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Panarchy of an indigenous agroecosystem in the globalized market: the quinoa production in the Bolivian Altiplano

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80 **Abstract**

82 Agricultural globalization is blamed for destructive impacts on small farms in developing countries. Yet,
84 many local societies are proactive in the face of these changes and show high adaptive capacity.
86 Investigating their transformations with an integrative perspective and enough hindsight may reveal
88 some of the bases of their resilience and adaptive capacity. Using field data and the panarchy concept
90 of resilience theory, we analyzed the territorial and social dynamics of quinoa growers' communities in
92 southern Bolivia over the last four decades, a case study of regime shift in a poverty-stricken rural
94 society which deliberately entered the global food market. Linking the dynamics of the household
96 economy to the territorial and social subsystems over several decades, we gained insights into the
98 interactions that shaped the rise of quinoa production in the region. We found that a vivid tradition of
mobility allowing for pluriactivity on- and off-farm, combined with community self-governance, explains
how local populations succeeded in articulating individual agency with collective control over their
commons of land, seed resources, and social rules. Our vulnerability analysis points to landscape
homogenization, social inequity, and increased dependence on external factors as potential sources of
unsustainability. We conclude that, to cope with the changes of unprecedented magnitude they are
facing, local producers should retain social cohesion and autonomous governance, without giving up
on their heritage of mobility and economic redundancy. As regards theory, we identified cross-scale
subsystem configurations critical for regime shifts, and confirm the value of panarchy in capturing
complex socioecological dynamics.

Keywords

100 adaptive cycle – integrated assessment – land use change – rural livelihood strategies –
transformative change

102

Highlights

- 104
- Rural societies in developing countries are not passive in the face of agricultural globalization.
 - Hindsight and interdisciplinarity enlighten the bases of their proactivity and sustainability.
- 106
- We reconstructed the socioecological panarchy of Bolivian quinoa growers since 1970s.
 - Commons governance and off-farm pluriactivity are critical to control latent unsustainability.
- 108
- Particular panarchy configurations give early-warning indicators for critical regime shifts.

110

1. Introduction

112 Quinoa is part of the diet of Andean populations for about 7000 years and has recently become a
114 dietetic, organic, and gourmet commodity for Northern consumers (Bazile et al., 2015; Hellin and
116 Higman, 2003). Family farmers of the southern Bolivian Altiplano initiated this change 40 y ago, but
118 are now worried about the sustainability of their production. Soil erosion, biodiversity loss, and dietary
120 degradation of local populations are pointed by development agents, researchers, and journalists,
122 sometime using simplistic arguments and promoting questionable solutions (Winkel et al., 2012). A
124 simple media campaign alerting consumers to emerging risks—be they real or not—could cause an
126 immediate loss of income for local growers, and social and natural capital could be lost for rural
128 Altiplano communities. Still, quinoa growers are quite efficient farmers and traders: producing a grain
130 considered of little economic value until recently, they have succeeded in selling it, firstly to the
132 neighboring market of Peru, and then to the international market in high-quality specialty foods
(Giuliani et al., 2012; Laguna, 2011; Rojas et al., 2004). Their increasing efficiency was achieved by
134 innovations such as partial crop mechanization or the incorporation in certified food-chains, combined
136 with their traditional risk-coping strategy of mobility and off-farm pluriactivity (Kerssen, 2015; Padulosi
138 et al., 2014; Walsh-Dilley, 2013). In fact, although quinoa growers produce for highly specialized
140 export markets, they are not specialist farmers and are not even permanent dwellers in production
142 areas. This is only one of the paradoxes that characterize quinoa production in this region. An
144 agriculture booming under an extremely harsh environment, an organic and fair-trade production
146 potentially threatening the local socioecosystem, and an opportunistic market searching for regulation:
148 as will be detailed below, quinoa production is in many ways paradoxical.

