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REVIEW ARTICLE

# Quinoa biodiversity and sustainability for food security under climate change. A review

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**Abstract** Climate change is rapidly degrading the conditions of crop production. For instance, increasing salinization and aridity is forecasted to increase in most parts of the world. As a consequence, new stress-tolerant species and genotypes must be identified and used for future agriculture. Stress-tolerant species exist but are actually underutilized and neglected. Many stress-tolerant species are indeed traditional crops that are only cultivated by farmers at a local scale. Those species

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have a high biodiversity value. Besides, the human population will probably reach nine billion within coming decades. To keep pace with population growth, food production must increase dramatically despite the limited availability of cultivable land and water. Here, we review the benefits of quinoa, *Chenopodium quinoa* Willd., a seed crop that has endured the harsh bioclimatic conditions of the Andes since ancient times. Although the crop is still mainly produced in Bolivia and Peru, agronomic trials and cultivation are spreading to many other countries. Quinoa maintains productivity on rather poor soils and under conditions of water shortage and high salinity. Moreover, quinoa seeds are an exceptionally nutritious food source, owing to their high protein content with all essential amino acids, lack of gluten, and high content of several minerals, e.g., Ca, Mg, Fe, and health-promoting compounds such as flavonoids. Quinoa has a vast genetic diversity resulting from its fragmented and localized production over the centuries in the Andean region, from Ecuador to southern Chile, and from sea level to the altiplano. Quinoa can be adapted to diverse agroecological conditions worldwide. Year 2013 has therefore been declared the International Year of Quinoa by the United Nations Food and Agriculture Organization. Here, we review the main characteristics of quinoa, its origin and genetic diversity, its exceptional tolerance to drought and salinity, its nutritional properties, the reasons why this crop can offer several ecosystem services, and the role of Andean farmers in preserving its agrobiodiversity. Finally, we propose a schematic model integrating the fundamental factors that should determine the future utilization of quinoa, in terms of food security, biodiversity conservation, and cultural identity.

**Keywords** Agrobiodiversity · Quinoa · Food security · Food quality · Stress tolerance · Andean farmers · Sustainability

Contents



## 1 Introduction

Global climate change is affecting the conditions under which crops can be grown, in particular due to increasing salinization and aridity. In fact, soil and water salinity is pervasive, with approximately one billion hectares estimated to be affected worldwide (Hasegawa 2013). Moreover, salinity is increasing at a rate of about 10 % annually. Climate change models also predict that future precipitation patterns will entail lower-frequency but stronger rainfall events, increasing the duration of dry soil conditions. Crop productivity may, as a consequence, be constrained by extended drought periods. Altered precipitation regimes also affect the composition of soil microbial communities, an important aspect of plant and ecosystem function (Zeglin et al. 2013). Farmers need new tools to adapt to these changes.

At the same time, it is predicted that the human population will reach nine billion within the next decades. This represents an urgent concern since already today 870 million people are hungry in underdeveloped countries, and more than two billion people are undernourished as a result of inadequate diets (Jacobsen et al. 2013). To keep pace with population growth, food production must increase greatly despite the limited availability of cultivable land and water, further accentuated by climate change.

Sustainability is also a major concern. Sustainable diets should provide nutritious food at affordable costs, while having a low impact on the environment. Thus, the growing demand for food must co-exist with the need to preserve arable land for agricultural food production, and genetic diversity to safeguard ecosystem resilience (Jacobsen et al. 2013). On the other hand, in many rich countries (and not only in those), health policies are addressed at contrasting obesity and at searching for new synthetic or natural products with functional properties that contribute to better health and well-being for an aging population.

Adaptation of agriculture to changing climatic conditions and dietary needs includes the use of suitable crops, for example species or genotypes within species resistant to abiotic stresses such as cold, drought, or saline soils. The use of tolerant species or genotypes can also reduce the cost of salty soil reclamation and clean-up of polluted sites. Although genetic variability within a species often leads to the identification of tolerant genotypes, salt tolerance is generally low in most crops, except some species, such as quinoa, that are extremely tolerant inasmuch as they are halophytes. Though all quinoa genotypes are salt tolerant, some are more so than others (Adolf et al. 2012), emphasizing the need to investigate and conserve its biodiversity. In addition, halophytes are likely to be tolerant to other types of abiotic stress (Ben Hamed et al. 2013).

