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ENVIRONMENTAL IMPACTS OF COMMUNITARY CROPS OF SWEET QUINOA (*CHENOPODIUM QUINOA WILLD. VAR. TUKAHUAN*) AT ANDEAN REGION IN ECUADOR

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Abstract: Quinoa (*Chenopodium Quinoa*) is a trendsetter crop as it is a great source of vitamins, proteins and minerals and it is a gluten-free pseudocereal. Agriculture is a sector that contributes to climate change through greenhouse gas emissions. In Ecuador, agriculture contributed to 18.03% of emissions. The purpose of this research was to determine the Life Cycle Analysis (LCA) of communitarian systems that produce Sweet Quinoa in Ecuador. It was carried out by an inventory of the LCA. The data collected were through interviews and surveys, chemical analysis of soil samples, plant structure and manure applied. A bag of 25 kg of Quinoa has been selected as a functional unit. Impact indicators were defined as Quinoa yield per single environmental impact index, including GWP, aquatic eutrophication potential and aquatic ecotoxicology. The results indicate that a Quinoa yield obtained by a suitable application of manure is lower or equal to Wheat. The mitigation of aquatic eutrophication caused by the excessive use of N-fertilizer is an important factor in improving the eco-efficiency of the Quinoa productive chain. The importance of the LCA of an agro-product lies in knowing and reducing different environmental impacts and encouraging sustainable production.

Keywords: Sweet Quinoa, Life Cycle Analysis, sustainability.

Introduction

Quinoa (*Chenopodium Quinoa Willd.*) has been cultivated in the Andean region since pre-Hispanic times (Jancurová *et al*., 2009), especially in those regions comprising modern-day crops systems like Peru, Ecuador and Bolivia. This crop could be found in areas ranging from 1 to 4,000 m.a.s.l. (Bazile *et al*., 2015). In recent years, the production of Quinoa, a pseudocereal that is considered strategic for food sovereignty in cited countries has been strongly promoted due to its nutritional and dietary characteristics (Alandia *et al*., 2020). Additionally, genetic diversity and the ability to adapt to different agroecological ecotypes (Jancurová *et al*., 2009; Vilcacundo & Hernández-Ledesma, 2017) have increased interest in this crop. The high nutritional value of Quinoa is attributed to its protein content (10.4 to 17% protein) (Bazile *et al.,* 2015; Nowak *et al*., 2016) and also it is a gluten-free source for processed food (i.e., beer, yogurt, flour, milk and so on). For these reasons, several authors consider Quinoa as the "only food of plant origin that has all the essential amino acids". The nutritional profile of Quinoa indicates that it constitutes a source of proteins with a good balance of all of the essential amino acids, necessary minerals, vitamins, high-quality oils and flavonoids (De Ron *et al*., 2017).

Furthermore, it contains polyunsaturated fatty acids, mainly ω6 (linoleic), followed by ω9 (oleic) and ω3 (linolenic acid), in turn, containing other nutritional components such as carbohydrates, vitamins and minerals (Vega-Gálvez *et al*., 2010; Vilcacundo & Hernández-Ledesma, 2017). It should be mentioned that Quinoa is highly valued for its minimal gluten content, which is why Quinoa is considered suitable for people with celiac disease (Ruiz *et al*., 2013). All these advantages lead to concerns about the sustainability and environmental performance of the Quinoa productive chain in Ecuador, considering the rise in its production and consumption worldwide.

In general, Quinoa crops tolerate a wide range of acidic soil conditions. It also tolerates temperatures ranging from -1 to 35°C. Quinoa is known for its frosting resistance. If frost occurs before flowering, significant damage may occur (Jancurová *et al*., 2009). It can grow even in regions where the annual rainfall varies from 200 to 400 mm. The planting season varies from August in the Andean highlands (Ecuador, Peru and Bolivia), extending through December and in some areas from January to March. Usually, seeds are spread in field, yet, weed control and mechanization become difficult. Quinoa is seeded in rows (spaced 40–80 cm), using mechanized agriculture practices (Ruiz *et al*., 2013; Vilcacundo & Hernández-Ledesma, 2017). The sowing density varies according to the region and variety of Quinoa. Different densities have been reported i.e., from 0.4 to 0.6 g/m^2 in Bolivian Altiplano, from 0.5 to 2.3 g/m^2 in Puno-Peru and from 0.8 to 1.4 g/m^2 in Ecuador.

Several of the greater producers around the world are the "traditional" producing countries of Quinoa: Bolivia, Peru and Ecuador. It is estimated that 80% of the production worldwide is in these countries, although in recent years crops have been cultivated in the Mediterranean region, Asia and also in North America (Ruiz *et al*., 2013; Skarbø, 2015). In Ecuador, Quinoa is distributed in several provinces (e.g., Azuay, Cañar, Chimborazo, Imbabura, Pichincha and Tungurahua), all of them in highlands. The highest yield in 2016 was at Pichincha with 1.79 tonnes/ha and the area of lower productivity was Tungurahua with 1.19 tonnes/ha (Monteros, 2016). This is a potential opportunity for introducing non-traditional crops to be promoted all around the world, in order to give alternatives of business to the Ecuadorian Andean communities, formerly focused on potato, tomato, beans and onions. Particularly, Quinoa var. *Tukahuan* (Peralta L., 1985; PROINPA, 2011), also called Sweet Quinoa due to this variety's lack of saponins, reduces the requirement of water in the productive chain.

