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Geographical distribution of quinoa crop wild relatives in the Peruvian Andes: a participatory mapping initiative

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Abstract

The Peruvian Andes are among the world's most important centers of origin for genetic diversity of crops and plants. Quinoa (*Chenopodium quinoa* Willd.) was domesticated in the Bolivian and Peruvian Andean region around Lake Titicaca. In situ conservation systems for quinoa germplasm and its wild relatives can still be found in the traditional systems of Peruvian farming communities. Quinoa crop wild relatives (CWRs), like the majority of CWRs of other agricultural species, are being affected by the considerable changes in the natural landscapes of the Andes. This article analyzes the presence and distribution of seven quinoa CWRs at the agroecosystem level and considers the social and environmental Andean contexts in which they are found. A qualitative research method based on participatory mapping in six local communities of the Puno region in Peru was applied to establish the presence and distribution of the species. We present the results that were confirmed with local actors on participatory GIS maps. Based on our analyses, we conclude that conservation programs should consider both permanent native meadows and cultivated land with their fallow cycles and plot borders. The diversity of the presence of quinoa CWRs is one result of the coexistence of these two land uses.

Keywords *Chenopodium quinoa* Willd. · Crop wild relatives · Participatory mapping · In situ conservation · Peruvian Andes · Agroecosystem

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1 Introduction

The Peruvian Andes are among the world's main centers of origin (Harlan 1971; Vavilov 1926) of the genetic diversity of crops and plants (Bonifacio 2003). Many of the 128 Peruvian native species (CONAM 2001) are cultivated on the Altiplano (highlands) in traditional agro-ecosystems by small-scale farmers (Mazoyer and Roudart 2017; Morlon 1992). The genetic diversification of crops is the result of the small-scale farmers' strategies (Fuentes et al. 2012) and actions (Altieri and Merrick 1987). The strategies are intended to develop landraces that are adaptable to a broad range of climatic, ecological, agronomic and social conditions (Bazile et al. 2014; Gonzales 2000; Graddy 2013; Mujica and Jacobsen 2006). The technologies developed to achieve these strategies are based on a coherent system inspired by the Andean Cosmovision (Gordon 2014), meaning that agricultural practices are managed in a cultural and religious context. Mother Nature (*pachamama*) always plays a central role and cultivated spaces are not separated from wild spaces because both are considered by local communities as cultivated. The main difference lies in the actors involved; in cultivated plots, it is the farmers (humans) who sow the crops, while in wild spaces, God is considered to manage and choose the species present (Gonzales 2000, 2015; Morlon 1992; Mujica 2008, 2011).

Quinoa (*Chenopodium quinoa* Willd.) was domesticated (Jellen et al. 2015) in the Bolivian and Peruvian Andean region 7000 years ago by indigenous groups around Lake Titicaca and continues to be cultivated in the region today (Bazile 2015; Mujica et al. 2001; Ruiz et al. 2014). Quinoa is now largely recognized at global level for its high nutritional value (Kozioł 1992; Vega-Gálvez et al. 2010). The in situ conservation systems (Rojas et al. 2015) for quinoa germplasm and its wild relatives can still be found in the traditional systems of Peruvian farming communities, encompassing both farmers' fields and non-farmed areas (Gomez-Pando 2015; Mujica and Jacobsen 2006; Ortiz et al. 2002; Tapia et al. 2014). Seven quinoa crop wild relatives (CWRs) (*Chenopodium carnosolum* Moquin, *Chenopodium petiolare* Kunth, *Chenopodium pallidicaule* Aellen, *Chenopodium hircinum* Schrader, *Chenopodium quinoa* ssp. *melanospermum* Hunziker, *Chenopodium ambrosioides* Linneo and *Chenopodium incisum* Poiret) (see Mujica and Jacobsen 2006) have genes of great potential value that could be used to help the crop better resist and adapt to climate change, extreme climatic events and emerging pest and diseases (Garcia et al. 2015; Mujica and Jacobsen 2006). Changing market and consumer preferences may also create opportunities to generate value from CWRs in the future (Hunter and Heywood 2010).

Our study area comprises the semi-natural region around Lake Titicaca in Peru, one of main areas of export-oriented quinoa production. In Andean countries, national and international demand for quinoa has increased rapidly since the 1990s (Bazile 2013). This increased demand has generated complex dynamics within agricultural communities in the region and has sometimes had a negative impact on farming systems and on their biodiversity, by reducing the number of local varieties cultivated per farm (Bazile 2015; Jacobsen 2011; Vargas Huanca et al. 2015; Winkel et al. 2016). Two main projects coordinated by United Nations Agencies to enhance the conservation of traditional quinoa landrace varieties in the High Andes region have consequently been implemented: the first one entitled "In Situ Conservation of Native Cultivars and Their Wild Relatives" (UNDP/GEF) and the second one entitled "Sustainable management of agro-biodiversity and vulnerable ecosystems recuperation in Peruvian Andean regions through Globally Important Agricultural Heritage Systems (FAO/GIAHS) approach."

In addition, the IMAS project for "*Impact of the Modalities of Access to Seed on the dynamic of genetic diversity in agriculture*" (Bazile et al. 2012; Fuentes et al. 2012) and the ADD-EQUECO project "*Emergence of the Quinoa in the world trade*" (Winkel et al. 2012) are also good examples of other efforts to address the sustainability of quinoa-based agricultural systems in Andean agroecosystems considering both social and biological issues. New rules for collective governance of agrobiodiversity were established during participatory activities like role-playing games and participatory simulations.

Only a few varieties of quinoa are certified and associated with the organic export market. Increasingly, farmers are mainly sowing these commercial varieties aimed at export-oriented markets rather than their diverse portfolio of local landraces (Meldrum et al. 2018; Narloch et al. 2017); local varieties are cultivated, often by the same farmers, for home consumption and local and national markets. Furthermore, the replacement of the traditional assortment of cultivated varieties over large areas is accompanied by the disappearance of associated weedy plants, most of which are close relatives of the cultivated crops (Bellon 2004; Heal et al. 2004; Maxted et al. 2008; Narloch et al. 2011). Since the 1960s, the recognition of CWRs as a significant component of agricultural plant genetic resources has led to the creation of a set of both national and international conservation programs (Brush 2000; Hunter and Heywood 2010; Louafi et al. 2013) where the Convention on Biological Diversity (CBD 1992) and the International Treaty on Plant Genetic Resources for Food and Agriculture (FAO 2002) are central.