The inclusion of measures aimed at promoting agrobiodiversity is paramount for securing the food basis and providing balanced nutrition for the rural population of many developing countries. Diversification away from over-reliance on staple crops is, therefore, regarded as an important way of achieving security of food production. Neglected and underutilized species are important components of agrobiodiversity (Baena et al. 2012). These comprise a broad variety of agricultural and wild crops in different countries, which are traditionally used, and that may have potential for adaptation to climate change, medicinal properties, as well as resistance genes against pests and diseases. There are in fact several reasons why neglected and underutilized species can contribute towards the diversification of agricultural systems and diets, which include reduction in inputs (e.g., fossil fuel-derived fertilizers), better food quality, and preservation of cultural diversity (Mayes et al. 2012). Many neglected and underutilized species are traditional crops that are still cultivated by farmers at a local scale, as in the case for quinoa. Indeed, farmers have an increasing role as guardians of traditional crops as well as neglected and underutilized species. This responsibility should be valued, not only by governments but also by private industry and other stakeholders who up to now have benefited from farmers' traditional knowledge of plants and conservation of biodiversity resources (Krishna et al. 2013). "We all lose when crops that could improve nutrition, health and income are abandoned by communities marginalized by agriculture, ignored by science, and eliminated from the diet of consumers" (Giuliani et al. 2012).

Quinoa (*Chenopodium quinoa* Willd.) seeds, and to some extent its leaves, are traditionally used for human and livestock consumption in the Andean region and have exceptional nutritional qualities (Repo-Carrasco et al. 2003; Stikic et al. 2012). The nutritional value of quinoa seeds is reported to meet, and even surpass, that recommended by the World Health Organization (Hirose et al. 2010). Moreover, the species, being adapted to the harsh climatic conditions of the Andes, exhibits remarkable tolerance to several abiotic stresses (Jacobsen et al. 2003), such as frost (Jacobsen et al. 2005), salinity (Adolf et al. 2013; Hariadi et al. 2011; Shabala et al. 2013), and drought (Jacobsen et al. 2012; Pulvento et al. 2010). Hence, quinoa has been indicated as a good candidate to offer food security, especially in the face of the predicted future world scenario of increasing salinization and aridity. This is why the United Nations Food and Agriculture Organization (FAO) declared 2013 to be the International Year of Quinoa (www.iyq2013.org). With this initiative, FAO has given special recognition to an ancient, but underutilized, Andean seed crop, as well as to the local populations of Bolivia, Peru, Chile, Ecuador, and Argentina, responsible for conserving its biodiversity.

In this contribution, we provide a brief overview of some of the key features of quinoa, such as its excellent nutritional properties, its high tolerance to salinity and drought, its biodiversity, its cultural contribution to the Andean region, and other reasons why quinoa is likely to emerge as a crop that can be cultivated on a worldwide scale in a sustainable manner, if a close link between past, present, and future knowledge will be maintained.

## 2 Origin, biodiversity, and distribution

Quinoa (*Chenopodium quinoa* Willd.) is a seed-producing crop, which has been cultivated in the Andes for thousands of years. Quinoa, a facultative halophyte (Adolf et al. 2012) belonging to the Amaranthaceae, is a dicotyledonous herbaceous plant comprising wild relatives and domesticated populations. The fruit is a tiny achene, and seed color ranges from white and yellow to purple and black (Fig. 1).

In the Andean region, five major ecotypes (highland, inter-Andean valley, *salares*, Yungas, and coastal lowlands) are associated with dispersion cores located around Lake Titicaca in Bolivia and Peru. Its natural spatial distribution ranges from Colombia (Nariño, 1°39′ N) to Chile (southern part of the Andes, ca. 42° S) and includes Bolivia, Peru, Ecuador, and Argentina (Fuentes et al. 2012). The high genetic diversity among and within Chilean populations of quinoa has been investigated by molecular methods (Fuentes et al. 2009). This study showed a good match between ecological constraints and quinoa biodiversity. Moreover, cluster analysis discriminated between the crops growing in the central Andes compared to southern latitudes.

