ground and transportation of inputs to the plots (26%). Finally comes the phase of tasks after sowing; that is, the harvest and postharvest, which includes transportation of products for storage prior to milling, and waste management (2%).

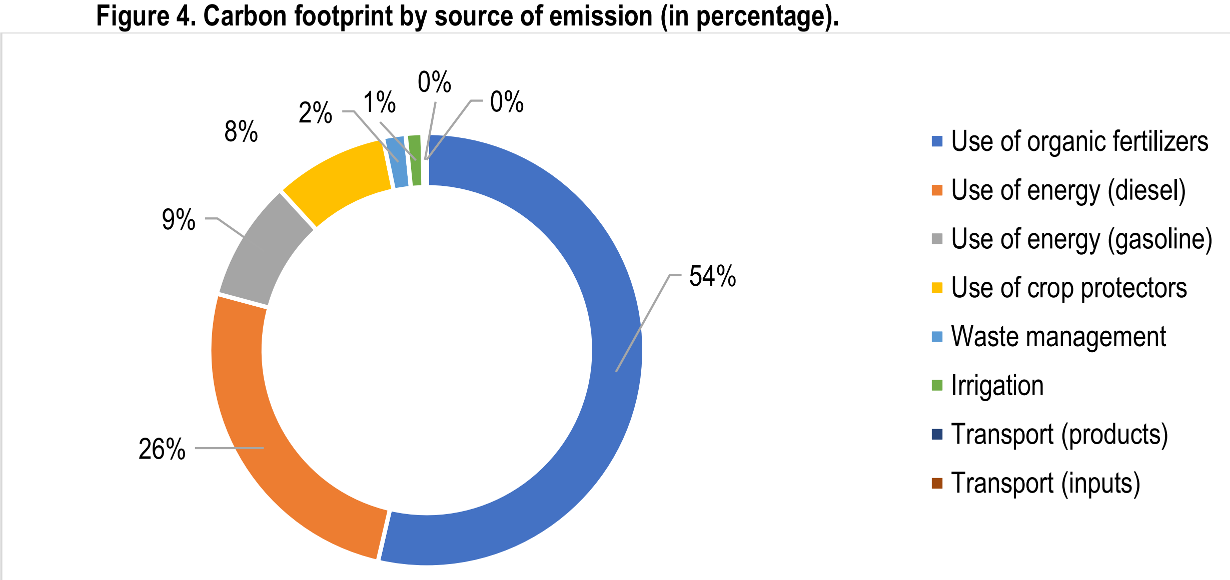
Figure 3. Carbon footprint by life cycle stage (in percentage)



Source: Own elaboration.

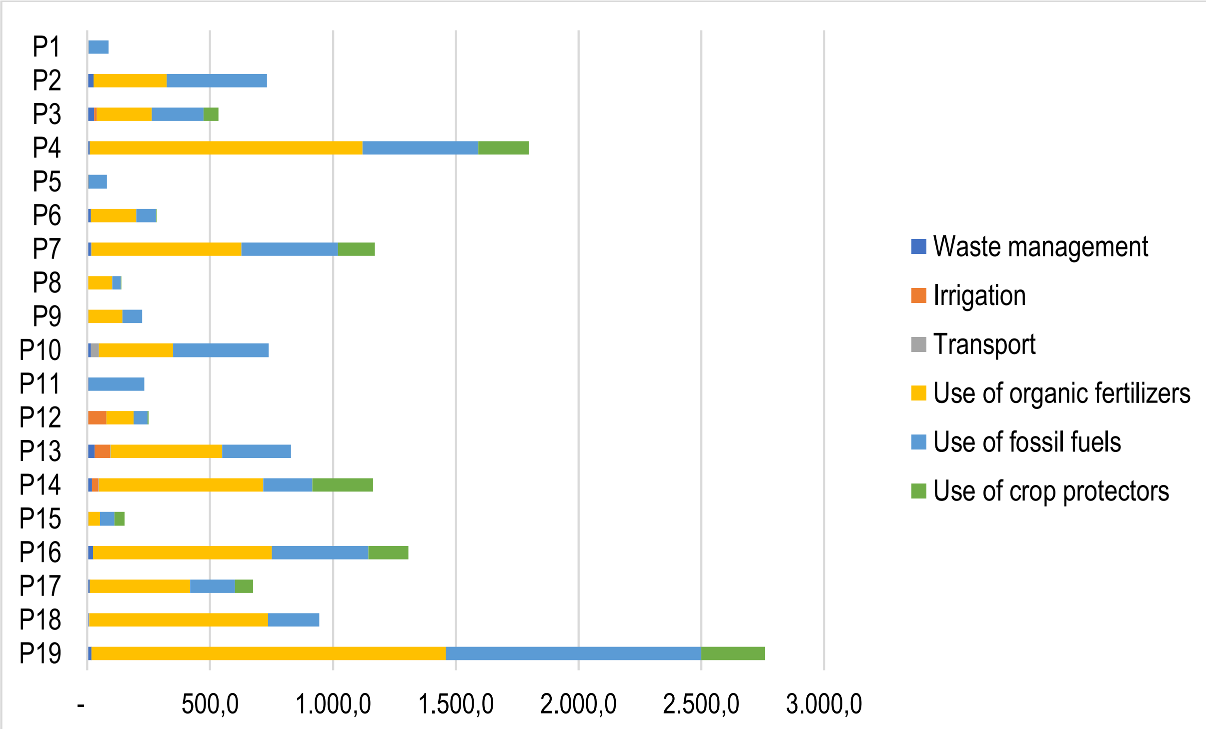
The main emissions are generated through the use of organic fertilizer (54%), given that the main greenhouse gas freed both from the decomposition of organic matter (from organic fertilizer in aerobic form) as a result of processes of nitrification and denitrification of the soil is N_2O (which has a GWP 273 times that of CO_2). Then comes consumption of fossil fuels (35%), mainly from the use of diesel in tractors for cultivation work and from consumption of gasoline for transporting persons. Following this is the use of protection inputs (8%), mostly insecticides made at home by the producers, applied in low doses and not in all cases, as the production is organic. Presented below is the waste (2%) management, which represents a lower contribution, given that in most cases residue is employed as livestock feed and the remainder is incorporated into the crop soil. Irrigation and transportation of the finished product constitute a lower level (1%). As mentioned, only four producers irrigated their plots and the finished product is transported short distances from the plot to the producers' homes, or to a storage area located in the communities themselves.