According to Maxted et al. (2006), "*CWR are wild plant species that have an indirect use derived from their relatively close genetic relationship to a cultivated crop*." Initially, the main focus was on information gathering to enhance ex situ conservation of agrobiodiversity at genetic and species levels (Rojas et al. 2015). However, since the 1990s, under the auspices of the CBD (1992) in situ agrobiodiversity conservation has been considered as a complementary strategy to ex situ conservation (Brush 2000; Hunter and Heywood 2010; Louafi et al. 2013; Maxted 2012; Narloch et al. 2011). In situ conservation mainly focuses on the ecological relationships, knowledge and cultural practices of local communities (Brush 2000; Ruiz et al. 2014). Although distinctions are sometimes made between on-farm management and in situ conservation of plant genetic resources in the wild, here in situ conservation includes the presence of CWR both in and around farmers' fields and in non-farmed areas, because we consider that Andean farmers are involved in managing the environment as a whole. However, little work has been done on the design of in situ conservation methods for plant genetic resources (Curti et al. 2017; Padulosi et al. 2014) and few standard operational procedures have been established (Hunter and Heywood 2010; Jarvis et al. 2011; Maxted et al. 2008).

The international conservation effort has given high priority to increasing knowledge of CWR through ecogeographic surveys (Brush et al. 1995; Hunter and Heywood 2010; Jarvis et al. 2015). One of the operational objectives of the CBD Program of Work on Agricultural Biological Diversity is to identify the geographical extent and distribution of the genetic diversity maintained by farmers in space and over time. Quinoa CWRs, like the majority of CWRs of other agricultural species, occur outside protected areas (Hunter and Heywood 2010) and are being affected by the considerable in the natural landscapes of the Andes, including changes in land use, social organization, livestock dynamics, loss of natural habitats and climatic fluctuations (Vassas Toral 2017; Vieira Pak 2012; Winkel et al. 2016). Even though quinoa CWRs are socioeconomically vital genetic resources for future food security and environmental sustainability, few studies have reported their distribution and in situ conservation in Andean agroecosystems. It is therefore important to identify the potential impact of the recently developed agricultural export market on the *on farm* management of quinoa cultivars and the in situ conservation of quinoa's wild relatives.

This article analyzes the presence and distribution of seven quinoa CWRs at the agroecosystem level and considers the Andean social and environmental contexts in which they are found. We investigated their geographical distribution in six local communities of the Puno region in Peru. A qualitative research method based on participatory mapping was applied to identify the presence of the species. This participatory research is expected to provide the basis of future investigations aimed at ensuring the proper conservation and sustainable use of CWRs in their native habitats. The research also takes into account the fact that these species represent an useful pool of genetic resources for both farmers and plant breeders (Jellen et al. 2015; Murphy and Matanguihan 2015).

2 Material and methods

This article draws on the participatory mapping (PM) methodology to collect information on the presence and distribution of the seven main quinoa CWR (*C. carnosolum* Moq., *C. petiolare* Kunth., C. *pallidicaule* Aellen, *C. hircinum* Schrad., *C. quinoa* ssp. *melanospermum* Hunz., *C. ambrosioides* L. and *C. incisum* Poiret) grown for social, medicinal and nutritional purposes in Andean agroecosystems (Tapia et al. 2014). The research reported in this article was undertaken in two stages. During the first stage, from October to December 2015, a preliminary meeting was held with the local communities selected for the study and the first participatory workshops were organized. In the second stage, from September to November 2016, the findings were checked and confirmed with each community in a second round of participatory mapping workshops, followed by some individual interviews. The research was undertaken in cooperation with the extension services of the Puno Agrarian Agency (Ministry of Agriculture). In this article, participatory workshops, field data collection and laboratory GIS processing are described as components of the participatory mapping initiative. Most of the selected methods were derived from Chapin and Threlkeld (2001) and Chapin et al. (2005). Following Levine and Feinholz (2015), the methods were completely revised and adapted to account for our specific uses, scales, as well as for the socio-cultural contexts of Andean agroecosystems (Canahua 2012; Mercado and Ubillus 2017; Morlon 1992; Tapia 1994; Tapia et al. 2014).

2.1 Background to participatory mapping

Increasing community participation in the definition of policies for the conservation and sustainable use of plant genetic resources is already being tested by some NGOs, international centers and national agricultural research systems, as well as in national plant genetic resources programs (refer to Friis-Hansen et al. 2000). For plant genetic resources conservation and sustainable use programs, the involvement of farmers as partners in a dialogue is considered crucial because farmers' day-to-day experiences are at the heart of in situ conservation (Hunter and Heywood 2010). Working closely with local communities facilitates data gathering (Hawthorne et al. 2015; Wakie et al. 2016). Proximity helps "*provide insights into CWR and indigenous knowledge, such as ethnobotanical knowledge on uses, understanding of the distribution of CWR, patterns of the use of CWR, and potential threats*" (Hunter and Heywood 2010).

Participatory research on plant genetic resources can make use of different tools and techniques (King 2000; Sthapit et al. 2016) including participatory mapping (PM). PM follows a landscape approach and involves community members in mapping their resource base to generate information and clarify relationships between environmental factors and agricultural activities (Bazile et al. 2008, 2011; King 2000). We wanted to use PM with local actors to gain a better understanding of their classifications for three main reasons. First, the classifications often reflect specific local needs that guide a range of in situ CWR conservation-related decisions. Second, they reflect how local actors perceive the landscape, understand and value landscape functions, and make landscape management decisions. Third, as Chapin and Threlkeld (2001) said, "*they are often more finely adjusted to the characteristics of a particular social-ecological system than other global taxonomic systems based on natural sciences*," which explains why they are able to describe local agroecosystem management (Chapin and Threlkeld 2001; Riu-Bosoms et al. 2015). CWR conservation and management through a landscape approach needs to be pursued in conjunction with the use and development of the natural resources of an agroecosystem to fulfill community aspirations (Ingram 1990). PM itself could be the first step in motivating local human communities to positively participate in collective quinoa CWR conservation efforts.

2.2 Site selection and sampling approach

Due to budget and time considerations, we chose six sites to represent the diversity of agricultural situations (Padulosi et al. 2014) according to the Andean agroecosystems characterization made by Morlon (1992) and the first studies available on Quinoa and its CWR's presence (Tapia et al. 2014). The research began by defining the geographic location of the six Andean communities selected and which collected information was to be mapped. The communities were identified using two geographical selection criteria:

1 Distance to the shores of Lake Titicaca and altitude, as these define different agroecological zones (Tapia 1994) (see Fig. 1).