132 Paradoxes reveal the complexity of reality, and sustainability science could benefit from analyzing
134 and conceptualizing such situations to foster debates on its bases, methods, and goals, including
136 political action and ethical controversies (Clark, 2007; Clark and Dickson, 2003; Müller, 2003;
138 O'Connor, 2006; Vucetich and Nelson, 2010). Complexity is inherent to any human-environment
140 interaction that includes various domains (ecological, social, economic, and cultural), scales (temporal
142 and spatial), and goals (growth, equilibrium, or reduction) (Kajikawa, 2008). The concepts of adaptive
144 cycles and panarchy help summarize part of this complexity. Adaptive cycles model living systems
146 dynamics into successive phases of growth (or exploitation), conservation (or maturity), release (or
148 collapse), and reorganization (or recycling) (Holling, 1973, 2001). Going a step further, panarchy
models identify cross-scale interactions within nested hierarchies of adaptive cycles (Gunderson and
142 Holling, 2002; Walker and Salt, 2006). These conceptual frameworks are powerful for articulating the
144 complex structure of socioecosystems to their dynamics, transformability, and sustainability. They are
146 relevant for many agricultural systems which show resilience in spite of harsh environment, weak rural
148 policies, and low control of local stakeholders over foreign markets (Darnhofer et al., 2010; Darnhofer
150 et al., 2016; Fraser and Stringer, 2009; Petrosillo et al., 2010; Salvia and Quaranta, 2015; Slaymaker,
2007).

148 This paper takes quinoa production in the Bolivian Altiplano as a test case to determine if adaptive
150 cycle and panarchy models have empirical relevance for real sustainability issues. More specifically
we seek to: (i) examine whether sustainability frameworks can yield insights into the paradoxes of an

ancestral food production recently entered into the globalized food market; (ii) identify emergent lessons for local management and policy in the world's major area of quinoa exportation; and (iii) identify scientific issues relevant for research on panarchy and sustainability.

2. Study area and theoretical backgrounds

2.1. Paradoxes, context, and drivers of quinoa success

Although quinoa is a specialized and highly valued export commodity, it is produced by part-time farmers frequently absent from the production areas. The rise in quinoa production triggered many emigrant people to return seasonally to their natal rural community for plowing, sowing and harvest. Here lies a major specificity of the social system sustaining quinoa production: local populations have high mobility and perform multiple farm- and non-farm activities in their originating rural communities and regional urban centers, respectively (Vassas-Toral, 2015c).

The natural environment in this region supports a flourishing export agriculture despite poor soils, cold desert climate, and high altitude. Crop lands, located 3,650–4,200 meters above sea level, receive an annual rainfall of 150–300 mm (regional south-north gradient), with frost on more than 200 days per year (Geerts et al., 2006; Pouteau et al., 2011). This harsh environment makes quinoa nearly the sole option for cropping. Regardless of its drought tolerance (Winkel et al., 2002), quinoa is unable to complete its growing cycle in that region with only the mean annual precipitation. Therefore, quinoa is grown in a 2-yr cycle (Joffre and Acho, 2008). After harvest, the land is left unseeded for a year but plowed so that the rainfall partly accumulates in the soil and becomes a water reserve available for the following year's crop (Giuliani et al., 2012)(**Supplementary Material A**). To our knowledge, quinoa is the only cash crop produced under low-input rainfed agriculture in extremely high, cold, and arid mountains.

Another paradox of quinoa is its status as a health food produced in small farms mostly under organic and fair-trade certification, but that might generate ecological and social ruptures. This would be opposite to the benefits expected from low-input organic agriculture in rural societies cultivating communal land supposedly governed by ancestral rules and traditional ecological knowledge. Researchers and journalists have blamed local growers for short-sightedness and individualism, but often with ill-founded arguments (Jacobsen, 2011; Winkel et al., 2014; Winkel et al., 2012). In fact, Bolivian farmers and decision makers are well aware of the rising vulnerability of their agroecosystem (Kerssen, 2015). Local and individual initiatives at the origin of the expansion of the crop now seek collective regulations involving local authorities, growers' unions, rural development agencies, the central government, and international food industries. Moreover, and contrary to the common situation of rural poor excluded from their own natural capital (De Schutter, 2011; Kajikawa, 2008), Bolivian quinoa growers fully control access to their land resources and own on-farm selected seeds (Baudoin-Farah, 2009), and take opportunistic advantage of global trends in food demand.

2.2. Adaptive cycles and panarchy

Adaptive cycles model the dynamics of a living system into successive phases of growth or exploitation (r), conservation (K), release (Ω), and reorganization (α), which provides for system

renewal (Holling, 1973, 2001) (**Fig. 1A**). Cycle speed and amplitude are controlled by two system properties: connectedness (or degree of organization) and potential (or amount of resources). Connectedness and potential are defined depending on the ecological, economic, or sociocultural specificities of the considered adaptive cycle. Novelty in adaptive cycles may appear by the end of the reorganization (α) phase, when low internal control (low connectedness) allows for external opportunities (or "chance events") to nucleate and open unexpected options for a new growth phase. Adaptive cycles should not be seen as 4-phase sequences "repeating themselves over history" (Bunce et al., 2009): depending on the adaptive capacity of the system, transitions may occur between virtually all phases (Walker and Salt, 2006). To avoid the deterministic connotation of the term "cycle", we adopt hereafter the expression "adaptive loop" used by various authors (e.g. Delcourt and Delcourt, 2004; Marsh, 2016).