Figure 4. Carbon footprint by source of emission (in percentage).



Source: Own elaboration.

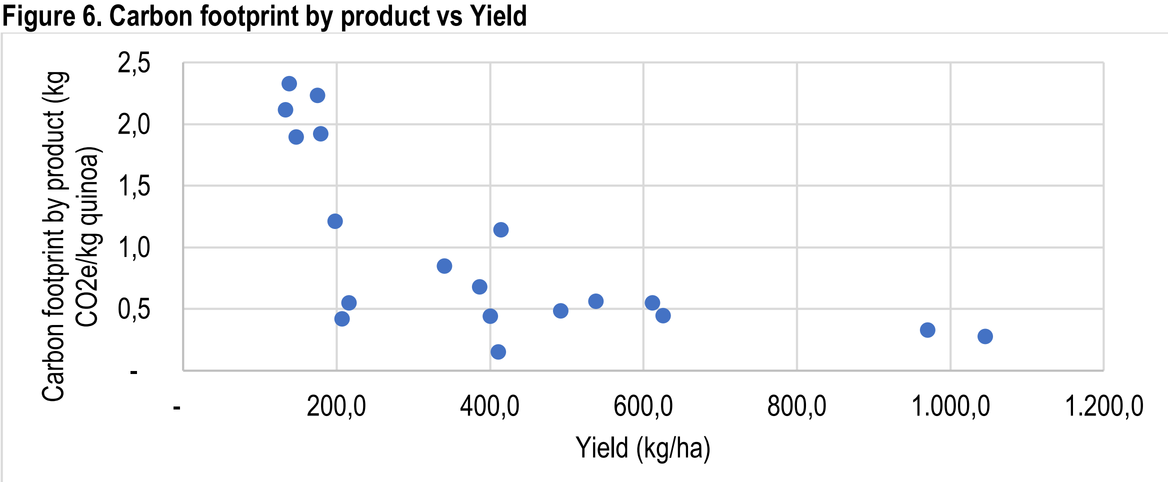
Figure 5. Carbon footprint by source of emission by plot (in kgCO₂e)



Source: Own elaboration.

In most plots there is a correlation between yield and the carbon footprint: greater yield generates more GHG emissions. Figure 6 presents a first group of plots with low yields and a greater carbon footprint in those employing organic fertilizer, protection inputs, fossil fuels, and irrigation if applicable. The plots that have low yield and a low carbon footprint do not apply organic fertilizer. A next group of plots with medium yield and carbon footprints of less than 1 t of CO_2eq/kg of product and a group with high yields and footprints lower than 0.5 t of CO_2eq/kg of product. There are variations that depend on the type of practices, activities performed, and inputs and the amounts used.

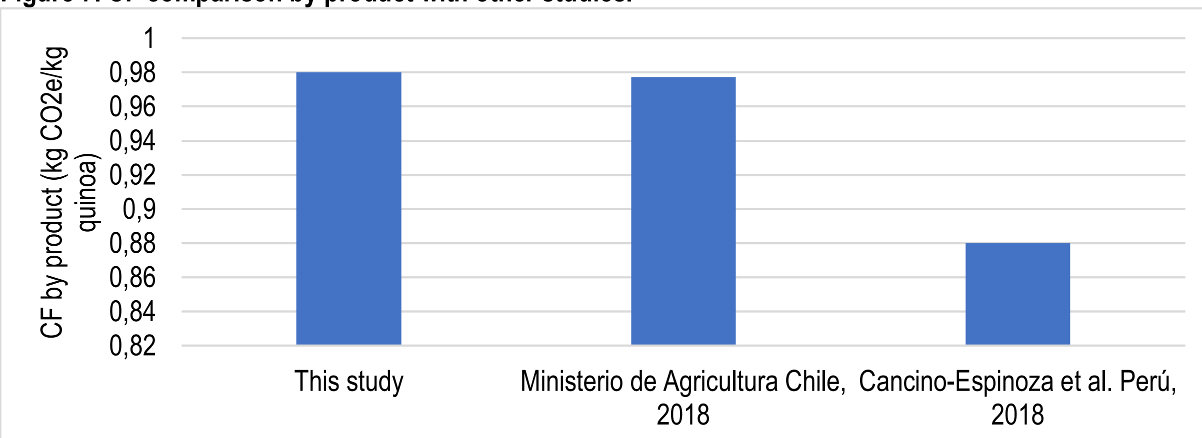
Figure 6. Carbon footprint by product vs Yield



Source: Own elaboration.

