Science of the Total Environment 637–638 (2018) 221–232

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Organic quinoa (*Chenopodium quinoa* L.) production in Peru: Environmental hotspots and food security considerations using Life Cycle Assessment

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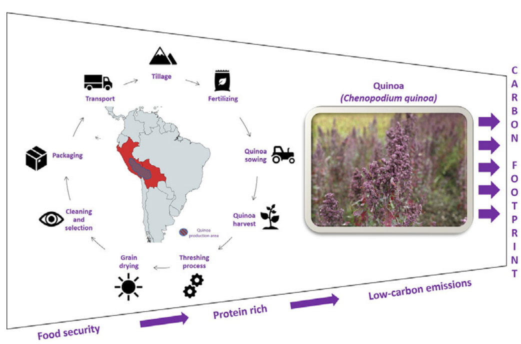
HIGHLIGHTS

- Peru is the main producer of quinoa worldwide with an increased demand for exports.
- Organic quinoa in Peru was analyzed using Life Cycle Assessment methodology.
- GHG emissions were dominated by on-field emissions due to fertilization.
- Organic quinoa is a low-carbon protein-rich product as compared to the literature.
- Shifting from subsistence to intensive farming defies environmental sustainability.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 21 March 2018
Received in revised form 2 May 2018
Accepted 3 May 2018
Available online xxxx

Editor: D. Barcelo

Keywords:
Andean crops
Food policy
Food security
Industrial ecology
Life Cycle Assessment
Protein

ABSTRACT

Quinoa is a plant that is cultivated in the Andean highlands across Peru and Bolivia. It is increasingly popular due to its high nutritive value and protein content. In particular, the cultivation of organic quinoa has grown substantially in recent years since it is the most demanded type of quinoa in the foreign market. Nevertheless, despite the interest that quinoa has generated in terms of its nutritional properties, little is known regarding the environmental profile of its production and processing. Therefore, the main objective of this study was to analyze the environmental impacts that are linked to the production and distribution of organic quinoa to the main export destinations through the application of the Life Cycle Assessment (LCA) methodology. An attributional LCA perspective was conducted including data from approximately 55 ha of land used for quinoa production in the regions of Huancavelica and Ayacucho, in southern-central Peru. IPCC, 2013 and ReCiPe 2008 were the two assessment methods selected to estimate the environmental impact results using the SimaPro 8.3 software. Results, which were calculated for one 500 g package of organic quinoa, showed that GHG emissions are in the upper range of other organic agricultural products. However, when compared to other high protein content food products, especially those from animal origin, considerably low environmental impacts are obtained. For instance, if 20% of the average annual beef consumption in Peru is substituted by organic quinoa, each Peruvian would mitigate 31 kg CO_2eq/year in their diet. Moreover, when the edible protein energy return on investment (i.e., ep-EROI) is computed, a ratio of 0.38 is obtained, in the higher range of protein rich food products. However, future research should delve into the environmental and food policy implications of agricultural land expansion to produce an increasing amount of quinoa for a growing global demand.

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https://doi.org/10.1016/j.scitotenv.2018.05.029
0048-9697/

1. Introduction

Quinoa (*Chenopodium quinoa* L.) is an Andean pseudocereal flowering plant of the Amaranthaceae family grown as a grain crop for the commercialization of its seeds (MINAGRI, 2017). Quinoa has adapted to different geographical areas throughout the Andes, which has derived in the existence of five different varieties of quinoa based on their ecotype (León, 2003; Bazile et al., 2015): i) Inter-Andean valleys ecotype, which has long growth periods between 2000 and 3000 m above sea level; ii) Highlands ecotype, a smaller variety resistant to frosts; iii) *Yungas* ecotype, which is common in the Bolivian subtropical forest; iv) *Salares* ecotype, which has high resistance to saline soils and has a higher protein content than the other varieties; and, v) Coastal ecotype, which occurs mainly in the lowlands in northern Chile. Quinoa is usually cultivated in sandy loam or clay loam soils, with an approximate pH of 5.5 to 8.5, with good drainage and moderate slopes. The optimal temperature for quinoa is around 8–15 °C, although it can withstand up to −4 °C (León, 2003). The vegetative period of quinoa ranges from 90 to 240 days.

Quinoa seeds have been an important source of protein for indigenous communities in the Andean *altiplano* in Peru, Bolivia and Ecuador for centuries, but have only become popular elsewhere in recent decades given their interesting nutritional properties (Jacobsen, 2003). Its protein content, according to León (2003), ranges between 12.5% and 14% dry content, but it is also highly considered due to its high vitamin levels (e.g., high levels of riboflavin – vitamin B_2 – and α-tocopherol – vitamin E as compared to other cereals) and the fact that, unlike most cereals, it is gluten free (Ruales and Nair, 1994; Vega-Gálvez et al., 2010; Ruiz et al., 2014).