The production of Sweet Quinoa began with the exchange of germplasm at Experimental Station "Patacamaya" in Bolivia in 1983. In 2001, this seed was evaluated to have low saponin content, which is why it is considered sweet and with a mid-high potential yield. In the following year, its production was evaluated in different zones of Ecuador´s highlands, starting from Carchi (north) and ending in Cañar (south). The average height of this variety is 95 cm. Its production is half-day, that is, the vegetative period is 140 days. It is of erect habit, with simple branching, medium-sized leaves, rhomboidal with an entire border with purple stretch marks. The panicle is amarantiform and turns pink at maturity. The grain is cream-colored with size from 1.7 to 2.1 mm and has saponin content of 0.05%, so it is considered sweet. It has 16.28% protein, with a yield potential (1,900 kg*ha-1). It is slightly susceptible to drought and frost and is tolerant to excess moisture and hail (Peralta L., 1985; Monteros, 2016). In this analysis, seasonal cropping is not considered due to the geographic location of Ecuador.

Community crop systems, also known as a farmers' or agricultural cooperative, is where farmers pool their resources in several activities areas. Different agricultural services are provided according to members' needs and production resources (e.g., land, manure and machinery) are collected and for members to use together (Valentinov, 2007; Org-Nte & Cucco, 2017). There are two principal categories of cooperatives systems: Supply cooperatives and marketing cooperatives. Supply cooperatives provide several inputs for agricultural production including seeds, fertilizers, fuel and machinery services. Marketing cooperatives are founded by farmers to engage the service such as transportation, packaging, distribution and marketing of farm products (both crop and livestock) (Valentinov & Iliopoulos, 2013). Agriculture is well known to contribute to climate change through greenhouse gas (GHG) emissions (Ramírez-Cando *et al*., 2017). Ecuador reported that agriculture contributed 18.03% of its emissions in 2010. Agriculture is the third largest GHG generating sector, with energy emitting the most at 44.49% of Ecuador's GHG emissions. As for agricultural soils, they contributed 6,795.00 Gg of CO_2eq, which corresponds to 46.81% within the agricultural sector, which issued 14 515.94 Gg CO_2eq (MAE, 2016). Another problem associated with agriculture is the use of water resources, since it uses between 2,000 to 5,000 liters/day/person (Molden & de Fraiture, 2004). According to the Water Secretariat in Ecuador, the country used 76% of the flow for irrigation in the agricultural sector (Pérez Arcos, 2012).

The International Organization for Standardization (ISO) divides LCA into four phases (ISO 14040) to assess environmental impacts (Guinée *et al.,* 2002; International Organization for Standardization, 2007). Life Cycle Inventory (LCI) is where the product system and its unit processes and transfers between the production system and the environment are unified and analyzed. Labeled elementary flows include inputs from nature (e.g., extracted raw materials, land used, raw materials and so on) and outputs to the ecosphere (e.g., emissions to air, water and soil). The total of elementary flows exchanged by the production system and the environment is relative to a functional unit as defined in the Goal and Scope phase. The magnitude and significance of environmental impacts associated with the elementary flows are defined by Life Cycle Impact Assessment (LCIA). This is possible by associating the life cycle inventory results with environmental impact categories and category indicators. LCI results, other than elementary flows are identified and their relationship to corresponding category indicators is determined. LCIA has several mandatory elements: Selection of impact categories, category indicators and characterization models, as well as assignment of the LCI results to the various impact categories (classification) and calculation of category indicator results (characterization). Lastly, Life Cycle Interpretation aims to couple the findings of the previous two phases with the defined goal and scope to reach conclusions or advice. It is important to note that Environmental-LCA (E-LCA) provides an assessment of potential impacts based on the chosen functional unit.

Considering that there is no information about Quinoa LCA (Clark & Tilman, 2017), the present work aims to estimate indicators of the environmental performance of Quinoa harvested in community systems. This system involves the cooperative of native communities, NGOs and enterprises dedicated to fomenting this kind of agribusiness. They are bearing in mind that GHGs of greatest concern for Agriculture Forestry and Other Land Use sector (AFOLU sector) are CO2, N_2O and CH_4 (IPCC, 2006a). However, as supported by the Food and Agriculture Organization of the United Nations (FAO) in crops such as Quinoa, methane emission is not considered. However, eutrophication, acidification and ecotoxicological potential were considered. The study considered the Life Cycle of Quinoa crops, from the preparation of the soil to the management of agricultural residues until its industrial processing (ready to sell), the research is based on the inventory of the agricultural production system. The data were collected through observations in the field, interviews with producers and sampling of soil, fertilizers, plant and roots. This research is carried out with the objective of estimating the LCA impacts and necessary data to boost the eco-labeling of Andean products linked to organic certification in the country, and to contribute to mitigating climate change and encouraging sustainable development.

Materials and Methods

Data Collection

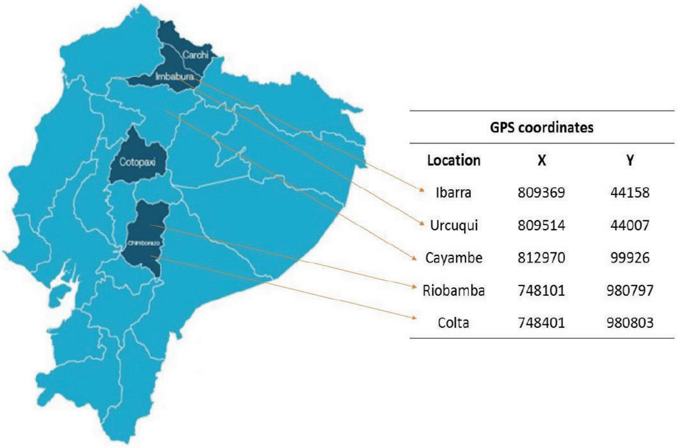
For collecting primary information, there were two main sources. First, samples were collected from 5 experimental plots (100 m^2) in three years (2014-2016) triplicated (45 samples total). It was done in order to typify the required characteristics of Quinoa under study. Second, surveys were conducted with producers to obtain input and output data used to produce a hectare of Quinoa. A series of questions were established to collect information on: (i) Yields, (ii) Quantity and variety of seed used in planting, (iii) Quantity and types of fuels used in machinery such as threshing machine, vending machine, an off-road transport such as tractor and land transport (truck used to transport panicles and machinery), (iv) Use of phytosanitary products, (v) Water source (if it was rain or irrigation systems) and (vi) Crop management practices. The data was collected from 2011 until 2016, this study includes historic data obtained directly from producers (surveys) and bibliographic reports. All trials and surveys were carried out in the three zones with major production, according to the Ministry of Agriculture (MAGAP), as presented in Figure 1.