Quinoa is an allotetraploid with chromosome number $2n = 36$; the haploid genome of quinoa is ca. 967 million nucleotide pairs, which is relatively small compared to most plant species (Maughan et al. 2004). The genetic basis of several quinoa traits was identified several decades ago (Lescano-Rivera 1980), but the first true genetic descriptions more recently provided the starting point for improvement of quinoa. Several genetic tools have been developed, and today we count 424 ESTs (expressed sequences tags), 379 proteins, and several microsatellite sequences among other genetic resources (GenBank 2013).

Production of quinoa has, until now, been prevalently conducted in Bolivia and Peru and still is (Fig. 1) with small productions in other Andean countries like Ecuador, Chile, Argentina, and Colombia. Production in Peru, Ecuador, and Bolivia has increased from 1980 to 2011 by approximately 300 %, with the largest increase (from ca. 9 to 38 metric tons) in the latter country (FAO-FAOSTAT 2013). Although, until the beginning of the 1980s, quinoa cultivation was specific to these countries, since then, others have understood the potential and benefits of this plant. Consequently, both research and production have been growing steadily worldwide (Jacobsen 2003; PROINPA 2011). In the USA, quinoa was first introduced in southern Colorado and then extended to other states, and later to Canada (e.g., Saskatchewan and Ontario). In

**Fig. 1** *Top left and right* inflorescence of a Chilean genotype; *center left* trial in Chile (garden of Chilean varieties); *center right* quinoa cultivation in the Chilean/Bolivian *altiplano*; *bottom left and right* trial and harvest in Mali, West Africa. Photos: A. Zurita, D. Bazile

Brazil, trials are ongoing to use quinoa as a cover crop in winter (Spehar and Souza 1993). Many other countries are performing tests on quinoa with very promising results. For example, its adaptability to both northern and southern European conditions has been investigated (Jacobsen 2003; Pulvento et al. 2010). Denmark and the Netherlands are important areas for quinoa improvement and breeding. In particular, a daylength-neutral quinoa variety, bred and selected at the University of Copenhagen from material originating from a cross between southern Chilean and Peruvian lines, has shown its potential in drought and salt stress conditions typical of Mediterranean-type agro-ecosystems (Cocozza et al. 2013). In the UK, quinoa is used as a cover crop, alone or mixed with rapeseed. In France, farmers have started growing quinoa through conventional and organic agricultural practices. India and Pakistan have been looking into this new crop since over 10 years with some promising results (Bhargava et al. 2006, 2007; Munir et al. 2011). Testing quinoa varieties in Indian