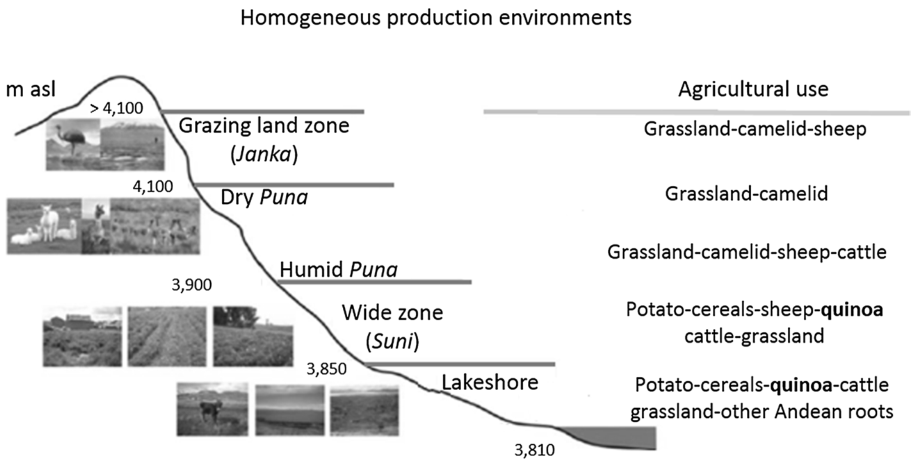

Fig. 1 Agroecological zones for the Peruvian Altiplano, adapted from Tapia (1994)

2 The location of the community to the north, central and south of Lake Titicaca, based on areas with the highest genetic diversity variation (Tapia et al. 2014) between types of cultivated quinoa that are considered as categories of landraces (Canahua 2012).

2.2.1 Distance from Lake Titicaca and altitude criteria

Tapia (1997) classified Andean quinoa germplasm in five ecotypes, and these classifications are generally accepted except that "*these ecotypes differ in adaptation to altitude, tolerance to drought and salinity, and photoperiod response*." The five ecotypes described by Tapia (1997) are the following: "(a) Andean Valley type; (b) Altiplano type; (c) Salar type; (d) Sea level type; and (e) Subtropical type of the Yungas." Only the Altiplano type was considered in the present study, due to its location precisely at the center of origin of the species where most of the quinoa CWRs that can intercross with native quinoa and cultivated species could be found (Mujica and Jacobsen 2006).

Drawing on the geographical works of Pulgar Vidal (1987) and Tapia (1994) also proposed an agroecological zoning of the Peruvian Andes. For each zone, he provided a list of indicators for cultivated species and a link to the different crop rotation patterns. Tapia (1994) described five agroecological zones for the Peruvian Altiplano (see Fig. 1). Each is determined by a range of variables such as latitude, altitude, exposure and land use: (1) Lakeshore zone, between 3810 and 3850 m asl; (2) Wide zone (*Suni*), between 3850 and 3900 m asl; (3) Humid *Puna*, between 3900 and 4100 m asl; (4) Dry *Puna*, between 3900 and 4100 m asl; and (5) Grazing land zone (*Janka*), located at 4100 m asl and above. Altiplano type quinoa germplasm is cultivated in two agroecological zones: (1) the Lakeshore zone and (2) the Wide zone. We took these two main zones for quinoa cultivation across communities into consideration to select the study sites based on the presence and diversity of quinoa types. However, we also analyzed the entire agroecosystem to describe the presence of quinoa CWRs due to their potential distribution in all the agroecological zones.

2.2.2 Geographic location relative to Lake Titicaca criteria

Domesticated quinoa and their CWRs "*are sympatric and share a fundamentally major autogamous reproductive system as well as a wide range of variation in leaf and grain size and color*" (del Castillo et al. 2007 cited by Gomez-Pando, 2015). According to del Castillo et al. (2007) and Fuentes et al. (2009), "*the natural hybridization between wild and domesticated populations probably occurs easily with 30% of pollination*" potentially coming from other plants, varieties and CWRs. In the Puno Altiplano, quinoa CWR and domesticated populations of quinoa exist in the same cultivation zones. According to Mujica (1994), this presence "*indicates that domesticated quinoas are generally accompanied by—semi-wild populations (when natural cross-pollination has occurred) and totally—wild populations (CWR) in their various distribution areas*" (Mujica 1994 cited by Gomez-Pando 2015).

In addition, Canahua (2012) (cited in Tapia et al. 2014) observed that Puno highland farmers mainly classify their quinoa types according to different quality criteria such as seed color, sensitivity to frost and food preparation. For the overall classification of highland type (Altiplano) quinoa, Canahua (2012) suggested a classification with eight sub-groups: Blancas/White; Chullpi; Amarilla/Yellow; Misa quinua; Witulla; Q'oitu; Pasancalla; Guinda. According to the criteria used for this classification, the highest variation in cultivated quinoa is found in four areas of the Puno region (Tapia et al.

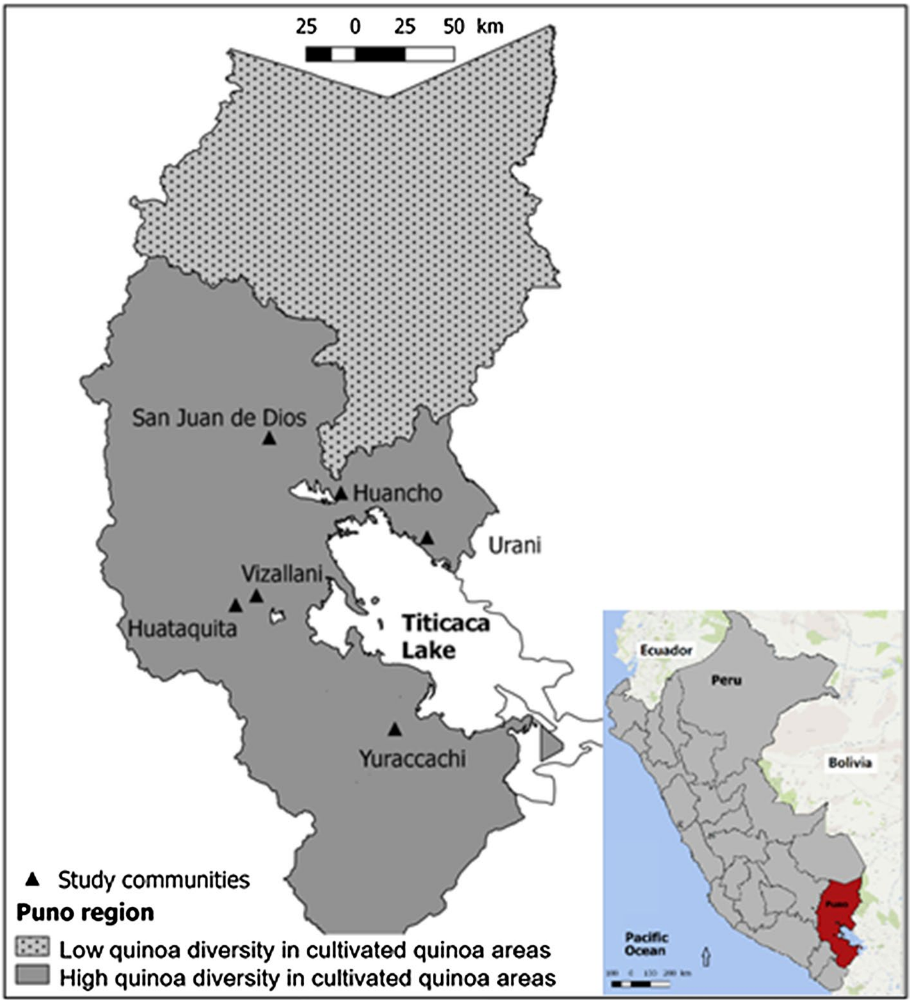

Fig. 2 Location of study communities in the areas with the highest diversity of *C. quinoa* Willd. (Puno region, Peru)