A complete panarchy model emerges when a nested hierarchy of adaptive loops is identified and cross-scale interactions are recognized (Gunderson and Holling, 2002; Walker and Salt, 2006) (**Fig. 1B**). A special case of cross-scale interaction, called "revolt" connection, occurs when a small-scale subsystem enters the Ω phase while the surrounding system is in late K phase (intermediate loop in **Fig. 1B**). This uniform and rigid intermediate-scale system is vulnerable to the propagation of a subsystem collapse ("revolt" arrow from the lower-scale subsystem at Ω) which may trigger a major catastrophic event. A typical example of such dynamics is the propagation of a local, small-scale fire (an Ω release phase) within a monospecific and even-aged forest in an advanced K phase. The renewal of the intermediate-scale subsystem will depend on the resources stored at the upper-scale subsystem ("remember" arrow). Typically, the recovery of a burned area will draw upon the seed bank and the surviving species present in the surrounding territory.

3. Methods

To gain insights into the social and ecological drivers of the agricultural sustainability in the world's leading area of quinoa production, a research-action project was implemented from 2007 to 2010 in rural communities of the departments of Potosi and Oruro in the southern Altiplano of Bolivia. This participative multidisciplinary research involved specialists in agroecology, agronomy, geography, and socioeconomics, with quinoa grower families and local stakeholders (workers in development agencies, quinoa growers' unions, local authorities, etc.). The results of this sustainability assessment are detailed in Vassas-Toral (2015c), Vieira-Pak (2015) and Winkel et al. (2015), and only relevant information will be retained here.

3.1. Socioeconomic surveys

The patterns of mobility and pluriactivity among quinoa growers from the study area were characterized in a socioeconomic survey conducted in 2007 and 2008 on 149 households from five rural communities (San Juan, Chilalo, Otuyo, Candelaria, Palaya). Using interviews and livelihood stories, we retraced the residential and professional trajectories of 170 members of quinoa grower families (**Supplementary Material B**). Different types of spatial mobilities were considered: (i) the migration of individuals, defined as a temporary or permanent change of residence, including mobility of bi-residential migrants, (ii) the seasonal and circular mobility of migrants linked to the agricultural

228 activity in their community. Collected data were structured by mapping the successive residencies of
each surveyed individual, and retracing the chronology of his/her life sequences (see Vassas-Toral,
230 2015abc, for detailed results). A second survey using semi-directive interviews was conducted in 2007
on 36 households from six communities (Buena Vista, Chacoma, Chilalo, Jirira, Playa Verde
232 Murmuntani, San Agustin) focusing on the household economy and the farming practices of quinoa
growers (see Acosta-Alba, (2007) for detailed results).

234 3.2. *Land use mapping*

Cropland expansion in the last five decades was mapped on a sample of six communities
236 representative of quinoa production in the study area, with altitudes ranging from 3700 to 4100 masl,
at distances from the shores of the Salar of Uyuni varying from 2 to 40 km (**Supplementary Material**
238 **C**). Some localities are mostly flat plains (Otuyo, Candelaria), while others are mostly sloping (Chilalo)
or with mixed plain/slope landscapes (Capura, Chacoma, Palaya).

240 Cropland mapping was based on aerial photographs and high-resolution satellite images. Early
panchromatic aerial photographs (Instituto Geográfico Militar, Bolivia) taken from 1961 to 1963 show
242 the croplands before the quinoa crop expansion. EROS satellite images (United States Geological
Survey, USA) dated from 27/04/1972 coincide with the initial phase of quinoa expansion in the Salar
244 region. SPOT satellite images (Centre National d'Études Spatiales, France) taken between 2005 and
2008 show the phase of fast expansion of the quinoa crop. After digitalization, the ground resolution of
246 the aerial photographs was 2 m. Satellite images had a ground resolution of 10 m for EROS data, and
20 to 28.5 m for SPOT (depending of the year of acquisition). Image distortions due to the sensors
248 and the uneven ground surface were rectified using a digital elevation model (SRTM 90m). All the
images were georeferenced in the UTM 19 S projection, with the datum Provisional South American
250 1956 mean. Croplands were identified visually in the images as polygons of bare soil areas, clearly
differentiated from the steppic vegetation of the surrounding pastures and non-agricultural land. After
252 extraction with the ENVI 4.2 software, the cropland polygons identified were superimposed to a digital
elevation model with a 20-m resolution using the ArcGIS/ArcView software. This allowed examining
254 the altitudinal distribution of crop areas in each community, as well as their temporal changes across
successive images.