Apical and below-ground biomass generated per hectare was estimated in three randomized subplots of 0.25 m^2, by drawing out plants and cutting them at the root collar after Quinoa-grains removal (twice in a year) (D'Avino *et al*., 2015). N-content in residues was estimated in each subplot using the Kjeldahl automatized method (Labconco, 1998; Sáez-Plaza *et al*., 2013). All samples were collected randomly from crops between 2014 and 2016. For the sample of fertilizer (animal manure) used in the crop, approximately 1° of storage tanks owned by the producer for the respective analysis in the laboratory were taken twice for crop cycle in established plots. Kjeldahl method, Colorimetric determination (Mullins & Evans, 1990) and atomic absorption (Hill & Fisher, 2010) were used to quantify N, P, K in manure, respectively.

System Description

This study was carried out in the Andean region in Ecuador ranging 2,500-4,000 m.a.s.l., a majoritarian cold weather (16°C in mean). In Ecuador, there are no four seasons, weather is divided in two main seasons: (i) Raining season (from November to April), when the temperature range is 0 to 15°C and rainfall from 300-490 mm and (ii) Sunny season (from May to October), when the temperature range is 13 to 22°C and rainfall from 150-230 mm. Data were taken from Ecuadorian Institute of Meteorology (INAMHI).

At the farming stage, combusted fossil fuel, air-emission sources (including fossil fuel combustion), fertilizer requirement and crop residue incorporation were used to assess the straight energy consumption. Total direct energy was used on a net calorific value basis while the emissions in fossil fuel combustion were calculated using the CO_2 and N_2O factors. Soil



GPS coordinates

Location	X	Y
Ibarra	809369	44158
Urcuqui	809514	44007
Cayambe	812970	99926
Riobamba	748101	980797
Colta	748401	980803

Figure 1: Zone of major production of Quinoa in Ecuador reported by MAGAP and GIS coordinates to the sites of sampling

carbon content was excluded from the GWP evaluation because it was difficult to combine data according to Quinoa systems at a regional level using a soil carbon balance model (Masuda, 2016). As seen in quite a few E-LCA studies for mountain crops such as grass, wheat, barley and maize, phosphorus leaching from the soil and its problems were not considered. The latter is related to the amount of phosphorus leaching that has a negligible value in most soil types in Ecuador's highlands (Podwojewski *et al*., 2002; Tischer *et al*., 2014; Masuda, 2016). Whereby, for each input, GHG emissions were estimated, added and total GHG emissions for each trial were linked to the corresponding Quinoa-grain yields.

Figure 2 shows the system boundaries for the LCA of Quinoa ready to sell. The boundaries include the burden of all inputs in agricultural production, transportation of seed to the processing facility (materials and energy) and shipping of packed Quinoa to market (to retailers' gate). Figure 1 illustrates the system boundaries for the Quinoa agricultural phase. Drying and packing involve no co-products. This avoids the typical allocation problem in E-LCA. The indicated problem refers to criteria for determining how input or output flows of a product or process and their associated environmental burdens should be allocated or partitioned for a product or process that has different co-products.

Goal and Scope

The goal of our study was to quantify the environmental impacts at a regional level, of Quinoa on GWP, EP, AP, WEP and EC as comparative indicators considering farm to gate system, following several bibliographic guidance (Guinée *et al.,* 2002; Ramiréz-Cando & Spugnoli, 2016). The effects of Carbon Dioxide (CO_2) were expressed as CO_2 equivalent (CO2eq), using equivalences as follow:

1 CO_2=1 CO_2eq; and nitrous oxide (N_2O) = 296 CO_2eq.

The aim of our research covered the whole life cycle (LC), from harvesting to transport and distribution to sellers or retailers (cradle to gate + gate to gate). The functional unit (FU) that impacts the system is a 25 kg bag of ready to sell Quinoa. The conversion factors were taken from Ecoinvent 3.3. database. Emissions were calculated following IPCC tier 1 (IPCC, 2006c) as described below. For the harvesting, drying, and packing phases, the impacts were assessed by in-field experimental data combined with secondary data when necessary. To evaluate E-LCA impacts due to additional subsystems, standard data from Ecoinvent was used to appraise transport, shipping and distribution to retailers. In the productive chain under study, expiation and allocation were not considered (see Figure 3).

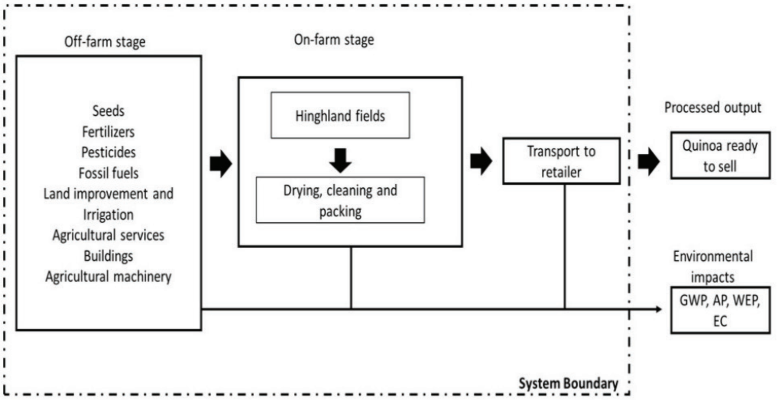


Figure 2: System boundaries to Quinoa harvested in Ecuador (cradle to gate + gate to gate). GWP = Global Warming Potential, AP = Acidification Potential, WEP = Eutrophication Potential and EC = Energy Consumption