2014) (see Fig. 2). However, in our study, we only considered spontaneous wild plants of quinoa CWR and not the cultivated populations of some quinoa CWRs like *cañahua* (*Chenopodium pallidicaule* Aellen).

The six communities studied were selected with the assistance of Puno's Agrarian Agency who knew the key members of the community. The communities are located in the areas of the greatest variation in cultivated quinoa defined by Tapia et al. (2014) and are primarily composed of agro-pastoralists. The communities are Urani, Huancho, San Juan de Dios, Vizallani, Huataquita and Yuraccachi (see Fig. 2). Each community has an own topographic profile at its specific location according to the different agroecological zones described in Fig. 1.

2.3 The PM workshops

We conducted PM research in six communities in the Puno region. The PM process started with the selection of the communities. Fieldwork included the first PM workshop and collection of GPS coordinates as control points. Fieldwork was followed by post-processing using geographic information systems (GIS). After checking and having the first map results approved by the actors of each community in the second workshop, final GIS post-processing allowed us to identify the geographical distribution of the seven quinoa CWRs. All the steps of the PM process are presented in Fig. 3.

2.3.1 Preliminary meeting

During the first meeting with community authorities, we explained our objectives and the PM methodology. After responding to any questions they had, we asked if they agreed to participate in the research. The authorities in each community said that they only would agree to participate if the information was not used for mining activities. For the PM

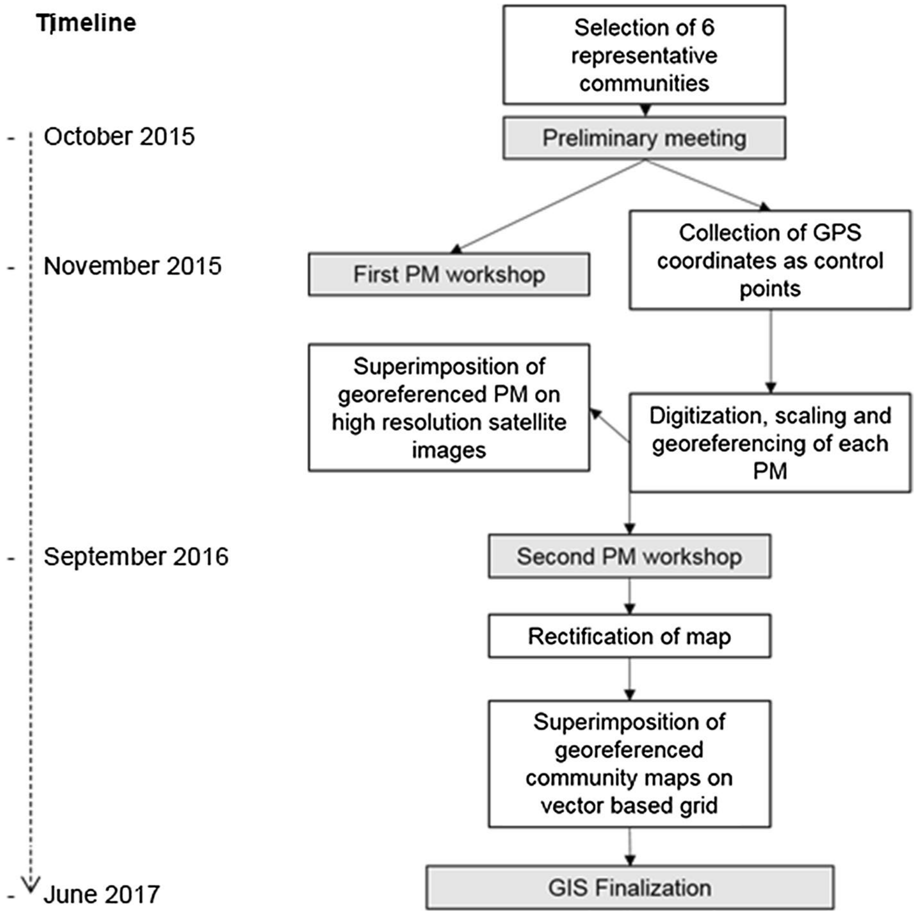

Fig. 3 Organizational chart of PM process methodology

workshop, the authorities from the six communities invited representative quinoa farmers (i.e., different ages and gender) to participate in the PM activities.

2.3.2 First workshop

Between October and December 2015, first PM workshop was conducted separately in each community at a location within the community (see Fig. 3). Blank sheets of paper and markers were provided. At the beginning of the workshop, we explained the key information we wanted to collect and discuss with knowledgeable participants. We reminded the group of the exact definition of the "presence of quinoa CWR" (i.e., the location where CWRs grow) and the designated scope of the agroecosystem map (different locations within the entire agroecosystem where farmers practice agriculture and perform cultural and social rites). Workshop participants then reached agreement about the places that should be drawn on the community map. As more areas were drawn on the map and a pattern began to emerge, the group was asked to refine and finalize the presence of quinoa CWRs. Other non-spatial information about the presence of quinoa CWR that could be relevant was recorded in notebooks but not marked on the map.

After the first collective mapping session (see Fig. 4), a walk through each community's agroecosystem allowed us to record the GPS coordinates of the key features. We followed a similar process to the one used by Wakie et al. (2016) "*as control points during the post-geo-referencing process*" and subsequently for the digitalization and georeferencing of the scaled maps with the QGIS software (version 2.14.2) using the OpenLayers plugin (Bing Aerial layer)." Each new map represented each community's agroecosystem with all the information concerning significant land features and subsistence patterns, including the community settlements, roads, dirt roads, water bodies, mountains (contours), quinoa plots, other crop plots, tree plantations, wetlands, grazing and the presence of the seven quinoa CWRs.