When analyzing the average value of the carbon footprint per product of 0.98 kg of CO_2eq/kg of harvested quinoa with values obtained from other studies, it may be observed that the value approaches the estimates reported by Vázques-Rowe *et al.* (2017), which analyze the emissions generated by different diet profiles in Peru. Similarly, the value is close to what is mentioned by Cancino-Espinoza *et al.* (2018), who did an analysis of the impacts on the environment related to organic quinoa production and its distribution to the main export markets of Peru by applying the LCA methodology, where they indicate a value of 0.88 kg of CO_2eq/kg of quinoa. Also, there is a study performed by the Ministry of Agriculture of Chile for the design and measurement of the quinoa, pomegranate, and cactus fruit carbon footprint (Ministry of Agriculture – Office of Agricultural Studies and Policies, 2018). This study reports an average value of 0.9774 kg of CO_2eq/kg of quinoa. In the Cancino-Espinoza study, a LCA was done with the Simapro software; and the Ministry of Agriculture of Chile study employed an own tool based on PAS 2050 methodology.

Figure 7. CF comparison by product with other studies.



Source: Own elaboration.

When an analysis is done by departments of the country, the communities of Potosí generate on average a carbon footprint 49% higher by product than the communities of Oruro. The community with the most emissions in Potosí is Tusqui, and the one with the most in Oruro is Florida. In Oruro not all producers employ organic fertilizer, while in Potosí all producers reported using organic fertilizer. Similarly, five out of 11 plots in Oruro employed protection inputs, and in Potosí only six out of eight plots used them. In Oruro irrigation was done only in one plot, while in Potosí, three plots were irrigated.

Table 5. Average carbon footprint per product by community.

Community	Average carbon footprint by product (kg CO_2e/kg quinoa)
Oruro	**0,69**
Bengal Vinto	0,55
Capura	0,35
Florida	1,20
Rodeo	0,90
Sighualaca	0,44
Potosí	**1,35**
Bella Vista	1,08
Tusqui	1,92
Vintuta	1,04

Source: Own elaboration.

Two plots evaluated – one in Florida, Oruro and the other one in Tusqui, Potosí – reported changes in soil use in a period of less than 20 years. Including this source of emissions, the carbon footprint is 16,076 kg of CO_2eq, and on average the carbon footprint by product is 1.1 kg of CO_2eq/kg of quinoa.

As part of the project, the application of a best agricultural practice (BAP) is being realized in the plots assessed, which consists of including a mix of household compost as fertilizer for increasing the levels of organic matter in the soil and increasing crop yield[4]. Considering a one-hectare plot that applies this best practice, obtaining a yield of 700 kg/ha (Fundación PROINPA, 2020) (García *et al.*, 2013), with no irrigation and no use of protection inputs, a value of 0.74 kg of CO_2eq/kg of quinoa is obtained, compared with the average obtained with the present practices of 0.98 kg of CO_2eq/kg of quinoa. However, this value must be updated with the actual values of the application of compost, organic matter in the soil and yield, obtained in the field.

Emissions considering the effect of *thola* shrubs

Fifteen of the 19 producers considered in the evaluation reported using plantations of *thola* shrubs (specifically, the *Parastrephia lepidpphylla* species, native to the location of the study) as a form of protecting the soil against erosion. As this is a perennial shrub, it works as a carbon reservoir. Taking as reference the study performed by Ponce Quispe (2018) on carbon content stored in the *thola* biomass, the shrubs of the study are considered small (of less than 40 cm) and generate, on average, 0.55 kg of CO_2/plant. Depending on the number of shrubs reported in each plot, sequestrations of 5 to 96 kg of CO_2/ha are obtained.