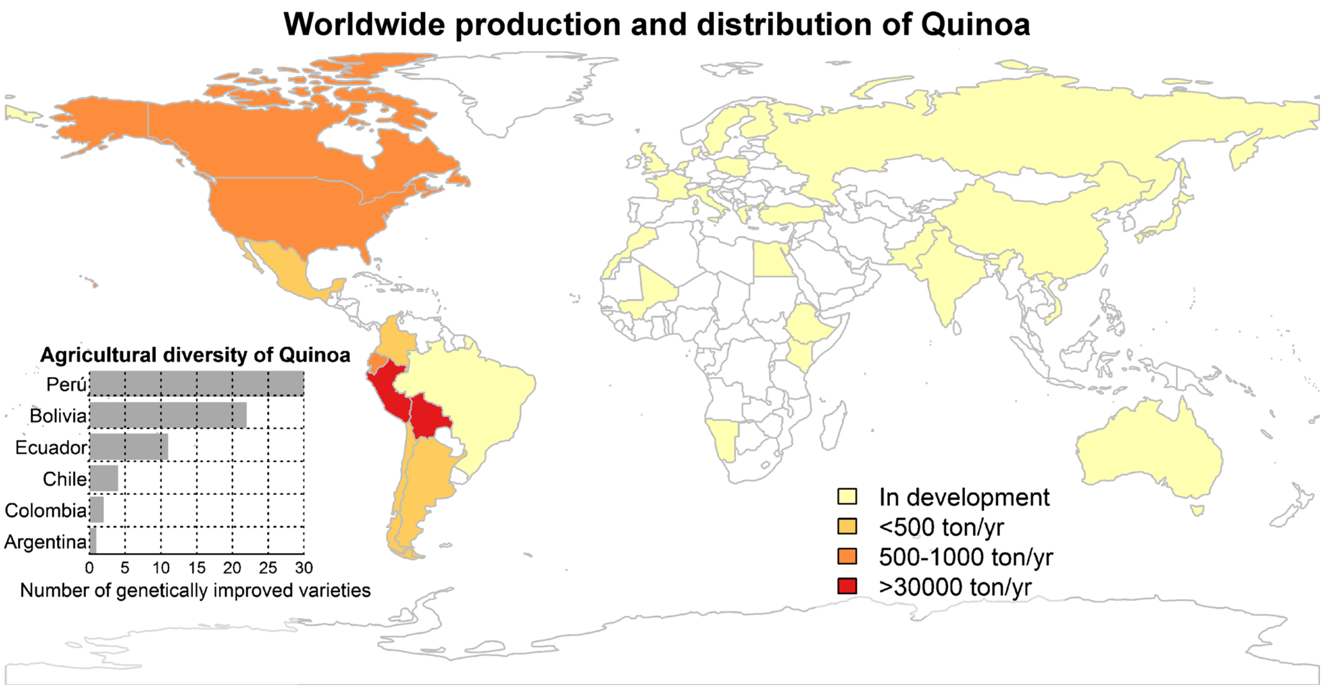


**Fig. 2** Global distribution of quinoa production. Bolivia and Peru are the main producers, followed by Ecuador, USA, and Canada. Chile, Argentina, Colombia, and Mexico produce mostly for local consumption. The other countries are currently developing quinoa projects (field trials). *Bar plot on the left* shows productive varieties developed by genetic improvement in countries within the original distributional range (FAO 2011)

pedo-agro-climatic conditions indicates that quinoa grows well and displays a high tolerance to local conditions while maintaining high productivity. According to Bhargava et al. (2006), there are good possibilities of expanding the crop to the Himalayas as well as the north Indian plains. To a growing Indian population, quinoa leaves and seeds could be a nutritious food source complementary to rice and wheat. Last but not least, preliminary trials are also being conducted in Africa (Figs. 1 and 2). It has been estimated that no other crop has been introduced faster if compared with other crops like potato, kiwi, or soybean. However, quinoa crop productivity remains low compared to that of wheat or maize with seed yields reaching, at best, 0.8 ton/ha (FAO-FAOSTAT 2013). Between 2006 and early 2013, quinoa crop prices have tripled. In 2011, the average crop value was $3,115 USD per ton with some varieties selling as high as $8,000 per ton. Although producers' associations and cooperatives have worked toward greater producer control of the market, the higher price fetched by quinoa does make it harder for people to purchase it, but it also brings livable income for farmers and is enabling many urban refugees to return to working the land. Promoting the localism vs the globalization of a crop is often cause for debate (Mayes et al. 2012); in the case of quinoa, the pros and cons of this situation have been delineated elsewhere (Jacobsen 2011, 2012). From the standpoint of scientific research, the number of publications on international peer-reviewed journals (in English) increased from 4 in 2008 to 17 in 2012 attesting to the growing interest for this plant both in terms of practical applications and fundamental research (mainly on stress tolerance mechanisms and nutritional aspects).

## 3 Quinoa as a model of tolerance to adverse environments

Security of food production for a growing population under low-input regimes is a main task for research in the present century. Today, the scarcity of water resources and the increasing salinization of soil and water are the primary causes of crop loss worldwide and may become even more severe as a consequence of desertification (FAO 2011). Quinoa's exceptional tolerance to hostile environments makes it a good candidate crop offering food security in the face of these challenges.

Quinoa may, for example, represent an opportunity for farmers in a drier climate (Martínez et al. 2009). We may also increasingly need to rely on plants like quinoa for revegetation and remediation of salt affected lands. In such areas, conservation and land management can benefit from knowledge of drought and salinity tolerance of local species (de Vos et al. 2013). In this context, quinoa is a good model crop, useful for investigating the mechanisms that plants adopt to deal with high salinity and drought tolerance (Adolf et al. 2013; Orsini et al. 2011; Pulvento et al. 2012; Ruiz-Carrasco et al. 2011; Shabala et al. 2013). The responses of quinoa to salinity are being investigated by comparing its performance with that of other halophytes like salt cress (*Thellungiella halophyla*; Morales et al. 2012) and by comparing a range of quinoa genotypes (Ruiz-Carrasco et al. 2011; Miranda et al. 2012; Adolf et al. 2012; Shabala et al. 2013).