256 3.3. *Vulnerability assessment*

Sustainability science needs vulnerability assessments integrating the human and environmental
258 components of socioecosystems. The "vulnerability scoping diagram" presented by Polsky et al.
(2007) provides multidisciplinary research teams with a common framework for organizing dissimilar
260 information about the three dimensions of vulnerability in human-environment systems exposed to
hazards, namely: exposure, sensitivity and adaptive capacity (Polsky et al., 2007; Turner II et al.,
262 2003). We used this conceptual diagram as a guide for the collection of data, the definition of
indicators and the specification of a set of hazards and outcomes relevant for quinoa production in the
264 study area (**Supplementary Material D**).

4. Results and discussion

266 4.1 Vulnerability assessment of southern Altiplano agriculture

268 Our multidisciplinary research in the Bolivian Altiplano identified quinoa field expansion as the
270 major indicator of environmental change in the study area (Winkel et al., 2015). Quantitative mapping
272 of six communities shows that total cropland area from 1963 to 2006 increased by 332%, mostly in flat
274 plains suitable for mechanization (**Fig. 2**). National statistics show that the total quinoa crop area in
276 Bolivia jumped from approximately 22,600 ha in 1963 to 42,431 ha in 2006, and 173,960 ha in 2014
278 (FAOSTAT, 2016). Quinoa yield variations and inequity in household incomes provide further
280 vulnerability indicators. A socioeconomic survey of 36 households in 2007 revealed two consequences
282 of the recent land use changes: (i) mean areas (\pm CV%) of individual quinoa fields increased from 3.1
284 ha \pm 4% on slopes, to 9.3 ha \pm 39% in plains; and (ii) mean quinoa yield (\pm CV) decreased from 0.91
286 t·ha⁻¹ \pm 13% on manually cultivated slopes to 0.60 t·ha⁻¹ \pm 13% on mechanically cultivated plains. The
288 increased CV in field area reflects a growing inequity among growers. Wealthy growers and tractor
owners capture and cultivate much larger land areas than poor growers. This growing inequity affects
household monetary incomes, which ranged from 200–18,000 US\$ per year among the 36 surveyed
families. Independent studies report similar socioeconomic changes (Astudillo and Aroni, 2012; Félix
and Villca, 2009; Kerksen, 2015; Ormachea and Ramirez, 2013). The grain yield decrease reflects the
sensitivity of quinoa production to mechanized cropping in plains. Soil overexploitation has been
claimed as the cause of reduced yield (Félix and Villca, 2009; Jacobsen, 2011). However, other
causes could include poor seed germination in mechanically sowed fields, increased frost risks in
lowlands, and pest proliferation in large monocultures. These and other ecological and social
indicators of the local agroecosystem show its vulnerability to recent land use and crop management
changes. Still, quinoa growers adaptively respond to new market opportunities, and display
commitment to diversified livelihood strategies, despite the unprecedented success of the global
quinoa market (Kerksen, 2015; Vassas-Toral, 2015c; Walsh-Dilley, 2013).

290 Grasping the ins and outs of the ongoing mutation of the quinoa socioecosystem requires adding to
292 this static review a dynamic scaling of the structures and processes driving the system. To this end,
294 recent changes in social context, household economy, and territorial patterns, were plotted in adaptive
loop models, and we analyzed where the growth, conservation, release and reorganization phases of
the adaptive loops fit these changes.