Fig. 4 A comprehensive location map for the six study communities (see Fig. 2) was elaborated during the PM at the first workshop. They describe the composition of each agroecosystem community and the presence of quinoa CWR

2.3.3 Second workshop

Between September and November 2016, as described by Wakie et al. (2016), we presented "*the geo-referenced community maps to the same communities for their approval: additional compass points, key geographic features such as neighboring villages, placed the communities at the center of the maps to simplify the verification process.*" For the geolocalization and GIS processes, please see the next paragraph 2.3.4. that was conducted in parallel with a 50-m square grid for validation. We conducted individual interviews about the map with key actors in each community who had been identified during a parallel ethnobotanical survey. They were asked to use markers to delete or add new information as needed. We updated the community maps by incorporating all the changes made during the second workshop (Fig. 5).

2.3.4 GIS finalization

We used a post-processing methodology based on a biogeographical approach (de Grenade and Nabhan 2013) developed on QGIS (version 2.14.2) and TerraView (version 4.2.0) software to finalize the resulting data of our two PM workshops. This methodology requires specific units that can be used to describe the spatial distribution, interrelationships and properties at a specified level of a spatial scale (Davidson-Hunt and Berkes 2012). Like Levine and Feinholz (2015), we applied "a spatial generalization process using vector-based grids which provided a consistent means to display overlapping data, and we used a 50-m square grid." This process resulted in a gridded representation of each significant

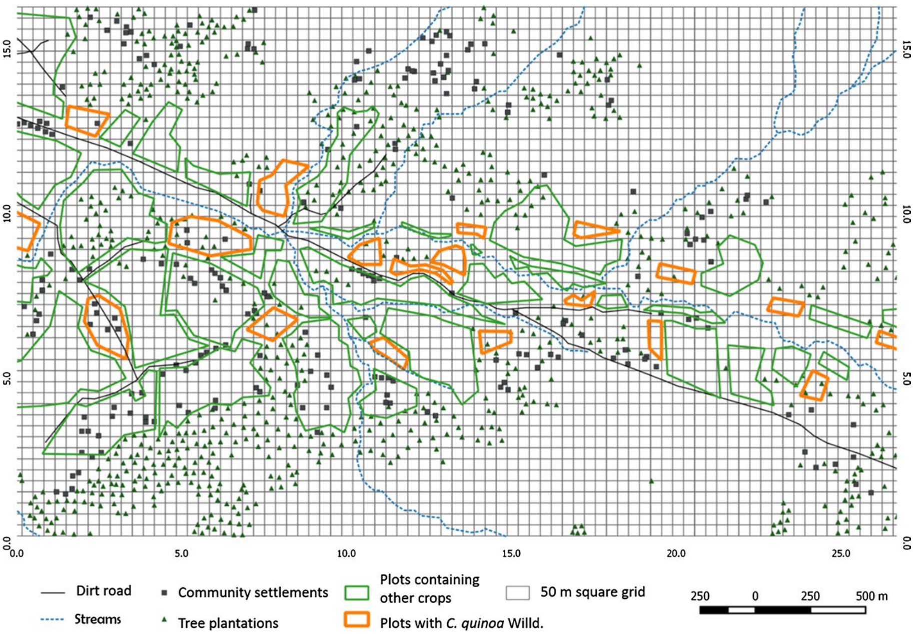

Fig. 5 Example of digitalization for the Urani community discussed at the second workshop at the end of 2016

land feature used by local communities for positioning their activities, the presence of quinoas' CWRs and subsistence patterns for each community's agroecosystem (Fig. 6). Each final gridded dataset used a binary attribute scheme to determine the following: the presence of each quinoa CWR; their distance from significant land features and subsistence patterns for each agroecosystem; and the presence of each CWR at different altitudes (Fig. 6).

3 Results and discussion

3.1 Regional observations of community maps

As a result, we obtained six participatory maps, one for each community (see 2.3, The PM workshops). On average, 17 people participated per community. All the participants were over 20 years old. The percentage of females was 65%. The average richness of quinoa type crops was five species, and that of quinoa CWRs was 5.8 species per community.

In the Andes, the system of production is based on the management of risks and crop diversification that ensures the food security of local families. Table 1 is an inventory of *C. quinoa* Willd. based on the classification made by Canahua (2012) and on the information provided by interviewees in each community. The quantities and types used per season are a function of the characteristics of each plot. Of the six communities, Huataquita was the only community that had already participated in an agricultural biodiversity conservation project, which probably explains why all quinoa types were present there. The most frequently cultivated quinoa in all the communities was Blancas/White, which is associated with a commercial type. Amarilla/Yellow and Q'oitu types were also planted in all communities but at a lower percentage (less than 5% of the surface).

Urani (northern location) was the community with the lowest number of quinoa CWRs (5 species). Yuraccachi (southern location) was the community with the highest quinoa CWR richness, (7 species). *C. petiolare* Kunth, *C. hircinum* Schrad. and *C. ambrosioides* L. were mapped by all of the communities. The least common quinoa CWR was *C. carnosolum* Moq., found in only two communities (Table 2).

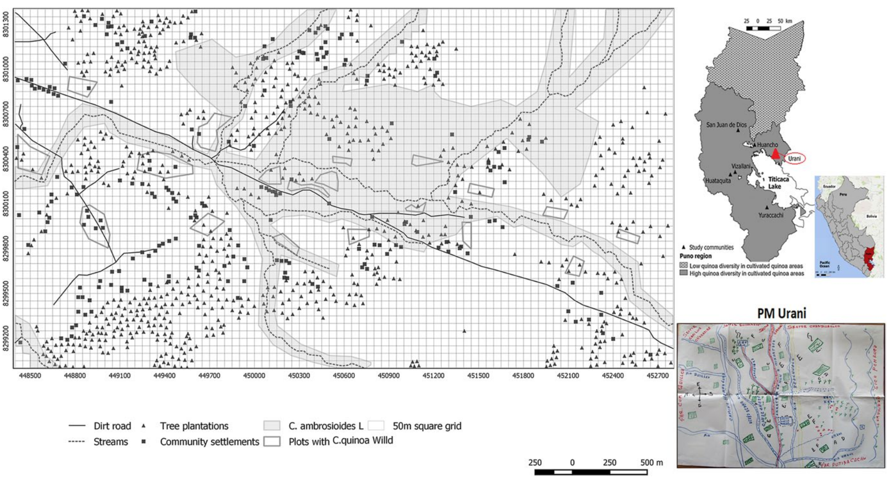

Fig. 6 Final quinoa CWR distribution. Case of *C. ambrosioides* L., Urani community

Table 1 Eight types of quinoa crops grown by the community in the 2015/2016 season (only plots cultivated by the interviewees are included)