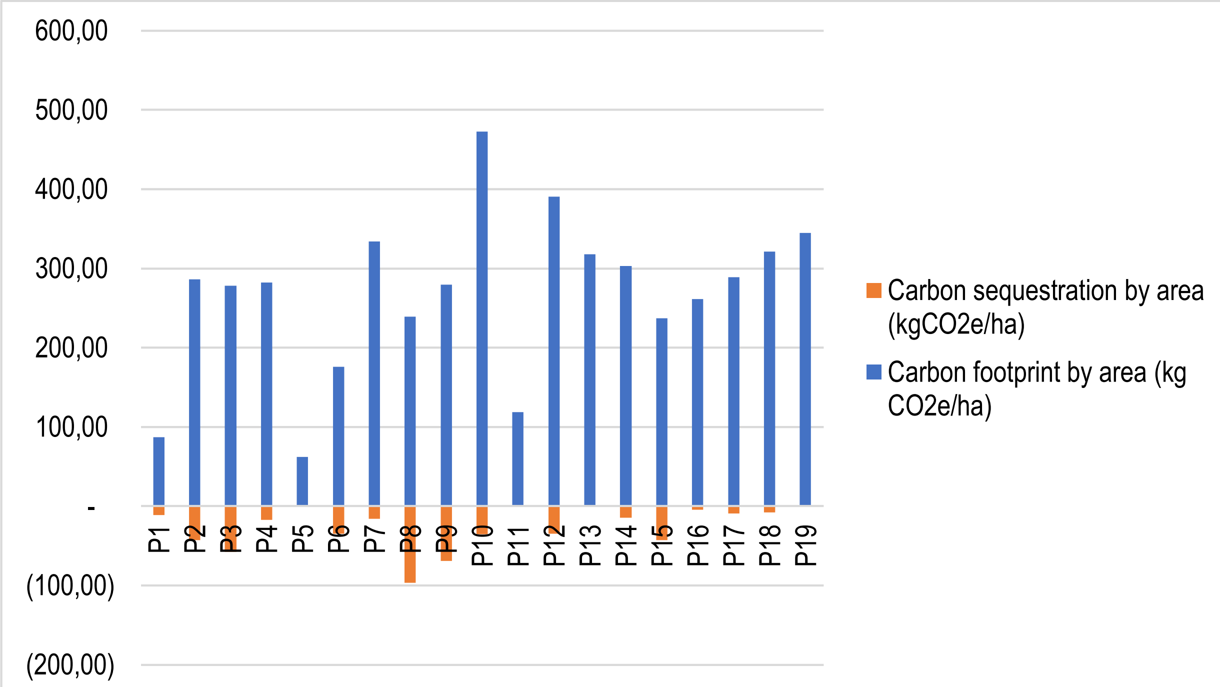
Table 6. Carbon footprint vs Carbon sequestration per hectare for each plot (kg CO_2e/ha)

Plot	Counted trees	Carbon footprint	Carbon sequestration	Total
P1	20	86,84	-11,0	75,84
P2	200	286,16	-4,97	243,19
P3	200	278,29	-57,29	221,00
P4	200	282,16	-17,27	264,89
P5	-	62,19	-	62,19
P6	100	175,65	-34,59	141,06
P7	100	334,35	-15,71	318,64
P8	100	239,44	-96,49	142,94
P9	100	279,29	-68,75	210,54
P10	100	472,84	-35,26	437,58
P11	-	118,64	-	118,64
P12	40	390,34	-34,38	355,97
P13	-	318,14	-	318,14
P14	100	302,9	-14,32	288,55
P15	50	237,5	-42,97	194,50
P16	40	261,3	-4,40	256,94
P17	40	288,7	-9,40	279,35
P18	40	321,3	-7,48	313,83
P19	-	344,7	-	344,72

Source: Own elaboration.

[4] The BAP was selected based on a diagnosis done of the soil of the communities and plots that are part of the assessment. The diagnosis had the result that lack of nitrogen was the main problem with the soil. Hence, a compost mix was constituted which began to be prepared in June 2023, was partially completed in September 2023, and was finalized in October of the same year. This material was provided for the 20 plots in which the pilot project was realized. The compost was made of sheep and camelid manure, with straw and wood shavings in a proportion of manure-wood shavings-straw of 1:1:1.

Figure 8. Carbon footprint vs Carbon sequestration per hectare for each plot (kg CO_2e/ha).



Source: Own elaboration.