4.2. Adaptive loops in the southern Bolivian Altiplano

296 4.2.1. Social subsystem

298 Historically, human demography in this highland region has been characterized by pendular
300 migrations to nearby Andean valleys or to the Pacific coast to exchange salt and agricultural goods or
302 to temporarily escape severe drought or frost in the Altiplano (Murra, 1984). Cycles of prosperity and
collapse in Bolivian and Chilean mining industries since the 19th century also contributed to population
movements in the region (Platt, 1995). From 1950 onward, distant cities attracted ever more people in
search of job opportunities and new lifestyles (Vassas-Toral, 2015c; Walsh-Dilley, 2013). Yet, the
most recent Bolivian census (2012) shows an incipient repopulation dynamics, suggesting a possible
304 re-peasantization of the southern Altiplano (Kerksen, 2015). At the same time, conflicts concerning

land access are proliferating in the communities because migrants with double residency in the city and the community claim land access rights inherited from their parents (**Supplementary Material B**). The national census registers these migrants in the community, which allows them to reaffirm local land rights. These migrations are generally seasonal or temporary, and quantifying whether rural communities are effectively regaining population or undergoing a demographic decline remains a complex issue (Laguna, 2011; Vassas-Toral, 2015c).

Regulations intended to guide local land access and use are also complex and ambiguous. The 1952 agrarian reform had little impact in this inhospitable region neglected by great landlords (Laguna, 2011; Walsh-Dilley, 2013), and a multiplicity of rules have subsequently piled up. Local rules and customs transmitted and controlled by traditional indigenous authorities co-exist with national laws enacted by the central government. As regards crop production, collective norms resulting from local consensus compete with food industry controls, foreign trade regulations, and intellectual property rights on quinoa varieties. Most of these rules are not uniformly applied in the region due to low rates of acceptance and lack of practical implementation. Some development agencies designate this plethora of non-uniform regulations as a "legal vacuum" (Félix and Villca, 2009). Thus, plotting population demography and social regulations as the respective potential and connectedness axes of the social adaptive loop in the region (**Fig. 3A**), the current situation appears to be a long-lasting reorganization (α) phase, with emigrants temporarily mixing with returning people, and with mixed rules of land management still not implemented. Notably, reorganization does not occur here after a collapse (Ω) phase of ancient local societies, but rather as progressive adjustments of their population dynamics and land management rules.

4.2.2. Household subsystem

Amid this varying social framework, the quinoa economy has flourished rapidly in the region. Quinoa as a cash crop expanded during 1970–1980 from the southern border to the western and northern borders of the Salar of Uyuni. This expansion was initiated in response to: i) massive job cuts in the mining and public sectors due to structural adjustment plans, ii) increasing demand for quinoa in neighboring Peru, a country much more populated than Bolivia and where urban consumers appreciated quinoa, which was not the case in Bolivia at that time. In 1970, a Belgian development aid program donated tractors to local, poor communities, a case of "chance event" which favored that initial phase of commercial production for the national and Peruvian markets (Kerssen, 2015; Laguna, 2011). In the mid 1980's, Bolivian quinoa growers opportunistically responded to new, increased demand from North America and Europe for gluten-free, protein-rich, organic food, often under fair-trade label. These new markets did not supplant the Peruvian market, which accounted for up to 40% of total Bolivian quinoa exports by the 2000's, though mostly as unofficial trade (Gandarillas et al., 2015; Laguna, 2002; Laguna, 2011; Rojas, 2011). Thus, local quinoa growers beneficially serve a diversity of quinoa market niches. Yet, this success did not spur them to fully specialize in quinoa production. The vast majority maintain off-farm activities and temporary migration (**Supplementary Material B: Table B-1** and reported individual cases), with a few even keeping on with llama and sheep rearing, despite lower economic profitability. Diversified household trajectories result from this redundancy in more or less rewarding activities involving different family members (Laguna, 2002;

Vassas-Toral, 2015c). This risk-coping strategy may prove to be useful under the market distortions
346 observed since 2014, when Peru began to supplant Bolivia in the international quinoa market
(Mercadero, 2015). If the household economic loop is plotted with quinoa income and market
348 connection as the potential and connectedness axes respectively (**Fig. 3B**), then quinoa growers of
the southern Bolivian Altiplano appear to follow multiple trajectories between the growth (r) and
350 conservation (K) phases, resolutely engaged in commercial production but avoiding connecting their
household activities exclusively to that opportunistic venture. Partial back loops exist, and moving from
352 one trajectory to another is relatively easy (Vassas-Toral, 2015c; Vieira-Pak, 2015). For example, if a
quinoa grower opted for the specialized certified market, he can easily move to the less constraining
354 and almost equally rewarding conventional market, or may choose to invest more effort in off-farm
activities (Ofstehage, 2012). However, achieving this flexibility is not easy for the poorest households
356 (single mothers or elderly single people) due to the lack of human and financial capital. The current
variety of household trajectories also reflects past social and economic disparities, which are
358 exacerbated by quinoa commercialization (Vassas-Toral, 2015c; Vieira-Pak, 2015).