Quinoa type	Communities					
	Urani	Huancho	San Juan de Dios	Vizallani	Huataquita	Yuraccachi
Blancas/white (%)	78	63	75	55	41	61
Chullpi (%)	0	0	10	3	10	0
Amarilla/yellow (%)	7	10	5	8	4	11
Misa quinoa (%)	11	0	5	0	8	0
Witulla (%)	0	0	0	0	3	18
Q'oitu (%)	4	10	5	13	8	11
Pasancalla (%)	0	17	0	23	24	0
Guinda (%)	0	0	0	0	1	0
Total (%)	100	100	100	100	100	100

Table 2 Presence of quinoa CWR in each community according to the information provided by the interviewees in each community). Code: 0 for absence, 1 for presence

Quinoa CWR	Communities					
	Urani	Huancho	San Juan de Dios	Vizallani	Huataquita	Yuraccachi
C. carnosolum Moq	0	0	1	0	0	1
C. petiolare Kunth	1	1	1	1	1	1
C. pallidicaule Aellen	0	1	1	1	1	1
C. hircinum Schrad	1	1	1	1	1	1
C. quinoa ssp. *melanospermum* Hunz	1	1	0	1	1	1
C. ambrosioides L	1	1	1	1	1	1
C. incisum Poiret	1	1	1	1	0	1
Number of species	5	6	6	6	5	7

For Urani, Huancho, San Juan de Dios (all three in the northern location) and Vizallani (central location), the richness per cell of the majority of cells in which quinoa CWR is present was three species (see Fig. 7 and Table 3). The CWR richness per cell of most of the agroecosystems located in Huataquita (central location) and Yuraccachi (southern location) was four species. Vizallani (central location) had the least overlap of species per cell; 25% of its cells represent a single quinoa CWR, and the highest richness (3 species) was present in 44% of the total number of cells in which a quinoa CWR was present. In contrast, Yuraccachi, the southernmost community in the study, was the only one with a richness per cell greater than 6, and the largest richness (4 species) was present in 44% of the total number of cells in which a quinoa CWR was present.

As can be seen in Table 4, the geographical distribution of quinoa CWRs per community generally is relatively homogeneous. Huancho stands out as it had the largest distribution of *C. ambrosioides* L. and *C. incisum* Poiret, i.e., 74.6% of the total number of cells in which quinoa CWR is present. Vizallani had a high percentage of distribution of wild *C.*

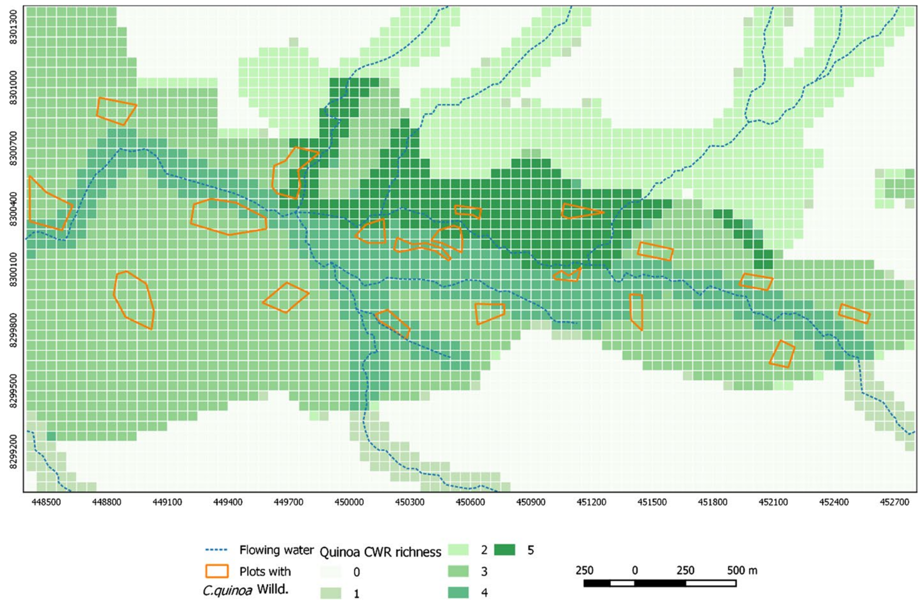

Fig. 7 Quinoa CWR richness per cell. In Urani, richness ranged from 0 to 5 perceived species

Table 3 Quinoa CWR richness per community, distributed as a percentage of cells in which the species were present

Quinoa CWR richness	Communities					
	Urani (%)	Huancho (%)	San Juan de Dios (%)	Vizallani (%)	Huataquita (%)	Yuraccachi (%)
1	5	7	16	25	39	27
2	25	33	13	21	0	6
3	50	43	53	44	0	9
4	19	15	12	10	53	44
5	12	2	2	0	8	0
6	0	0	4	0	0	9
7	0	0	0	0	0	5
Total	100	100	100	100	100	100

pallidicaule Aellen (in 100% of the total number of cells in which quinoa CWR is present) compared with the other communities. This can be explained by the presence of *cañihua* (*C. pallidicaule* Aellen) crops within the community agrarian landscape.

In the six communities, all the quinoa CWRs are present in *C. quinoa* Willd. plots (see Fig. 8). As reported by Geerts et al. (2008) and Mujica and Jacobsen (2006), even today "*traditional wild types are still locally conserved for different purposes or as a security crop in case of natural disasters*." Concerning our quinoa CWRs of interest, the largest number of cells accounting for *C. quinoa* Willd. plots in which quinoa CWR is present, are represented by *C. hircinum* Schrad (97% of the number of cells covered by *C. quinoa*

Table 4 Presence of Quinoa CWR distribution per community, as a percentage of the total number of cells in which quinoa CWRs are present on each participatory map

Quinoa CWR	Communities					
	Urani (%)	Huancho (%)	San Juan de Dios (%)	Vizallani (%)	Huataquita (%)	Yuraccachi (%)
C. carnosolum Moq	0	0	9.9	0	0	9.5
C. petiolare Kunth	49.1	35.5	41.9	44.6	49.9	35.6
C. pallidicaule Aellen	0	6.6	52.2	100	49.9	66.5
C. hircinum Schrad	49.1	14.9	41.9	60.7	49.9	35.3
C. quinoa ssp. *melanospermum* Hunz	49.1	14.9	0	8.9	49.9	35.3
C. ambrosioides L	35.8	74.6	11.7	10.9	37.9	24.9
C. incisum Poiret	21.8	74.6	11.7	12.3	0	24.9