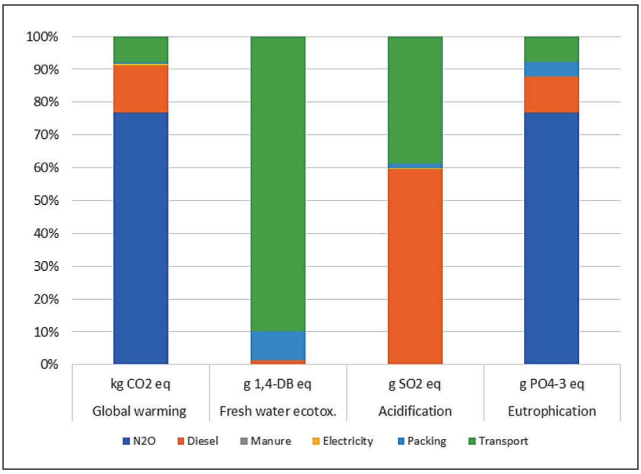


Figure 3: Impact categories (relative), for entire productive chain considered

Life Cycle Inventory

Agricultural Cultivation

Quinoa can be harvested profitably in a variety of soils and altitudes including marginal lands at low rates of N-fertilizer application and lower maintenance costs. It has generally been cultivated with no herbicide application. (Arendt & Zannini, 2013; Matteo *et al*., 2020). The total amount of N_2O emissions from the agricultural production process was calculated by the methodology developed by IPCC. Methane is excluded from the estimation following the recommendation of FAO and other institutions in agriculture, as only selected crops must be estimated for methane emission to air (OECD/FAO, 2015). N_2O emissions from cultivation were calculated following the IPCC methodology reported in chapter 11 (IPCC, 2006c). Direct and indirect yearly N_2O emissions from harvesting residuals (all agricultural residues were considered to remain in the ground in order to calculate N_2O emissions) and fertilizers were assessed using the following equations proposed in IPCC guidelines (IPCC, 2006b; Sato *et al.,* 2019):

Direct N_2O emitted from fertilizer applied, using Equation 1:
Direct N_2O(Fert)=(Syn-N+Org-N)*EF1*k (1)

As presented in Equation 1, direct emission is a function of N inputs, Syn-N (Applied synthetic fertilizer), Orf-N (Applied organic fertilizer, analytically determinated), the emission factor for direct emission (EF1) and the molar relation N_2O/N (k=1.5714). There is no irrigation and tillage considered. This study ignores animal excretion and considers that methane did not produce a significate impact.

Indirect N_2O emitted from fertilizer, using Equation 2:

Indirect N_2O(Fert)=([(Syn-N+Org-N)*EF5*FrLeac]+[Syn-N*EF4*FrGas])*k (2)

As presented in Equation 2, indirect emission is a function of N inputs (Syn-N and Org-N) emission factor for N_2O emissions from atmospheric deposition of N on soils and water surface (EF4), emission factor for N_2O emissions from N leaching and runoff (EF5), fraction of synthetic fertilizer N that volatilizes as NH_3 and NOx, weight of N volatilized (FrGas), fraction of all N added to/mineralized that is lost through leaching and runoff (FrLeac) and the constant k.

Direct N_2O emitted from agricultural residues, using Equation 3:

Direct N_2O(residuals)=(Egr*Nbg)*EF1*k (3)

As presented in Equation 3, the direct and indirect emission is a function of epigeal residues (Egr) and its N content (Nbg).

Indirect N_2O emitted from agricultural residues, using Equation 4:

$$\text{Indirect } N_2O(\text{Fert}) = (\text{Egr}*\text{Nbg})*\text{EF5}*\text{FrLeac}*k \quad (4)$$

Quinoa Processing

For industrial processes, optical separation, drying and packing were considered. In this regard, electricity, heat and fuels related impacts were assessed. To arrive to a local retailer, 300 km of transport was assumed, which is the mean distance from the production zone to the most important cities in Ecuador. For instance, Quito´s distance to the main production facility is 190 km, for Guayaquil is 500 km and for Cuenca is 250 km. Consequently, 300 km is a reasonable approximation to transport Quinoa to be sold locally.

Data Analysis

To calculate impacts a matrix based LCA was performed (Canals *et al*., 2007). The main analysis was based on Global Warming Potential (GWP). Moreover, the LC impact estimation phase was conducted through the methodology developed by Guineée and coworkers (CML baseline 2000) (Guinée *et al*., 2002) and in specific the impact categories frequently considered in an agricultural sector E-LCA (global warming potential (GWP), acidification potential (AP), eutrophication potential (EP) and photochemical oxidant formation (POP)) were evaluated, as well as the use of non-renewable energy resources. The choice of these impact categories seems to be appropriate for the assessment proposed of crops related to industrial goods. The impact assessment was implemented using SimaPro 8.4.0 (PRé Consultants).

According to practitioners' recommendations, an uncertainty analysis was performed supported by SimaPro 8.4.0. tool. It was fixed at 50,000 runs with 1,000 seed to warm up the model. This number of runs was selected after a preliminary Monte-Carlo analysis result that after 50,000 simulations the model was stable, thus, reducing resource consumption.

Results and Discussion

Survey indicated that Quinoa var. *Tunkahuan* was the predominant variety in the study zones (72%), followed by Quinoa var. Chimborazo bitter, which was in line with information reported by Monteros, 2016, in Ecuador (80% for 2015). For these reasons, further study was fixed for this Quinoa var. On the other hand, the 18 farmers consulted (who grow Quinoa var. *Tunkahuan*) from 2011 to 2016 said they did not use inorganic fertilizers, urea, additional irrigation and pesticides. These results are in line with biological agricultural practices and also with low input crops thinking (LISA) (SAN, 2010; Robertson & Harwood, 2013) (see Table 1).