4.2.3. Territorial subsystem

360 This subsystem appears more constrained than the household subsystem. A single quinoa harvest
is the product of a 2-year cycle and, thus, represents a doubled land area: the current cultivated field,
362 plus the plowed fallow waiting for the next year's crop (**Supplementary Material A**). Quinoa
expansion pushed herbaceous and shrub species to marginal lands. These wild plants hardly
364 recolonize the fallow due to their slow dynamics and the depletion of soil seed banks (Joffre and Acho,
2008). Conversion of pastures into quinoa fields thus results in an essentially irreversible change in
366 land use, with a striking loss of landscape patchiness. Bare fallows are exposed to strong and frequent
windstorms. The newly converted quinoa fields are mostly located in flat lowlands prone to frost due to
368 cold air drainage at night (Pouteau et al., 2011). Frost events in 2007 and 2008 revealed the
vulnerability of lowland production with 2008 referred to as a tipping point in the quinoa market (Núñez
370 de Arco, 2015). Production was low due to these frost events but commercial demand remained high,
which caused the quinoa price to increase by 175% from 2006 to 2008 (Gabriel, 2013). These high
372 prices encouraged farmers to continue taking the risk of cultivating quinoa in the lowlands.

Most of the areas apt for mechanized cropping have already been converted into quinoa fields, and
374 many communities can no longer respond to the continuing demand for new croplands. A decline of
soil fertility in the region has been denounced (Félix and Villca, 2009; Jacobsen, 2011), allegedly
376 showing that the ecosystem's carrying capacity has been exceeded. However, this opinion has not
been corroborated by any *in situ* study, and the evidence used to support it consists of gross regional
378 or national grain yield statistics, which mix concomitant effects of climate, soil, pests, and poor seed
germination in mechanized crops (Walsh-Dillely, 2013; Winkel et al., 2012). While soil degradation
380 remains debatable, land conversion to quinoa cropping thus appears as the most reliable indicator of
the ecosystem's carrying capacity reaching an upper limit. Land conversion resulted from the decision
382 of local producers to favour quinoa at the expense of the economically less-rewarding components of
their agricultural system, namely pastures and potato crops (Laguna, 2011; Walsh-Dillely, 2013). After
384 a sustained growth phase (r), the territorial adaptive loop appears locked into an ending conservation

phase (*K*) with contiguous quinoa monocultures resulting in minimum landscape patchiness (maximum field connectedness, x-axis), and the maximum available land area (natural capital, y-axis) already converted to cropland in most communities (**Fig. 3C**).

4.3. Panarchy of the quinoa's rise

4.3.1. Nested adaptive loops

A hierarchy linking the adaptive loops for social, household, and territorial subsystems is organized with respect to time and population scales (**Fig. 4**). The household loop occupies the lower scales since it primarily refers to individual decisions regarding annual on-farm and off-farm activities. Typically, household dynamics occur on a 1- to 6-month scale, e.g. to choose temporary migration or which parcel to plow. The territorial loop is located at the larger landscape scale, with a minimum 2-year cycle for field crop, and a grossly decadal dynamics for land use changes and natural vegetation regeneration. Next, the social loop operates from the community to the nation and from decadal to multidecadal periods corresponding to background demographic trends and land access/land use regulations. Demographic and institutional changes commonly show slower dynamics than do ecological changes (Young, 2010). In fact, the social loop could be extended up to the global level, as the current international market directly affect the local agrarian dynamics through the commercial demand and trade regulations (Gabriel, 2013; Giuliani et al., 2012; Rojas, 2011).

The phases currently reached by each adaptive loop show that the territorial component is locked in a potentially vulnerable conservation phase (*K*) between household and social loops (**Fig. 4B**). Yet, a "revolt" connection (see **Fig. 1B**) amplified by this broad-scale vulnerability seems unlikely, as the lower-scale household economic loop is far from the release phase (Ω). The diversified household livelihood strategies, associated to rural-urban mobility (**Supplementary Material B**) (Laguna, 2011; Vassas-Toral, 2015c) prevent any locking into a specialized commodity chain. If commodity chains were to experience sudden collapse, it would trigger the abandonment of croplands—a release phase Ω in the territorial adaptive loop—but without catastrophic impact on households which opportunistically maintain their economies between growth (*r*) and conservation (*K*) extremes by repeated migration and shifting between farm- and non-farm activities (**Fig. 3B**).