In Peru, the production of quinoa has been concentrated in a variety of agro-ecological and physiographic zones of the *altiplano*. Despite the fact that quinoa is highly resistant to pH and droughts, its proliferation at different heights above 3000 m responds to the need of quinoa farmers to avoid crops losses (Morlon, 1982; Aguilar and Jacobsen, 2003). In fact, new climate change patterns, that expect longer drought periods in many areas of the Peruvian Andes (SENAMHI, 2009), constitute an important threat to the production of quinoa, although climatic uncertainty has not prevented the crop from growing at an annual rate of 5.8% in terms of cultivated area (FAO, 2016). The most recent available data for the 2013–2014 campaign indicate that a total of 114,725 metric tons of quinoa were produced in Peru in an area of 68,140 ha (FAO, 2016). In that same campaign, economic revenue related to quinoa exports surpassed 200,000 USD (MINAGRI, 2017). Although worldwide data on quinoa production is not consistent through different sources, it coincides in the fact that Peru is the main producer, followed by Bolivia (59.8% and 38.8%, respectively, according to FAOSTAT). Ecuador and the north of Chile also have small productions of quinoa, although some farming is starting in France and Spain in an attempt to extend its production (El Pais, 2016; Quinoa d'Anjou, 2017).

Yield rates vary considerably between varieties of quinoa and regions. For instance, Fairlie-Reinoso (2016) reports that grain yield can be as high as 3820 kg/ha in Arequipa, whereas in the highlands of Puno this value tends to range from 800 kg/ha to 2500 kg/ha depending on the degree of mechanization and technical assistance that the farmers receive. In addition, it should be noted that organic quinoa production rarely surpasses 1600 kg/ha. According to FAOSTAT, the average yield in Peru in 2014 was 1683 kg/ha (FAO, 2016). However, the cultivation of organic quinoa has increased tenfold in the period 2008–2016 for two main reasons (MINAGRI, 2017; Willer and Lernoud, 2014): i) it is the most demanded type of quinoa in the ever growing foreign market (Fairlie-Reinoso, 2016); and ii) the economic revenue, if well managed, is considerably higher (i.e., from 50% to 120% times higher depending on market fluctuations) than that of conventional quinoa despite the lower yield rates (Fairlie-Reinoso, 2016). Organic agricultural production in Peru is regulated by Supreme Decree N°044-2006-AG that fixes a technical regulation for organic production and Law N°29,196 that advocates for the promotion of organic products. Regardless of the common enforcements on organic products, which include the control on the types of fertilizers and plant growth agents allowed, the clear division from conventional cultivation areas, traceability and clear labelling, Peruvian legislation also states that organic production should aim at minimizing all forms of pollution and (El Peruano, 2008).

From an environmental perspective, current field management activities for organic quinoa lack an irrigation system and present low mechanization levels. Moreover, organic quinoa presents a minimal use in the amount of plant protection agents (e.g., *Serenade* or *Xentari*) used, and most of the organic fertilizers are either local *guano* from cattle or *guano de isla* from the Peruvian coastal isles. Although evidence in the scientific literature concerning whether the choice of organic food products as compared with conventionally-grown products is beneficial to human health is sparse and inconclusive (Williams, 2002; Smith-Spangler et al., 2012), organic production is commonly perceived by consumers as being free of pesticides, better for one's health and better for the environment (Padel and Foster, 2005; Lee and Hwang, 2016). This situation explains the high amount of organic quinoa that are demanded from abroad (Gestión, 2016; MINAGRI, 2017), mainly the United States, Australia, Canada and the European Union (Fairlie-Reinoso, 2016), although it is worth noting that consumption of organic products, including quinoa, has experienced a considerable surge in the city of Lima (Higuchi, 2015).

However, the environmental profile of quinoa using environmental assessment tools remains unexplored. Hence, the main objective of this study is to analyze the environmental impacts that are linked to the production and distribution of organic quinoa to the main consumption destinations (domestic and abroad) through the application of the Life Cycle Assessment (LCA) methodology (ISO, 2006a, 2006b). In addition, the aim of the study is focused on aiding stakeholders in the identification of environmental hotspots and supporting public policies. Thereafter, the results obtained were linked to dietary patterns and food security in Peru in terms of policy support. As far as the researchers were able to ascertain, this study constitutes the first full LCA on quinoa production and distribution, providing life cycle inventories and impact assessment for researchers and other stakeholders.

2. Materials and methods

2.1. Methodological framework, goal and scope

The environmental assessment methodology considered in this study, LCA, was used following the ISO 14040 standard (ISO, 2006a). The main goal was to bring forward a thorough environmental analysis linked to the production and distribution of organic quinoa in Peru to the main destinations, in order to identify the main environmental hotspots throughout the production system. The methodological advance of the study is justified based on the fact that, as far as we were able to ascertain, this study is the first application of LCA to Andean grains. Moreover, results are intended to provide a basis to suggest improvement actions in a sector that is expected to experience important growth in the next decade. Finally, results aim to be of interest for the wider LCA community, since quinoa is starting to be incorporated into diets worldwide due to its high protein content (Navruz-Varli and Sanlier, 2016).

Data for the study were collected in late 2016 for the 2015–2016 quinoa production season. The function of the system was to deliver organic quinoa cultivated in several sites to the main export destinations (mainly abroad, but also the city of Lima) ready to supply wholesalers. Therefore, the selected functional unit (FU), in other words, the quantifiable reference to which material and energy flows referred (ISO, 2006b), was set as one 500 g packet of quinoa ready for retailing in a supermarket in Lima or exported to the United States (US) or the European Union (EU) by marine freight through the port of Callao (12° 2′S; 77° 8′W). In addition, as part of the sensitivity analysis (see