Since the advent of new technologies applied to crop genomics, such as next-generation sequencing, cost-effective improvements in underutilized crops can be made (Varshney et al. 2009). Such molecular tools can generate sequence data from any species at a much faster rate allowing, for example comparisons between underutilized crops and staple crop relatives or between stressed and unstressed plants of the same genotype. The identification of salt tolerance-related genes in quinoa is ongoing. At present, two homologous Salt Overly Sensitive 1 (*SOS1*) loci and an *NHX* gene have been identified, and their expression patterns analyzed in several genotypes under salt stress (Maughan et al. 2009; Ruiz-Carrasco et al. 2011). With regard to drought stress-related genes, transcriptomic studies by sequencing techniques are being developed (H. Silva 2012, personal communication). In a Chilean accession (R49), RNAseq identified 150,952 contigs (18,124 contigs over 1 kb); digital expression analysis allowed the identification of 737 differentially expressed genes exhibiting greater than fourfold change under drought conditions (Morales et al. 2011). Dehydrin-like proteins have also been isolated from quinoa embryos, and their expression in two genotypes from contrasting environments and in response to high salinity have been investigated (Burrieza et al. 2012; Carjuzaa et al. 2008).

A deeper understanding of the physiological and structural mechanisms that determine tolerance in quinoa is a prerequisite for its sustainable utilization as a crop (Jacobsen 2011). Integrating the many mechanisms, including those at the gene level, involved in stress tolerance will generate knowledge for breeding improved varieties. Research on quinoa is now moving beyond salt and drought tolerance to studies on the effects of other abiotic (macro- or micro-nutrients, heavy metal excess, high and low temperature, UV/FR radiations) and biotic (pathogens) stressors (Bhargava et al. 2008; Buss et al. 2012; Jacobsen et al. 2003; Urcelay et al. 2011). An interdisciplinary effort is required in order to integrate the knowledge generated by quinoa researchers worldwide to successfully reach future goals. As the crop will expand to new areas, genotype × environmental effects on yield and nutritional properties should be one of the main research focuses.

Good tolerance to adverse soil and climatic conditions is one of the several reasons why quinoa can be regarded as a crop suitable for contributing towards achieving food security. Deficit irrigation studies have shown that reducing water use by up to 50 % of full irrigation has no effect on quinoa crop yield (Pulvento et al. 2012; Razzaghi et al. 2012). Quinoa is also known to grow satisfactorily on poor soils, although yield is compromised, an effect that can be diminished by adding composted organic matter, which is particularly recommended for soils of arid zones (Martínez et al. 2009). To counteract this problem, other practices, such as incorporation of green manure from legumes like Andean lupin (*Lupinus mutabilis*) and llama and sheep manures, are also being currently tested for increasing or maintaining soil fertility and preserving soil humidity (Jacobsen 2011).

Because the potential market for quinoa is huge (Jacobsen 2003, 2011), production of quinoa outside the traditional areas of cultivation could help to stabilize the Andean cropping system's sustainability (Jacobsen 2011, 2012) and promote markets for quinoa in a larger geographical region, thus benefiting farmers in other parts of the world and expanding the socio-ecological system associated with quinoa production (Bazile 2013).

In spite of quinoa's huge potential, some obstacles related to crop management still need to be overcome. For example, (1) quinoa is small seeded, therefore sowing under the right conditions is crucial. After a quick emergence, further development is slow, and quinoa may be grown over by weeds. The plant, however, has a deep, ramified root, which after some weeks will enable the crop to develop quickly. (2) Photoperiod requirements can constitute a problem at some latitudes, and suitable varieties, such as daylength-neutral ones, may need to be developed. (3) Postharvest conservation of seeds requires particular care because the embryo, with its external position (peripheral around the perisperm), has a short lifespan. (4) The abundance of saponins requires dehulling and prolonged washing of the seeds before consumption. Moreover, seeds of the "sweet" low-saponin quinoa varieties are more palatable than bitter ones to birds and rodents and may be more susceptible to fungal attacks, leading to losses in productivity.

## 4 Quinoa crop expansion implies new ecological interactions: pests and symbionts

Quinoa cultivars introduced to areas outside their traditional growing regions are exposed to new conditions, including different climate and crop management techniques (Danielsen et al. 2003). The expansion of quinoa cultivation to other areas also brings with it an extension of the spectrum and number of attacks by pests and diseases (Chakraborty et al. 2008; Dwivedi et al. 2013).