Because the trajectories of many agroecosystems lack of certain phases or appear stuck in particular stages of the adaptive loop, some authors call into question the usefulness of Holling's model in resilience studies (Bunce et al., 2009). Also, it has been argued that Gunderson and Holling's theory is more adequate to describe ecological processes than to capture adaptive responses related to human decisions (Fraser and Stringer, 2009). Both critiques should be relativized since: i) adaptive loops are not deterministic 4-phase sequences: the panarchy theory states that alternative paths and shortcuts might occur within adaptive loops, some of which open the way towards resilience (Gunderson and Holling, 2002; Walker and Salt, 2006); besides, stagnation in one adaptive loop of the system does not impede rapid changes in other components, as found comparing the social subsystem to the other two components in our case study; ii) in agroecosystems in particular, alternative paths of resilience depend strongly on human decisions: our analysis of quinoa growers' strategies demonstrates that these decisions are adequately captured by an adaptive loop model.

424 Thus, contrary to the suggestion of Fraser and Stringer (2009), it seems not justified to restrain the
panarchy approach to the environmental component of the socio-ecosystem. In fact, the main interest
426 of the panarchy theory lies in its capacity to encompass environmental as well as social, economic,
and institutional dynamics: disaggregating the environmental and human components of change may
428 be necessary in an early phase of analytical assessment but then, ordering them across nested
hierarchies to reveal their interdependencies is what makes the value of this transdisciplinary and
430 relational approach (Darnhofer et al., 2016; Kajikawa, 2008; Scholz and Steiner, 2015; Sundstrom et
al., 2014).

432 4.3.2. *Retroactive search for causalities*

A retroactive examination of quinoa panarchy can provide insight into recent events (Westley,
434 2002) and identify circumstances, actors, and organizations that shaped the historical development of
quinoa production in southern Bolivia. At the end of the 1960s, crop production and pastoralism
436 provided low income due to the lack of markets, conducting a growing part of the local population to
frequent and prolonged migration to cities and other countries in search of non-farm activities. Thus,
438 the territorial and household subsystems were in a reorganization (α) phase but with still uncertain
prospects as regards local development (**Fig. 4A**). The declining rural population was ageing, which
440 caused local institutions and social rules to lose vitality. The social subsystem found itself caught
between collapse (Ω) and reorganization (α) phases (**Fig. 4A**). The wealthiest among the permanent
442 rural dwellers were those who owned a substantial number of sheep and llamas and had greatest
access to communal pastures. Rural migrants with savings from off-farm activities were also in a
444 favorable position to assert land usufruct rights which families always retain in their natal communities.
Both categories of households had the potential to invest capital in new economic activities. As
446 regards the territorial land resources at that time, there was little competition for land access and little
control on land use due to the low interest in farming activities. In 1970, these circumstances enabled
448 some individuals to respond opportunistically to newly available tractors and the continuous Peruvian
demand for quinoa. New quinoa fields were opened in common pastures in flat lowlands, easily
450 mecanizable, lacking individual property rights, and considered of little value. The social, territorial,
and household subsystems were then positioned in similar reorganization (α) phases, ready to
452 produce a cascade of new patterns across the hierarchy of adaptive loops—viz the panarchy—of the
local quinoa production (**Fig. 4A**, dashed line). In the following years, however, the dynamics of the
454 three adaptive loops rapidly diverged. This led to the present situation (**Fig. 4B**) with multiple
household activities and adjustments (loop E between r and K), maximum pressure on land resources
456 (loop T near K), and prolonged experimentation and uncertainty in social and institutional issues (loop
S near α).

458 4.4. *Lessons for local development*

The rise of quinoa production in southern Bolivia began 40 years ago. Large changes have
460 occurred in society, agrotechnology, and economics which preclude a mere return to traditional
agricultural models. The transition from ancestral manual cropping to mechanized cropping exemplifies
462 an agricultural revolution (Mazoyer and Roudart, 2006) that triggered an unprecedented landscape

change. As in other rural societies in the Andes (Lennox and Gowdy, 2014; Zimmerer, 2013), new
464 challenges regarding land management have emerged, which require new visions for a sustainable
future.