These communitarian systems (see Figure 4) are strongly supported in Ecuador by NGOs such as *Maquita Cushunchic*. In this system, using machinery is limited or none at all and it depends not only on local geography but also on collaboration among community members. This reduces environmental and social costs of farming. However, it can increase several costs and reduce yield compared with conventional farming systems.

Net yield for this variety of Quinoa was in the range presented by (Monteros, 2016), our study presented a little increase in it (19%) confronted with national average for sweet Quinoa, moreover in terms of the single variety, there were no differences (lower than 5%). On the other hand, comparing net yield with it in other countries we found: (i) Comparing results with Bolivia and Peru (regional similar countries), yield ranges within 1,200-2,500 kg*ha-1 (Bazile *et al*., 2015); Quinoa var. *Tukahuan* has presented yields in this range (see Table 1), without taking into account variety, region or farming practices. However, its farming inputs were lower compared with conventional Quinoa farming practices (Robinson *et al.,* 2013; Ruiz *et al*., 2013), (ii) Emerging production of Quinoa in the Mediterranean zone in Chile and in several places in Asia and North America allows to see a worldwide panorama of its performance, averages productions are around 2,000 kg*ha-1

Table 1: Inputs and output flows of the agriculture step in production per ha (mean values 2011-2016)

Farming Data			**Mean**	**CV**
		Inputs		
Handwork	Workers	Worker*Hours/ha	6.00	11%
Fertilizers	Manure	$ton*ha^{-1}$	5.00	25%
	N	$kg*ha^{-1}$	296.91	46.6%
	P	$kg*ha^{-1}$	2.76	43.2%
	K	$kg*ha^{-1}$	35.27	44.9%
Fuels	Diesel	$kg*ha^{-1}$	39.08	18,5%
Seeds	-	$kg*ha^{-1}$	15.00	0.0%
Phytosanitary	Biocides	$kg*ha^{-1}$	0.00	0.0%
		Outputs		
Net yield		$kg*ha^{-1}$	1650.00	31%
Above ground residues		$kg*ha^{-1}$	2340.00	30%
Total biomass		kg*ha-1	5320.00	30%
Biomass N-content		%	0.98	45.9%
Emission to air (N_2O)		kg*ha-1	4.92	24%

Figure 4: Communitarian practices cycle around Quinoa crops in Ecuador

(Garrido *et al*., 2013; Ruiz *et al*., 2013; Bazile *et al*., 2015) for Quinoa and Genetic Modified Quinoa seems to be higher. Productive reduction appears to be a disadvantage hence environmental performance and reduction in agrochemical use are fundamental to understand the benefits of this crops systems in Ecuador and further worldwide.

Data collected to perform LCA were summarized in terms of mean and coefficient of variation (see Table 1). N, P, K concentrations in manure were obtained through experiments. Fertilization was done using manure as this practice has no impact in terms of any category analyzed in the present work, however N-content of manure influences N_2O emitted in farming (see Table 4). Manure has great environmental and economic advantages (as shown in Tables 2 and 4). Community systems reduce their emission compared with conventional crop systems due to fertilizer use, transport and final disposal. Farmers said that they produce manure about 1 or 2 km away.

Total biomass was estimated using the harvest index of Quinoa (0.31) (Garrido *et al*., 2013). The fuel used by the workers in this part of the process was Diesel at 39.08 kg*ha-1 and 18.5% variation. Compared with crops cultivated under conventional systems, this figure is almost 46% lower (Lloveras *et al*., 2006; Masuda, 2016; Bacenetti *et al*., 2017) assuming 72 kg*ha-1 as standard value for diesel used in conventional agriculture, in terms of GWP and acidification this leads to a greater reduction of impacts in farming phase.

To model the drying and packing process, information was collected from several facilities that process Quinoa, showing homogeneous processes. All data from the process, excluding infrastructure, is presented in Table 3. The desaponification process was excluded due to the variety of Quinoa harvested containing no saponins (<1%), reducing the impact of using dry or humid desaponification processes. Another important finding regarding the industrial process was the use of jute bags that are reusable and biodegradable.

In environmental impacts evaluated, the GWP along the productive chain of Quinoa was essentially influenced by farming phase, as reported for most crops all around the world (Hixson & Parrish, 2014; Masuda, 2016; Pil *et al*., 2016). Table 4 shows the results of LCA separated by inputs and subprocess throughout five years (2011-2016). The findings to note regarding harvesting phase were:

(i) Using manure caused no impact in any considered category, which is one of the strongest factors in favor of community systems regarding environmental performance

Table 2: Life Cycle Assessment uncertainty analysis for 1 hectare of harvested Quinoa

Impact Category	**Unit**	**Mean**	**Median**	**SD**	**CV (%)**	**2.5%**	**97.5%**	**SEM**
Acidification	kg SO_2 eq	0.87	0.87	0.04	4.60	0.79	0.95	0.01
Eutrophication	kg PO_4^{---} eq	1.52	1.52	0.16	10.53	1.20	1.84	0.004
Fresh water aquatic ecotox.	Kg 1,4-DB eq	0.15	0.15	0.01	6.67	0.13	0.16	0.00
Global warming (GWP100a)	ton CO_2 eq	1.513	1.508	0.156	10.35	1.180	1.799	4.05

Table 3: Inputs and output flows of typical process for Sweet Quinoa grains in Ecuador

Industrial Process		**Units**	**Mean**	**CV**
		Inputs		
Hand work		Workers*horas	8	0%
Packing	Jute bags	Bags/batch	65	5%
Quinoa grains		kg/Batch	1650	12%
Electricity	Hydroelectric	kW.hour/ton	46.34	9%
		Outputs		
Packed Quinoa	Total batch	Bag (25 kg)	65	5%
Residues	Water	kg	180	5%

(ii) Diesel consumption influences GWP and acidification the most

(iii) Emission of N$_2$O, due to application of manure and residues in soil has a greater influence over GWP and eutrophication (Figure 3)

When calculating the means and coefficient of variance throughout Monte Carlo simulation, fresh water ecotoxicity shows the lowest dispersion in the information, while eutrophication has the highest value. Therefore, the standard error of mean shows that the accuracy for acidification, according to the data provided, will be higher as shown in Figure 5, with 95% confidence (see Table 2, Table 5 and Figure 5).