The most common disease of quinoa is downy mildew caused by *Peronospora farinosa* (Fr.: Fr.) Fr. 1849. Despite the disease's wide dissemination and significant effects on quinoa production, little is known about its epidemiology, host specialization, population structure, and host plant resistance (Danielsen et al. 2003). There is a similar lack of information regarding other quinoa diseases, such as *Rhizoctonia* spp., *Fusarium* spp., *Ascochyta hyalospora*, *Sclerotium rolfsii*, *Pythium zingiberum*, and *Phoma exigua* var. *foveata*. Recently, it was found that quinoa was infected by the root pathogen *Olpidium* spp. (Urcelay et al. 2011) and by unidentified fungi on panicles in Mali in the rainy season (A. Coulibaly 2009, personal communication).

By using molecular tools, 36 *Peronospora* isolates from quinoa with different geographic origins (Argentina, Bolivia, Denmark, Ecuador, and Peru) were morphologically and molecularly compared with *Peronospora* isolates from other *Chenopodium* species. A phylogenetic analysis based on ITS rDNA sequences indicated that the pathogen responsible for the quinoa downy mildew was identical to *Peronospora variabilis* and that it should not be confused with *Peronospora farinosa* as claimed previously by Choi et al. (2010). Different degrees of mildew tolerance have been observed in quinoa (Bonifacio et al. 2010). The tolerance trait is especially associated with brown-colored seeds and related to intermediate and late-maturing varieties. The traits associated with mildew tolerance could be incorporated with the aim of releasing tolerant varieties.

During the vegetative period, quinoa is affected by a range of insects, including *Eurysacca melanocampta*, *Eurysacca quinoae*, defined by Rasmussen et al. (2001) as the main pest of quinoa, and the complex *Copitarsia turbata*, *Feltia* sp., *Titicaquensis heliothis*, and *Spodoptera* sp. Productivity losses in quinoa caused by these pests are huge, reaching, in some cases, as much as 70 % (PROINPA 2011)

Plants in natural ecosystems are symbiotic with microorganisms such as mycorrhizal fungi or fungal endophytes. These microbial symbionts can have profound effects on plant ecology, fitness, and evolution (Cicatelli et al. 2010). An interesting research topic would be to investigate the relationship between quinoa root exudates and fungal symbiosis. Recently, the presence of some endophytic bacteria and fungi have been reported in quinoa (Claros et al. 2010), and the colonization by fungal root symbionts in quinoa and 12 other species that dominate plant communities in the Bolivian *altiplano* has been described (Urcelay et al. 2011). The most abundant functional groups in this area were arbuscular mycorrhizal fungi (AMF) and dark septate endophytes (DSE). In quinoa, the ratio between DSE and AMF colonization was negatively related with the proportion of fine roots, suggesting that DSE may play a more important role in the plant's adaptation to extreme environments (Urcelay et al. 2011). Beneficial quinoa–microbe interactions require further investigation in order to assess their potential applications as a means of improving adaptation to new environments.

## 5 Quinoa: a good candidate to offer an ecosystem service

The UN Millennium Ecosystem Assessment Report (2005) defined "ecosystem services" as benefits people obtain from ecosystems. The report distinguishes four categories of ecosystem services: *provisioning*, such as the production of food and water, but also pharmaceuticals, biochemicals, and industrial products; *regulating*, such as the control of climate and disease; *supporting*, such as seed dispersal and primary production; and *cultural*, such as spiritual and recreational benefits.

The need to use quality foods for a growing and aging population has focused attention on functional foods and nutraceutical compounds. In this context, quinoa appears as a good option that fulfills almost all nutritional requirements while supplying compounds with health-promoting properties (reviewed by Abugoch 2009; Vega-Gálvez et al. 2010).

In quinoa seeds, all 20 proteinogenic amino acids have been identified, and proteins are accumulated in quantities higher than those found in cereals (12–20 %). Quinoa seeds also contain vitamins (B, C, and E) and several antioxidants, such as flavonoids (Miranda et al. 2012; Repo-Carrasco-Valencia et al. 2010). Populations consuming flavonoids-enriched foods reveal low cancer frequency. Moreover, nursing women fed with quinoa may have a higher production of better quality milk as found in animal models fed with isoflavone-rich fodder (Zhengkang et al. 2006). Seeds also possess large amounts of flavonoid conjugates, such as quercetin and kaempferol glycosides. Flavonoids can prevent degenerative diseases such as coronary heart disease, atherosclerosis, cancer, diabetes, and Alzheimer's disease through their antioxidative action and/or the modulation of several protein functions, thus exerting health-promoting effects (Hirose et al. 2010).