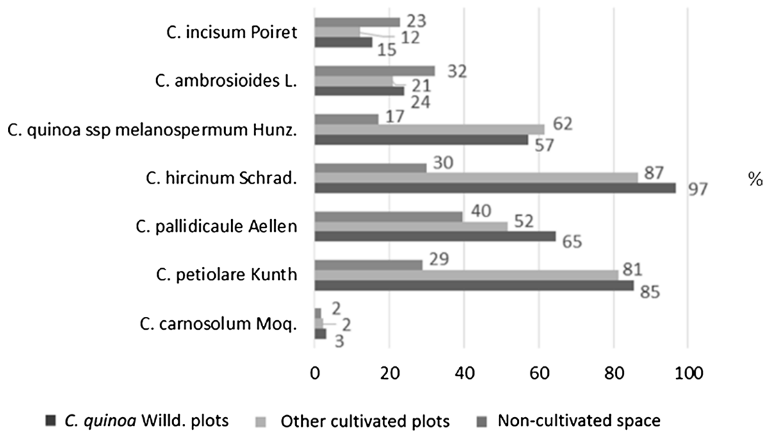

Fig. 8 Estimation of areas with the presence of seven quinoa CWRs, as a percentage of the number of cells covered by each type of space: within *C. quinoa* Willd. plots; in plots with other cultivated species; and non-cultivated space

Willd. plots), *C. petiolare* Kunth (85% of the number of cells containing *C. quinoa* Willd. plots) and *C. pallidicaule* Aellen (65% of the number of cells containing *C. quinoa* Willd. plots). According to Jacobsen and Mujica (2002), *C. hircinum* Schrad. is considered to be the closest ancestor of *C. quinoa* Willd. because of its chromosomal and phenotypic similarity. In contrast, *C. quinoa* ssp. *melanospermum* Hunz. could be a natural cross between *C. hircinum* Schrad. and *C. quinoa* Willd. (Mujica and Jacobsen 2006).

In the traditional Andean system of territorial organization of agricultural production, there are interchanging cycles of cultivation and pasture. The crop rotation cycle and the periods of fallow under pasture conditions are very important for the sustainability of the system (Swinton and Quiroz 2003), and the spatial and temporal distribution of the quinoa crop is consequently variable. The crop rotation cycle usually is composed of potato/quinoa/barley-oats. The presence of quinoa CWRs in crop plots other than *C. quinoa* Willd. was above 60% (% of cells containing plots cultivated with other species) for *C. quinoa* ssp. *melanospermum* Hunz. (62% of the number of cells containing plots cultivated with other species), *C. carnosolum* Moq. (2% of the number of cells containing plots cultivated with other species), *C. petiolare* Kunth (81% of the number of cells containing plots cultivated with other species) and *C. hircinum* Schrad. (87% of the number of cells containing plots cultivated with other species).

Although quinoa CWRs grow alongside cultivated quinoa, they "*are sometimes found in isolation, either at the edges of the farmers' fields or in places considered sacred*" (Gomez-Pando 2015). In our case study, the percentage of cells containing quinoa CWR located in the other parts of the agroecosystem within a radius of 200 m of a *C. quinoa* Willd. plot was over 30% for *C. ambrosioides* L. (41% of the number of cells labeled non-cultivated space), *C. pallidicaule* Aellen (35% of the number of cells labeled non-cultivated space), *C. incisum* Poiret (32%), *C. carnosolum* Moq. (31% of the number of cells labeled non-cultivated space) and *C. hircinum* Schrad. (31% of the number of cells labeled non-cultivated space).

3.2 Abiotic environmental factors affecting quinoa CWR distribution

The management of climatic, biogeographic and altitudinal systems of the Andes has led to successful diversification and varied adaptation of many species of crops and animals in higher altitudinal ranges. In the past, people "*selected genotypes on the basis of their use and resistance to adverse biotic and abiotic factors*" (Garcia et al. 2015). Quinoa CWRs continue to have valuable genes that can be "*exploited in the future to increase crop resistance to climate hazards and adaptation*" (Garcia et al. 2015) and could ensure long-term food security.

Some quinoa CWRs are characterized by growth at even higher altitudes than *C. quinoa* Willd. plots (see Fig. 9 and Table 5). In our study, the seven quinoa CWRs were mainly identified below 3900 m asl. The species that grow at the highest altitudes were *C. ambrosioides* L. (76% of presence above 3900 m asl) and *C. incisum* Poiret (68% of presence above 3900 m asl) (Table 5). These species have been identified on pastureland at altitudes between 3900 and 4100 m asl (Puna agroecological zone). Quinoa is an allotetraploid species with 36 somatic chromosomes, and of the seven quinoa CWRs studied, *C. ambrosioides* L. is the only quinoa CWR with a different number of chromosomes than *C. quinoa* Willd. (Mujica and Jacobsen 2006). The difficulty of inter-specific crosses has restricted the role of wild relatives in the past, but this role can be substantially increased given recent developments in controlled crossing (Peterson et al. 2015) and the use of biotechnologies. Among other aspects, breeders are interested in developing cultivars with higher yields (Bhargava et al. 2006); in this case, *C. ambrosioides* L. and *C. incisum* Poiret can be used in research aimed at the genetic improvement of quinoa varieties.

Whenever a quinoa CWR appeared on a PM or was mentioned in an interview, the probability of finding it decreased with distance from a water source. This was the case of all quinoa CWRs. Over 50% of the cells in which quinoa CWRs were present (on the participatory map) were located at a distance of less than 400 m from a water source (see Fig. 10).

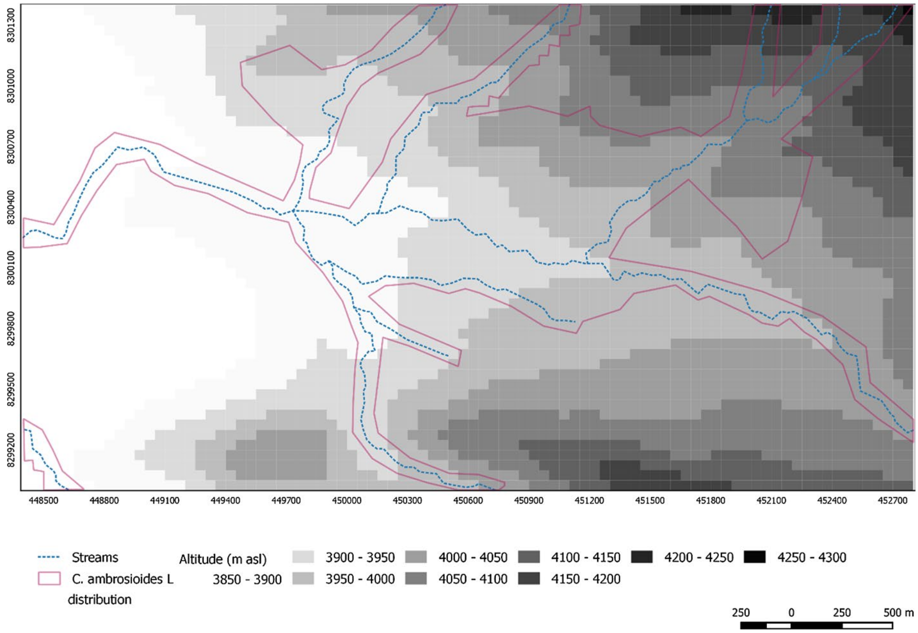

Fig. 9 Geographical distribution and altitude (m asl). Case of *C. ambrosioides* L. in Urani