There is no information about LCA performed over Quinoa productive system in

Table 4: Life Cycle Assessment results concerning a bag of (25 kg)

Impact Category	**Unit**	**Total**	**N$_2$O**	**Diesel**	**Manure**	**Electricity**	**Packing**	**Transport**
Global warming	kgCO$_{2}$-eq	24.510	18.82	3.546	0.000	0.125	0.095	1.925
Fresh water ecotox.	g 1,4-DB-eq	148.63	0.00	2.052	0.000	0.009	13.095	133.474
Acidification	g SO$_{2}$-eq	20.216	0.00	12.082	0.000	0.005	0.328	7.801
Eutrophication	g PO$_4^{-3}$-eq	24.124	18.56	2.611	0.000	0.001	1.135	1.815

Table 5: Life Cycle Assessment uncertainty analysis for 1 bag of processed Quinoa (25 kg)

Impact Category	**Unit**	**Mean**	**Median**	**CV**	**Q 2.5%**	**Q 97.5%**	**SEM**
Acidification	g SO2 eq	22.624	22.621	4.27%	20.757	24.518	0.006
Eutrophication	g PO4-3 eq	27.308	27.249	8.92%	21.535	33.487	0.018
Fresh water ecotoxicity	g 1,4-DB eq	149.072	149.067	2.26%	142.445	155.706	0.020
Global warming (GWP100a)	kg CO$_2$ eq	26.463	26.405	8.78%	20.806	32.526	0.018

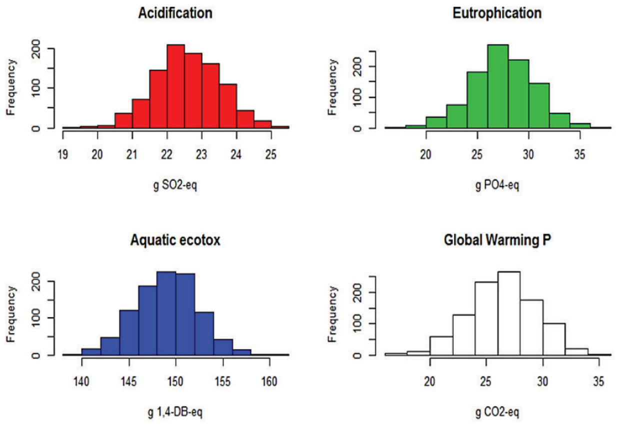


Figure 5: Uncertainty of impact categories estimated by Montecarlo simulation (distributions), for entire productive chain considered, to approximate to Ecuadorian mean value (95% of confidence)

other locations. However, considering that Quinoa is used to produce Gluten-free food and beverages, it is reasonable to compare Quinoa's environmental performance with Wheat produced around the world. GWP of wheat for a hectare range from 2.85 to 3.15 ton CO_2eq/ha (Charles *et al*., 2006; Schmidt, 2008; Masuda, 2016) while Quinoa's GWP is 50% lower for unit of land used. However, yield of wheat ranges from 2.8-3.0 ton/ha, which is almost twofold higher than the Sweet Quinoa under study. This means that GWP of wheat and Quinoa seem to be equal considering that the GWP of Sweet Quinoa ranged 715-1,090 gCO_2eq/kg (with differences lower than 5% compared with Wheat). Therefore, this analysis must point out the advantages of non-use of synthetic fertilizers and phytosanitary, and also that Sweet Quinoa does not require water in farming and industrial processing. On the other hand, Quinoa cultivation's Eutrophication impact is 60% lower compared with wheat in terms of soil and mass it is due to non-use of N-P-K fertilizers. It is evident that the use of N-fertilizers (ammonia or urea) negatively influences GWP and eutrophication. Not using them reduces eutrophication and acidification potentials, as seen in the community cultivation of Sweet Quinoa studied here.

Conclusion

The results showed that the environmental performance of sweet Quinoa production is achieved when an adequate N-fertilizer is used. On the report of the results of operational targets, improving harvest for the advance of the environmental outcome of Quinoa crops is strongly connected to low inputs systems.

These low inputs systems should be encouraged not only in Quinoa or Amaranthus, which are marginal crops in Ecuador but also to crops like potato or tomatoes, which are the most prolific crops within the zones studied in this work.

This study suggests that Quinoa under communitarian systems produces a good reduction in eutrophication (at regional level). Moreover, on a global scale, GWP has presented values closer to other crops with the advantage of non-use of pesticides or additional irrigation that may increase water use. Combining these results with the nutritional advantages of Quinoa makes the case for a great opportunity for Andean countries to promote superfood crops.

Quinoa is a fascinating plant whose ability to tolerate hostile and different environments, with singular nutraceutical properties justifies and warrants future research in agronomy, plant biology, and/or eco-efficiency. It is also important to remember that the heterogeneous genetic and cultural heritage of Quinoa must be preserved and encouraged in its use as a food source. The commercial benefit from the employment of Quinoa varieties with large, white seeds, called "Quinua Real" has to be considered with reference to other elements present within the "Quinoa network".

However, Sweet Quinoa has demonstrated that it is environmentally suitable and in several aspects, a more robust performer compared with other crops such as wheat and rice. Furthermore, its nutritional profile and eco-friendly behavior allows it to be an excellent food crop for the future.