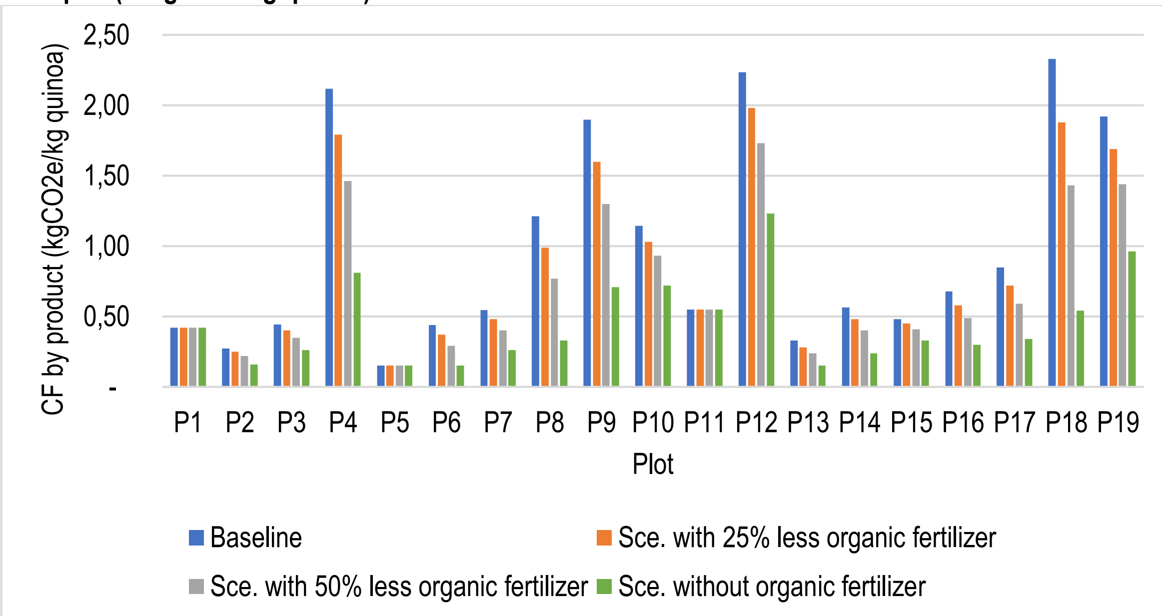
Sensitivity analysis

For evaluating the effect of certain variables in the results, a sensitivity analysis was done with a one-at-a-time variable method. This analysis allows evaluating the impact that changes in a determined parameter have on the results of an assessment. Additionally, the analysis was done on the main emission sources, which are use of organic fertilizer and diesel consumption in machinery used in cultivation tasks. The analysis was done by changing the input parameters entered to Cool Farm Tool.

Use of organic fertilizer

In terms of the analysis of CO_2eq emissions by product and use of organic fertilizer, three scenarios were considered. The first of these reduces the amount of organic fertilizer applied by 25% in relation to the baseline of each plot; the second applies a reduction of 50%; and the third considers no fertilizer applied. In all cases, the fertilizer used is sheep manure with 0.7% N. In plots P1 and P11, the values remained the same, as it was reported that no fertilizer was used for the crops. The results are presented in Figure 9.

Figure 9. Carbon footprint by product according to sensitivity analysis for the use of organic fertilizers for each plot (in kg CO_2e/kg quinoa)

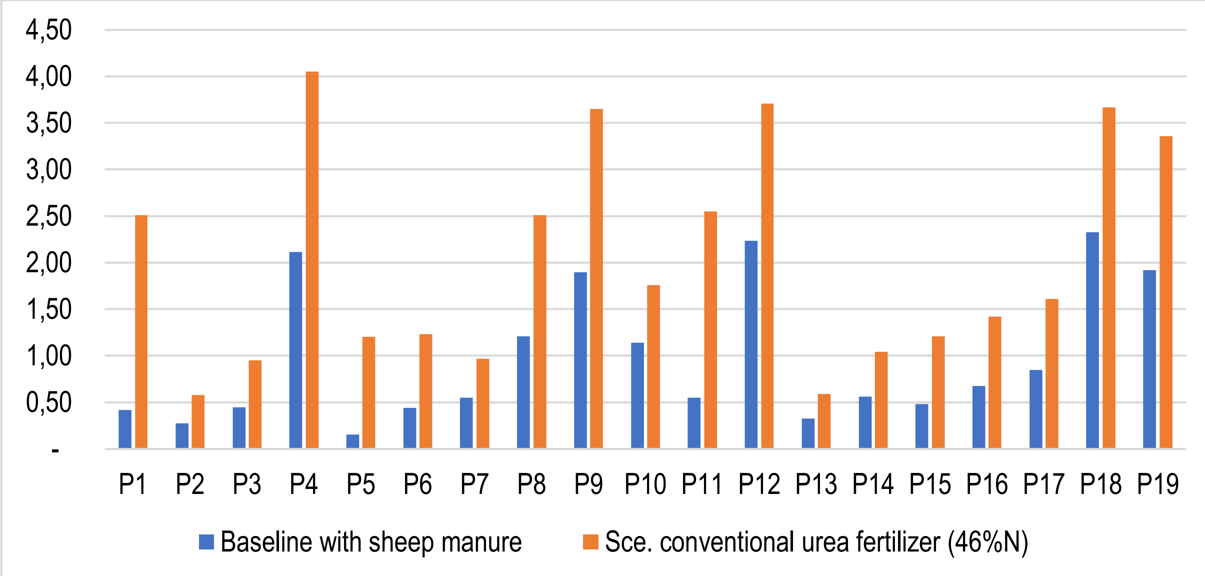


Source: Own elaboration.

As may be observed, there is a reduction in emissions as the amount of fertilizer applied is reduced. On average, for the scenario with 25% less fertilizer, the carbon footprint by product is reduced by 13% (from 0.98 to 0.85 kg of CO_2eq/kg of product). In the scenario with 50% less fertilizer, the carbon footprint by product goes down by 27% (from 0.98 to 0.71 kg of CO_2eq/kg of product). In the scenario with no fertilizer, the reduction is 54% (from 0.98 to 0.45 kg of CO_2eq/kg of product). This means that there will always be reductions in emissions with less use of fertilizer, which may be considered positive if only the effect of the carbon footprint is considered; however, consideration must be given to the fact that this may imply a lower level of organic matter in the soil, and thus lower yield for the producers.