Table 5 Distribution of the presence of seven quinoa CWRs according to altitude (below and over 3900 m asl), all villages combined, as a % of cells with perceived presence of quinoa species

Quinoa CWR	m asl	
	Percentage of presence (%)	
	Under 3900	Over 3900
C. carnosolum Moq	44	56
C. petiolare Kunth	56	44
C. pallidicaule Aellen	69	31
C. hircinum Schrad	61	39
C. quinoa ssp. *melanospermum* Hunz	41	59
C. ambrosioides L	24	76
C. incisum Poiret	32	68

3.3 Participatory approach

The participatory approach is part of the social utility of science. It aims to co-construct a conservation plan with and for local actors and not against or independently of them (Brown 2003). It does so by trying to identify the broadest common interests between the different actors in the planning process (Pelenc et al. 2015). Our participatory mapping includes in situ conservation activities within a social, economic and territorial context because the management of a territory must be considered in the context of negotiations with other social groups whose interests diverge (farmers, livestock breeders, etc.)

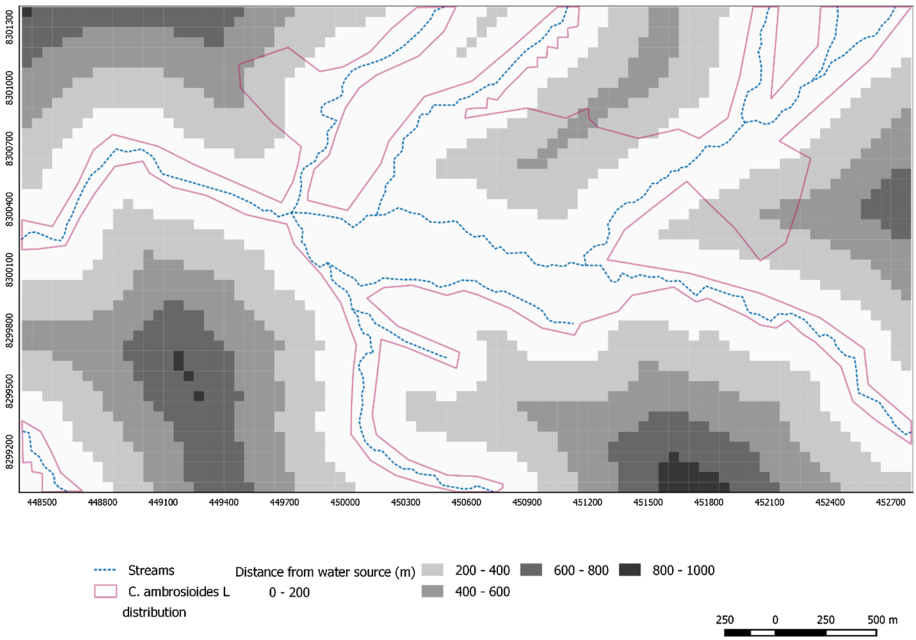

Fig. 10 Geographical distribution and distance from flowing water (m). Case of *C. ambrosioides* L. in Urani

(Narloch et al. 2011). Our participatory maps produced in the field are socially constructed data and must consequently be used with care. Because of the local context of their development, the participatory maps cannot be used for generalization at regional level. The GIS approach described in this article is designed as a complement to the future construction of a participatory model of quinoa CWR in situ conservation.

4 Conclusions

Peru is a "mega-diverse" country with a large number of neglected and underutilized species. One of the arguments concerning quinoa CWRs is lack of knowledge, or in some cases, ignorance, about their distribution and advantages. Applying PM techniques proved to be very useful to characterize the presence and the distribution of CWRs at the agroecosystem scale both for their local management and for biodiversity conservation. PM methods revealed the communities' knowledge of the presence of quinoa CWRs and explored changes in land use. The methodologies we adapted for our study can be used elsewhere for the mapping of other CWRs or other plant genetic resources. The mapping described in this paper could be exploited at greater depth in future research using "chorematic diagrams" as prospective candidates for sharing, discussing and understanding geographic information about quinoa CWR in order to generate specific conservation activities in a given region of interest.

With this paper, we demonstrate that six of the seven quinoa CWRs studied (except for *C. pallidicaule* Aellen) are mainly found along the borders of quinoa plots or in marginal areas. These CWRs display great ability to adapt to new areas of cultivation, especially at high altitudes, over 3900 m asl. The interest of their geographical distribution in the Andean agroecosystem argues that their conservation should mainly take place outside farmers' plots. For any in situ conservation strategy to be effective, this fact thus needs to be taken into account considering the expansion of quinoa's area of cultivation under climate changes and the potential of intercrossing quinoa with its CWRs showing more adaptability for these high altitudes. Our results reveal crucial elements about quinoa CWR distribution that will be very helpful in drawing up further recommendations for in situ conservation of agrobiodiversity. As reported by Louafi et al. (2013), "*there is a pressing need to identify priority areas for the conservation and development of* in situ *conservation strategies*" to ensure the protection of genetic diversity richness of quinoa CWRs (Hunter and Heywood 2010). Monitoring the dynamics of quinoa CWR will have to integrate the complex dynamics of Andean agroecosystems. Given the importance of farmers' participation not only in on-farm conservation activities in their fields but also for developing new conservation activities in field borders where interactions between quinoa and CWRs may occur, incentive mechanisms are likely to be needed. Cost-effectiveness and distributional issues related to the participation of more vulnerable farmer groups (such as the poor, youth and women) are essential for designing appropriate CWR conservation incentive mechanisms as part of further participatory research into agrobiodiversity in situ conservation.

Given the social, economic and political pressures in the new global context of quinoa, especially in the Peruvian Andes, the large genetic diversity traditionally preserved in local Andean cultivation systems is under threat due to increasing demand for quinoa for export that is affecting not only cultivated biodiversity but also CWRs and wild species. Global changes that are affecting quinoa CWR in the Andes highlands require further investigation, but to preserve Peruvian agrobiodiversity, conservation needs to be effective immediately.

National and international conservation policies have to take the complexity of Andean agroecosystems into account and to refer to additional multidisciplinary research works on land cover change dynamics and their importance as drivers of changes in current uses.

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