The environmental performance of the Quinoa in Ecuador shows that it is a candidate for expanded cultivation. However, sustainability of a productive chain must be assessed in base of the three dimensions (Environmental, Social and Economic). Applying Social Life Cycle Assessment (S-LCA), which may be a method accustomed to evaluating the social and sociological dimensions of products and their actual and potential positive effects as well as negative consequences along the LC, we are able to highlight the recent spots in a very local level i.e., child work, work conditions, discrimination, etc. (Unep Setac Life Cycle Initiative, 2009; Ramiréz-Cando & Spugnoli, 2016). The latter looks at the drawing and processing of zero materials, manufacturing, distribution, use, reuse, maintenance, recycling and final disposal. The use of generic and site-specific data may be quantitative, semiquantitative or qualitative, and complements the environmental LCA and LCC completing LCSA and dynamic components to LCSA must be also added in future research. It is often applied on its own or not to mention the opposite techniques, moreover, S-LCA does not answer the question of if a product may be produced or not, though details obtained from an S-LCA may offer something to consider and may be useful for reaching such a decision. However, a large number of factors must be contemplated, besides social analysis at the local level, one of the foremost factors are social issues at the national and regional scale associated with this productive system, and also the indigenous culture within the country. This must be assessed as a key part of the Life Cycle Sustainability Analysis (LCSA). This analysis is vital to policymakers and other social stakeholders to grasp and promote the sustainable potential of this crop and protect heritage and traditional practices on a local and national scale.

References

Alandia, G., Rodriguez, J. P., Jacobsen, S. E., Bazile, D., & Condori, B. (2020). Global expansion of quinoa and challenges for the Andean region. *Global Food Security*, *26*, 100429. https://doi.org/10.1016/J.GFS.2020.100429

Arendt, E. K., & Zannini, E. (2013). Quinoa. In *Cereal Grains for the Food and Beverage Industries* (pp. 409-438). https://doi.org/10.1533/9780857098924.409

Bazile, D., Bertero, H. D., & Nieto, C. (2015). *State of the Art Report on Quinoa around the World in 2013.*

Canals, L. M. I., Muñoz, I., McLaren, S., & Miguel, B. (2007). LCA methodology and modelling considerations for vegetable production and consumption. CES Working Papers 02/07. *United Kingdom, Centre for Environmental Strategy, University of Surrey*, *46*.

Charles, R., Jolliet, O., Gaillard, G., & Pellet, D. (2006). Environmental analysis of intensity level in wheat crop production using life cycle assessment. *Agriculture, Ecosystems & Environment*, *113*(1-4), 216-225. https://doi.org/10.1016/j.agee.2005.09.014

Clark, M., & Tilman, D. (2017). Comparative analysis of environmental impacts of agricultural production systems, agricultural input efficiency, and food choice comparative analysis of environmental impacts of agricultural production systems, agricultural input efficiency, and food. *Environmental Research Letters, 12*. https://doi.org/https://doi.org/10.1088/1748-9326/aa6cd5

De Ron, A. M., Sparvoli, F., Pueyo, J. J., & Bazile, D. (2017). Editorial: Protein crops: Food and feed for the future. *Frontiers in Plant Science*, *8*(February), 105. https://doi.org/10.3389/FPLS.2017.00105/BIBTEX

FAO. (2013). *State of the Art Report on Quinoa around the World in 2013*.

Fonte, M., & Cucco, I. (2017). Cooperatives and alternative food networks in Italy. The long road towards a social economy in agriculture. *Journal of Rural Studies*, *53*, 291-302. https://doi.org/10.1016/j.jrurstud.2017.01.019

Guinée, J. B., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., van Oers, L., Wegener Sleeswijk, A., Suh, S., Udo de Haes, H. A., de Bruijn, H., van Duin, R., Huijbregts, M. A. J., & Gorrée, M. (2002). Life cycle assessment. Operational guide to the ISO standards. I: LCA in perspective. IIa: Guide. IIb: Operational annex. III: Scientific background. *The Netherlands: Ministry of …*, 692. https://doi.org/10.1007/BF02978784

Hill, S. J., & Fisher, A. S. (2010). Atomic absorption, methods and instrumentation. In *Encyclopedia of Spectroscopy and Spectrometry* (pp. 46-53). https://doi.org/10.1016/B978-0-12-374413-5.00099-3

Hixson, S. M., & Parrish, C. C. (2014). Substitution of fish oil with camelina oil and inclusion of camelina meal in diets fed to Atlantic cod (Gadus morhua) and their effects on growth, tissue lipid classes, and fatty acids. *Journal of Animal Science*, *92*(3), 1055-1067. https://doi.org/10.2527/jas.2013-7146

International Organization for Standardization. (2007). NTC-ISO 14044. In *Gestión ambiental, análisis del ciclo de vida.* (Issue 571, p. 16). http://tienda.icontec.org/brief/NTC-ISO14044.pdf

IPCC. (2006a). 2006 IPCC Guidelines for National Greenhouse Gas Inventories. *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, *3*(Chapter 2: Mineral Industry Emissions), 1-40.

IPCC. (2006b). Capítulo 1: Introducción. In S. Eggleston, L. Buendia, K. Miwa, T. Ngara, & K. Tanabe (Eds.), *Directrices del IPCC 2006 para los Inventarios Nacionales de Gases de Efecto Invernadero Volumen 4 Agricultura, Silvicultura y Otros Usos de la Tierra.* (pp. 1-25). IGES.

IPCC. (2006c). Capítulo 11: Emisiones de N2O de los suelos gestionados y emisiones de CO2 derivadas de la aplicaciónde cal y urea. In S. Eggleston, L. Buendia, K. Miwa, T. Ngara, & K. Tanabe (Eds.), *Directrices del IPCC 2006 para los Inventarios Nacionales de Gases de Efecto Invernadero Volumen 4 Agricultura, Silvicultura y Otros Usos de la Tierra.* (pp. 1-56). IGES.

Jancurová, M., Minarovičová, L., & Dandár, A. (2009). Quinoa - A review. *Czech Journal of Food Sciences*, *27*(2), 71-79.

MAE. (2016). *Primer Informe Bienal de Actualización del Ecuador a la Convención Marco de las Naciones Unidas sobre el Cambio Climático*.