Additionally, an analysis was done considering use of a traditional chemical fertilizer (urea at 46% N) to compare it with the application of organic fertilizer that is performed in the study zone. According to a YPFB study (2022) with trials of the application of urea in quinoa crops in the community of Lequezana, Potosí, the recommended dose is 150 kg of urea/ha through incorporation. Given this, these values were used, and the following results were obtained:

Figure 10. Carbon footprint by product for the use of organic fertilizer vs. Use of traditional fertilizer (in kg CO_2e/kg quinoa)



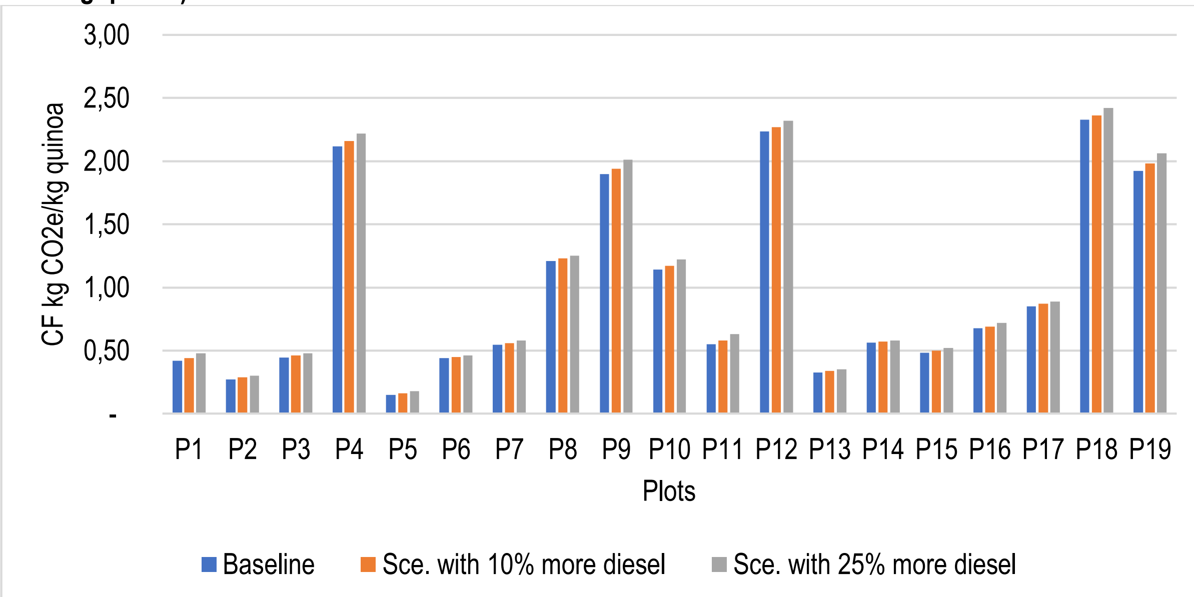
Source: Own elaboration.

There is a considerable increase in emissions in each plot when a traditional fertilizer such as urea is applied, demonstrating that the present traditional practices, which can nonetheless be improved, generate a lower carbon footprint. On average there was an increase of 108%, going from 0.98 to 2.03 kg of CO_2eq/kg of product.

Diesel use

In terms of the analysis of CO_2eq emissions by product due to diesel use, two scenarios are considered. The first contemplates a 10% increase in diesel consumption; here it was observed that there is no considerable increase in the carbon footprint, given that on average the increase is only 2.4% (from 0.98 to 1 kg CO_2eq/kg of product). The second scenario considers an increase of 25% in diesel consumption, which translates into an increase in the carbon footprint of 6% on average, compared to the baseline (from 0.98 to 1.04 kg of CO_2eq/kg of product).

Figure 11. Carbon footprint by product according to sensitivity analysis for diesel use for each plot (en kg CO_2e/kg quinoa)



Source: Own elaboration.

Use or organic fertilizer, and mainly the type of fertilizer employed in the study, can generate a difference in the carbon footprint of quinoa crops.

The results of the estimate of the carbon footprint may be associated with various types of uncertainties: in the parameters and values reported by producers and systematized in surveys, such as diesel and gasoline consumption or the distances of transporting the harvested quinoa; in the factors of emissions, where the tool employs default values provided by IPCC which may not faithfully reflect local reality; and in the model and the equations that CFT employs, which are continuously subject to revision and updating.

IV. Conclusions

Quinoa is a crop with great potential for the rural development of the country. Although quinoa production in the study area is done organically and it is observed that this method generates less GHG than cultivation with chemical fertilizers, it is however necessary to foster more sustainable practices. The study allows concluding that the life cycle phase that generates the highest carbon footprint is that of sowing and tasks during crop growth, mainly from the use of organic fertilizers and protection inputs. The next highest carbon footprint phase is that of work prior to sowing, which includes diesel consumption in tractors employed in preparing the soil. The case study estimates that on average 0.98 kg of CO2eq per kilogram of harvested quinoa is generated; this value is close to the data estimated in other studies performed in Peru and Chile. It is important to mention that not many studies on the carbon footprint of quinoa cultivation were found.

The results allowed identifying opportunities for improvement by applying different best agricultural practices (BAP) focusing on regenerative agriculture. Given that the use of fertilizer significantly contributes to the carbon footprint, BAP strategies that are being applied in the context of the present project may be implemented; they consist of preparing organic fertilizer from sheep and camelid manure (available in the study area). This provides the soil with greater fertility and structure, avoids the generation of disease focal points when applied with prior treatment (and not directly, as occurs with the present practice), and improves the soil's carbon sequestration capacity through the incorporation of organic matter. Employing organic compost can provide the producers with benefits and allow prevalence in time, given that it satisfies the organic certification requirements under which the producers work.