Good quality fatty acids and minerals (Ca, Fe, K, Mg, Mn, P, Zn) are also present in high quantities in quinoa (Abugoch 2009). In addition, the absence of gluten in quinoa seeds offers alternative nourishment for the celiac population, and due to its balanced nutritional values, it could counteract the increasing problems of obesity in the developed world. In less developed countries, quinoa could make a great contribution towards reducing malnutrition and death by hunger, one of the reasons why FAO declared this the International Year of Quinoa.

Recently, quinoa seeds have been analyzed for their ecdysteroid content (Kumpun et al. 2011). Phytoecdysteroids are plant secondary metabolites that have a protective role (in plants) against insects and nematodes. These compounds also have positive effects on human health through their antioxidant properties and are able to inhibit collagenase, thereby preventing skin aging. Phytoecdysteroids are limited to a few cultivated plant species, and it is therefore significant that quinoa may represent an important source of these metabolites.

Saponins, natural detergents commonly found in plants, are abundant in quinoa (Gómez-Caravaca et al. 2011). They are distributed throughout the plant but are mainly accumulated in the seed coat. Saponins have insecticidal, antibiotic, fungicidal, and pharmacological properties (Carlson et al. 2012; Vega-Gálvez et al. 2010), thus contributing to the plant's defense against pests and pathogens. These antinutritional compounds have a bitter taste but there are some "sweet" quinoa varieties without or with less saponins. The abundance of saponins in quinoa offers an additional use for

**Fig. 3** *Left* Mapuche woman selling quinoa products in a local market (southern Chile); *right* Caritayama community woman (Rosa Quispe) in a field of quinoa (Peru). Photos: D. Bazile, A. Canahua-Murillo

this species (or for its side products) as an alternative source of these compounds for industrial (wetting agents, emulsifiers), agricultural (crop protection), cosmetic, and medicinal (as adjuvants in vaccines and for cholesterol reduction) applications (Balandrin 1996; Güçlü-Üstündağ and Mazza 2007). It, therefore, represents an opportunity to diversify the interest in cultivating this crop, beyond human and animal nutrition.

## 6 Andean farmers: key actors in the perpetuation of quinoa biodiversity

Quinoa seeds of different accessions are currently being conserved in several seed banks around the world (ex situ conservation). However, preserving agrobiodiversity means preserving also the associated culture, that of indigenous farmers living in the Andean region (Bazile et al. 2012; Fuentes et al.