Masuda, K. (2016). Measuring eco-efficiency of wheat production in Japan: A combined application of life cycle assessment and data envelopment analysis. *Journal of Cleaner Production*, *126*, 373-381. https://doi.org/10.1016/j.jclepro.2016.03.090

Matteo, R., D'Avino, L., Ramirez-Cando, L. J., Pagnotta, E., Angelini, L. G., Spugnoli, P., Tavarini, S., Ugolini, L., Foschi, L., & Lazzeri, L. (2020). Camelina (Camelina sativa L. Crantz) under low-input management systems in northern Italy: Yields, chemical characterization and environmental sustainability. *Italian Journal of Agronomy*. https://doi.org/10.4081/ija.2020.1519

Molden, D., & de Fraiture, C. (2004). Investing in water for food, ecosystems and livelihoods. Blue Papel. *Comprehensive Assessment of Water Management in Agriculture*, 25.

Monteros, A. (2016). Rendimientos de Quinua en el Ecuador 2016 (octubre 2015 - agosto 2016). In *Dirección de Análisis y Procesamiento de la Información Coordinación General del Sistema de Información Nacional Ministerio de Agricultura, Ganadería, Acuacultura y Pesca*.

Mullins, G. L., & Evans, C. E. (1990). Field evaluation of commercial triple superphosphate fertilizers. *Fertilizer Research*, *25*(2), 101-106. https://doi.org/ 10.1007/BF01095089

Nowak, V., Du, J., & Charrondière, U. R. (2016). Assessment of the nutritional composition of quinoa (*Chenopodium quinoa Willd.*). *Food Chemistry*, *193*, 47-54. https://doi.org/10.1016/j.foodchem.2015.02.111

OECD/FAO. (2015). OECD-FAO Agricultural Outlook 2015. In *OECD-FAO Agricultural Outlook 2013* (Vol. 82, Issue 1999). OECD Publishing. https://doi.org/10.1787/agr_outlook-2015-en

Peralta, L. E. (1985). La Quinua un gran alimento y su utilización. *Instituto Nacional de Investigaciones Agropecuarias (INIAP)*, 23.

Pérez Arcos, S. isabel. (2012). *Evaluación y análisis de la huella hídrica y el agua virtual de la producción agrícola en el Ecuador*. 62.

Pil, L., Bensadoun, F., Pariset, J., & Verpoest, I. (2016). Why are designers fascinated by flax and hemp fibre composites? *Composites Part A: Applied Science and Manufacturing*, *83*, 193-205. https://doi.org/10.1016/j.compositesa.2015.11.004

PROINPA. (2011). La quinua: Cultivo milenario para contribuir a la seguridad alimentaria mundial. In *FAO*.

Ramírez-Cando, L. J., Paolo, S., Roberto, M., Manuela, B., Silvia, T., Lara, F., & Lazzeri, L. (2017). Environmental assessment of flax straw production for non-wood pulp mills. *Chemical Engineering Transactions*, *58*(July). https://doi.org/10.3303/CET1758132

Ramiréz-Cando, L., & Spugnoli, P. (2016). A review of life cycle assessment: Agroproducts modeling. *La Granja*, *24*(2), 5-15. https://doi.org/10.17163/lgr.n24.2016.01

Robertson, G. P., & Harwood, R. R. (2013). Agriculture, sustainable. *ABT - Encyclopedia of Biodiversity (Second Edition)*, *1*, 111-118. https://doi.org/http://dx.doi.org/10.1016/B978-0-12-384719-5.00287-2

Robinson, T. F., Roeder, B. L., & Johnston, N. (2013). Nitrogen balance and blood metabolites of Llama (Lama Glama) Fed Barley Hay supplemented with Alfalfa and Quinoa Straw in Bolivia. *Journal of Animal Science Advances*, *3*(8), 386-391.

Ruiz, K. B., Biondi, S., Oses, R., & Acuña-rodríguez, I. S. (2013). Quinoa biodiversity and sustainability for food security under climate change. A review. In *Agronomy for Sustainable Development*, *34*(2), 349-359. https://doi.org/10.1007/s13593-013-0195-0

SAN. (2010). Sustainable Agriculture Standard. *Agriculture*, *2010*(July), 49. https://doi.org/10.1007/978-90-481-2666-8

Sato, A., Vitullo, M., & Gschwantner, T. (2019). Chapter 8 Settlements - *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (1-15). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Schmidt, J. H. (2008). System delimitation in agricultural consequential LCA. *The International Journal of Life Cycle Assessment*, *13*(4), 350-364. https://doi.org/10.1007/s11367-008-0016-x

Skarbø, K. (2015). From lost crop to lucrative commodity: Conservation implications of the Quinoa renaissance. *Human Organization*, *74*(1), 86-99. https://doi.org/10.17730/humo.74.1.09276v70638x8q01

Valentinov, V. (2007). Why are cooperatives important in agriculture? An organizational economics perspective. *Journal of Institutional Economics*, *3*(01), 55. https://doi.org/10.1017/S1744137406000555

Valentinov, V., & Iliopoulos, C. (2013). Economic theories of nonprofits and agricultural cooperatives compared: New perspectives for nonprofit scholars. *Nonprofit and Voluntary Sector Quarterly*, *42*(1), 109-126. https://doi.org/10.1177/0899764012436399

Vega-Gálvez, A., Miranda, M., Vergara, J., Uribe, E., Puente, L., & Martínez, E. A. (2010). Nutrition facts and functional potential of quinoa (*Chenopodium quinoa Willd.*), an ancient Andean grain: A review. *Journal of the Science of Food and Agriculture*, *90*(15), 2541-2547. https://doi.org/10.1002/jsfa.4158

Vilcacundo, R., & Hernández-Ledesma, B. (2017). Nutritional and biological value of quinoa (*Chenopodium quinoa Willd.*). *Current Opinion in Food Science*, *14*, 1-6. https://doi.org/10.1016/j.cofs.2016.11.007