Another possible action is planting or conserving vegetation cover, particularly with native plants such as *thola* or *Parastrephia lepidophylla*, which also contribute organic matter and improve the soil's carbon sequestration capacity, besides protecting the soil against erosion. Crop rotation and diversification can help avoid pests and diseases that monoculture generates, as well as increasing soil fertility. However, more research is needed for determining which crops adapt to the Southern Altiplano for generating positive impacts in combination with quinoa crops. Additionally, given that the second largest source of emissions is diesel consumption in machinery for preparing the soil, consideration may be given to applying zero tillage practices which would help reduce emissions from the use of machinery and soil movement.

Implementation of BAP by the quinoa sector, and even by other producers, can generate a series of positive impacts. One of these impacts is a reduction in GHG emissions. Another one is more carbon sequestration, reducing the sector's contribution of emissions to the national GHG inventory (61.6% of emissions). Aligning with the global target of zero net emissions can also increase yield, which would translate into providing towards the Nationally Determined Contributions commitments expressed in the country's NDC[5]. This could also generate competitive advantages by entering new markets that demand this type of products. Finally, it could improve the quality of life of farmers, especially of family farmers.

It would be important, for future studies, to consider expanding the scope in two regards: the number of plots analyzed – to have more representative data of the carbon footprint – and to include environmental impacts, given that the study centers on the climate change impact category and there is no assessment of synergies with other types of impacts such as land use, eco-toxicological impacts, and acidification. It would also be interesting to expand the LCA's scope from cradle-to-gate to cradle-to-cradle or cradle-to-grave. In compiling information, it is important to consider the cultivation periods, so that the manner of collecting information does not interfere with important dates such as those of sowing. It is also important to have technical staff with knowledge of the crop, and a rapprochement with the producers is also needed. The recommendation is made to do a more detailed report on fuel consumption in machinery and on the different phases of the crop's life cycle.

Fostering sustainable agricultural production, as well as ensuring the management of natural resources is essential for avoiding additional vulnerabilities that affect quinoa producers.

[5] Nationally Determined Contribution. Goal (30). By 2030 the average yield of strategic crops at the national level will have increased by 60%.