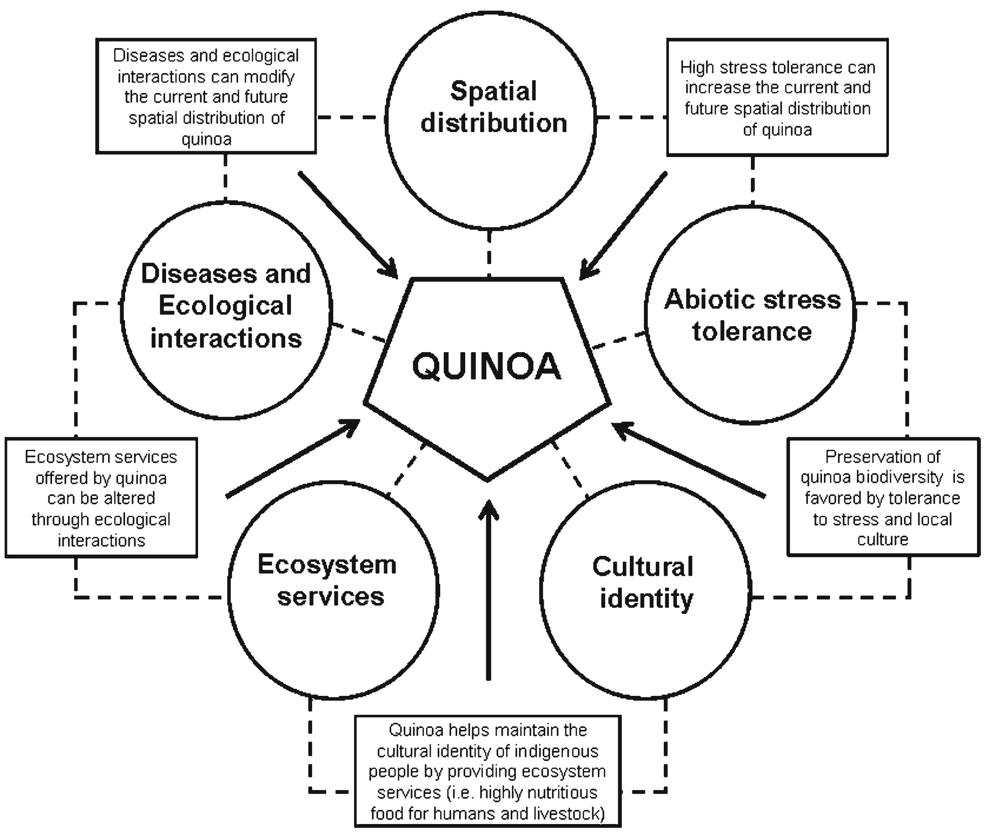


**Fig. 4** Proposed cluster for a sustainable quinoa productive system

2012; Jacobsen 2011). Thus, although the importance of seed banks in biodiversity conservation is well known, the success of future conservation and breeding programs also depends on the on-farm conservation of this diversity. Moreover, the transfer of knowledge and associated practices will help to adapt quinoa to new regions.

Quinoa is a family heritage; knowledge is acquired from the parents who have cultivated it since their childhood. Fuentes et al. (2012) indicate the Andean farmers as a valuable resource due to the fact that they preserve the genetic diversity of quinoa in their fields, have the necessary expertise for the agronomic management of their own genotype/accession, and use farmers' networks for seed fluxes via exchange (between individuals or families) within the community or between close-by communities during events, such as local markets or traditional ceremonies (Fig. 3).

Industrial development is causing migration from rural areas to the cities (Bazile et al. 2011). This social and economic situation, added to the increasing demand for quinoa, is changing land use and increasing the crop's genetic homogeneity (i.e., few genotypes are grown for commercial purposes; Fuentes et al. 2012; Martínez et al. 2009). Due to better profits from quinoa export and the higher income achieved by bigger land owners, small farmers migrate, thus jeopardizing their cultural and agro-biodiversity legacy (Jacobsen 2011, 2012). It is, therefore, of primary importance to preserve small-scale farming where the greatest genetic diversity of quinoa and associated human culture is found (Bazile et al. 2012). In Chile, quinoa is still grown in the three major historical areas of cultivation (Tarapacá, Maule, and Araucanía) and remains an essential part of the rural cultural heritage and identity (Fuentes et al. 2012). Quinoa is a promising crop in a broader context too, but scientists and stakeholders must do all they can to preserve the heritage of quinoa so that this crop can continue to be cultivated in a sustainable way, while contributing to food quality and security in the Andean region and worldwide.

## 7 Conclusion

Quinoa is an interesting plant whose capacity to tolerate adverse environmental factors and exceptional nutritional qualities warrant further research in all fields of plant biology, agronomy, and ecology. However, in FAO's International Year of Quinoa, we believe it is also important to bear in mind that the heterogeneous genetic and cultural heritage of quinoa must be preserved. The economic profit obtained from the exclusive use of few quinoa varieties with large, white seeds, called quinoa Real, needs to be viewed in the light of other components present in the "quinoa network" and of other possible applications (e.g., industrial, pharmaceutical). To this end, we propose a schematic model (Fig. 4) integrating the fundamental factors that explain and determine the future of quinoa, in terms of food security, biodiversity conservation, and cultural identity. The "quinoa network" ought to rely on a more transparent commercial chain policy (fair trade) jointly with effective educational and dissemination strategies. Additionally, consumers should be encouraged to rely on a wider range of genotypes in order to sustain small-scale farmers and their economic, social, and cultural interactions. This will reinforce local conservation dynamics and ensure the sustainability of quinoa locally and around the world. One interesting challenge remains as an open question. Quinoa, presently an underutilized crop, could become a major crop, but how can a fair reward be guaranteed to Andean farmers, to acknowledge their contribution to the conservation and breeding of this plant carried out for so many generations (Louafi et al. 2013)?

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