Annex 1. The information used in the study

Detalles del cultivo				Características del suelo					Insumos								Uso de combustibles y energía				Riego						Transporte			
									Fertilizantes					Insumos de protección																
Parcela	Comunidad	Área parcela (ha)	Rendimiento (kg/ha)	Textura del suelo	Materia orgánica del suelo (%)	C total (%)	Drenaje del suelo	pH del suelo	Tipo de fertilizante	Método de fertilización	Cantidad aplicada (kg/ha)	Cantidad de veces aplicado	Origen de fertilizante	Tipo insumo prot cultivo	Cantidad aplicada (kg/ha)	Cantidad de veces aplicado	Diésel (litros)	Maquinaria	Gasolina (litros)	Vehículo	Cantidad de veces que se regó	Método	Fuente de agua	Cantidad de agua (litros)	Profundidad de bombeo (m)	Distancia horizontal (m)	Producto (kg)	Insumo (kg)	Distancia (km)	Modo transporte
Oruro																														
P1	Capura	1	207	Franco arenoso	0,4	0,2	Pobre	9,0	Estiércol de oveja	Siembra a voleo	-	-	N/A	N/A	-	-	14,1	Tractor agrícola	11,8	Camioneta	N/A	N/A	N/A	N/A	N/A	N/A	207,0	N/A	5	Road HGV (Vehículo pesado medio)
P2	Capura	2,6	1.045,6	Franco arenoso	0,6	0,3	Pobre	8,9	Estiércol de oveja	Siembra a voleo	6.400	1	Misma comunidad	N/A	-	-	98,2	Tractor agrícola	27,5	Camioneta	N/A	N/A	N/A	N/A	N/A	N/A	2.676,7	N/A	5	Road HGV (Vehículo pesado medio)
P3	Rodeo	1,9	625,6	Franco arenoso	1,5	0,9	Pobre	8,7	Estiércol de oveja	Siembra a voleo	6.400	1	Misma comunidad	Insecticidas	3	2	53,7	Tractor agrícola	10,7	Moto	1	Inundación	Río/arroyo/ acequia	10.000	3	600	1.201,2	N/A	5	Road HGV (Vehículo pesado medio)
P4	Rodeo	6,4	133,4	Franco arenoso	0,7	0,4	Pobre	9,0	Estiércol de oveja	Siembra a voleo	9.600	1	Otra comunidad	Insecticidas	3	1	109,5	Tractor agrícola	35,8	Camioneta	N/A	N/A	N/A	N/A	N/A	N/A	849,8	N/A	5	Road HGV (Vehículo pesado medio)
P5	Rodeo	1,3	410,7	Franco arenoso	0,6	0,4	Pobre	8,9	Estiércol de oveja	Aplicado en solución	2	2	Misma comunidad	N/A	-	-	18,2	Tractor agrícola	4,6	Moto	N/A	N/A	N/A	N/A	N/A	N/A	533,9	20	5	Motocicleta
P6	Sighualaca	1,6	400,2	Franco arenoso	0,5	0,3	Pobre	8,9	Estiércol de oveja	Siembra a voleo	6.400	1	Otra comunidad	Insecticidas	0,02	2	19,3	Tractor agrícola	4,8	Moto	N/A	N/A	N/A	N/A	N/A	N/A	636,3	N/A	5	Road HGV (Vehículo pesado medio)
P7	Florida	3,5	611,8	Franco arenoso	0,4	0,2	Pobre	8,0	Estiércol de oveja	Siembra a voleo	9.600	1	Misma comunidad	Insecticidas	4	1	96,6	Tractor agrícola	24,1	Moto	N/A	N/A	N/A	N/A	N/A	N/A	2.141,3	N/A	5	Road HGV (Vehículo pesado medio)
P8	Florida	0,6	197,8	Franco arenoso	0,4	0,2	Pobre	8,8	Estiércol de oveja	Siembra a voleo	9.600	1	Misma comunidad	Pesticidas	0,02	1	5,2	Tractor agrícola	6,2	Camioneta	N/A	N/A	N/A	N/A	N/A	N/A	112,7	N/A	5	Road HGV (Vehículo pesado medio)
P9	Florida	0,8	147,2	Areno francoso	0,2	0,1	Pobre	8,2	Estiércol de oveja	Siembra a voleo	9.600	1	Misma comunidad	N/A	-	-	15,4	Tractor agrícola	10,1	Camioneta	N/A	N/A	N/A	N/A	N/A	N/A	117,8	N/A	5	Road HGV (Vehículo pesado medio)
P10	Florida	1,6	414	Franco arenoso	0,6	0,3	Pobre	8,9	Estiércol de oveja	Siembra a voleo	9.600	1	Misma comunidad	N/A	-	-	61,9	Tractor agrícola	61,9	Moto	N/A	N/A	N/A	N/A	N/A	N/A	645,8	N/A	442	Road HGV (Vehículo pesado medio)
P11	Bengal Vinto	2	216,2	Franco arenoso	0,4	0,2	Pobre	8,9	Estiércol de oveja	Siembra a voleo	-	-	N/A	N/A	-	-	41,0	Tractor agrícola	30,8	Moto	N/A	N/A	N/A	N/A	N/A	N/A	423,8	N/A	5	Road HGV (Vehículo pesado medio)
Potosí																														
P12	Vintuta	0,6	174,8	Franco arenoso	0,7	0,4	Pobre	8,9	Estiércol de oveja	Siembra a voleo	9.600	1	N/A	Insecticidas	0,3	2	11,9	Tractor agrícola	5,9	Moto	1	Inundación	Río/arroyo/ acequia	50.000	5	500	111,9	N/A	5	Road HGV (Vehículo pesado medio)
P13	Vintuta	2,6	970,6	Franco arenoso	0,5	0,3	Pobre	8,8	Estiércol de oveja	Siembra a voleo	9.600	1	Misma comunidad	N/A	-	-	62,3	Tractor agrícola	24,9	Moto	1	Inundación	Río/arroyo/ acequia	50.000	3	1.000	2.533,3	N/A	5	Road HGV (Vehículo pesado medio)
P14	Vintuta	3,8	538,2	Franco arenoso	0,4	0,3	Pobre	8,7	Estiércol de oveja	Siembra a voleo	9.600	1	Misma comunidad	Insecticidas	3	2	41,4	Tractor agrícola	20,7	Camioneta	1	Inundación	Río/arroyo/ acequia	50.000	3	300	2.066,7	N/A	5	Road HGV (Vehículo pesado medio)
P15	Bella Vista	0,6	492,2	Franco arenoso	0,4	0,2	Pobre	8,8	Estiércol de oveja	Siembra a voleo	4.000	1	Misma comunidad	Insecticidas	3	2	13,8	Tractor agrícola	4,6	Moto	N/A	N/A	N/A	N/A	N/A	N/A	315,0	N/A	5	Road HGV (Vehículo pesado medio)
P16	Bella Vista	5	386,4	Franco arenoso	0,4	0,2	Pobre	9,1	Estiércol de oveja	Siembra a voleo	4.000	2	Misma comunidad	Insecticidas	3	1	100,7	Tractor agrícola	20,1	Moto	N/A	N/A	N/A	N/A	N/A	N/A	1.932,0	N/A	5	Road HGV (Vehículo pesado medio)
P17	Bella Vista	2,3	340,4	Areno francoso	0,2	0,1	Pobre	9,0	Estiércol de oveja	Siembra a voleo	9.600	1	Misma comunidad	Insecticidas	3	1	42,4	Tractor agrícola	13,9	Moto	N/A	N/A	N/A	N/A	N/A	N/A	796,5	N/A	5	Road HGV (Vehículo pesado medio)
P18	Bella Vista	2,9	138	Franco arenoso	0,3	0,2	Pobre	8,3	Estiércol de oveja	Siembra a voleo	13.600	1	Misma comunidad	N/A	-	-	44,0	Tractor agrícola	21,3	Moto	N/A	N/A	N/A	N/A	N/A	N/A	405,7	13.600	2	Road HGV (Vehículo pesado medio)
P19	Tusqui	8	179,4	Arenoso	0,2	0,1	Pobre	8,3	Estiércol de oveja	Siembra a voleo	9.600	1	Misma comunidad	Insecticidas	3	1	232,1	Tractor agrícola	91,8	Camioneta	N/A	N/A	N/A	N/A	N/A	N/A	1.435,2	N/A	5	Road HGV (Vehículo pesado medio)

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