466 Panarchy highlights the importance of individual initiatives for adaptability of quinoa growers.
Mobility and pluriactivity are key components of the household's functional redundancy, a concept that
468 date back to an ancestral economic mobility (Núñez Atencio and Hall, 1982; Saignes, 1995), and has
been adjusted to current technical and trading innovations. With a singularity however: for the first time
470 in centuries, local agriculture is an economically attractive enterprise, which stimulates seasonal
returns of migrants to their natal communities (Walsh-Dilley, 2013). Since growing quinoa entails a
472 hereditary access to communal land, it enables autonomy to local populations, which is radically
different from selling their labor force in cities or mining industries. This change was quickly
474 assimilated by rural dwellers who then adopted a patrimonial logic and tried to hoard the largest
possible cropland area, within the bounds of the customary land tenure rules. This quantitative
476 patrimonialization rapidly reached the limits of available space, and a qualitative patrimonialization is
now needed to improve cropping practices, and negotiate comprehensive agreements for using
478 common land resources.

Thus far, the social system also contributed to changes in quinoa production, though in an
480 ambiguous way. Heirs of a tradition of self-governance and rotating public responsibilities, local
authorities and quinoa growers' unions did not exert any strong social control on their own members
482 until recently. This behavior enabled the free transformation of an agroecosystem with manual
cropping and long fallows to mechanized monocultures and short fallows. The prevalence of oral rules
484 during the early transformation may have promoted these changes. Ambiguity in the social control
system also appears to be part of a logic of the local institutions to avoid contradictory commitments to
486 the traditional subsistence system and the market-oriented system. Rivalry between local authorities
and quinoa growers' unions could emerge, the latter relaying the top-down market demand for
488 international norms of sustainable production, and the former engaging in a bottom-up renovation of
local ancestral rules governing their commons. Both adaptability and transformability are essential for
490 resilience (Walker and Salt, 2006). In the southern Bolivian Altiplano, the household adaptability and
the social transformability may result in contradicting influences (see subsequent discussion on
492 adaptation traps). These properties rely primarily on the capacity of the institutions controlling common
resources to evolve by self-transformation, which requires social cooperation and commitment to
494 avoid centralized regulation or privatization (Vollan and Ostrom, 2010).

The observed territorial vulnerability suggests a central role for the landscape structure in
496 determining the agroclimatic risks faced by quinoa growers. Frost risks persist in the region despite
climate warming trends (Pouteau et al., 2011; Rambal et al., 2015), and monocultures in vast lowland
498 areas may worsen drought, pest outbreaks, and soil degradation. Local agronomic institutes are
conducting participatory research on these issues to design innovative land management practices
500 (Bonifacio et al., 2014). Numerous communities have begun using integrated organic pest
management and planting living fences against wind erosion (Lino et al., 2014). These agroecological
502 practices promoted by farmers' unions and NGOs illustrate social learning and innovation drawn from

504 local experimentations (Knight and Meffe, 1997). Pilot experiments on new payment for ecosystem
service schemes are another example of collective action to conserve local quinoa biodiversity
(Narloch et al., 2015).

506 The southern Bolivian Altiplano socioecosystem conforms to the conditions for adaptive land
management—persistency, change and uncertainty (Holling, 1973). Persistency of the local society
508 relies on mobility and flexibility of the growers' families, self-governance of their communities and
organizations, and material and symbolic territorial valorization. Changes in land use and household
510 activities enable land transformation as new opportunities appear. This illustrates how local
populations cope with, rather than confront, uncertainty due to fluctuations in climate or economy
512 (Walsh-Dilley, 2013). Similar synergies between off-farm migration, governance of the commons and
innovation leading to social and ecological resilience have been described in smallholders
514 communities engaged in agricultural intensification in other regions of Bolivia (Zimmerer, 2013). In
other Andean regions, however, the sustainability of smallholder agriculture may rely on different
516 bases, depending on local settings of land tenure, social organization, opportunities for off-farm
activities and market access (Lennox and Gowdy, 2014; Padulosi et al., 2014; Sietz et al., 2012).

518 Although quinoa growers tried to adaptively manage their territorial resources, there are several
indicators of latent unsustainability. In some communities, vast quinoa monocultures have generated
520 conflicts over land access (Laguna, 2011; Vassas-Toral, 2015c). This partly resulted from familial and
social agreements that permit families to cultivate without being present in the community. These are
522 the same agreements that support household adaptability and territorial transformability, illustrating an
adaptation trap in which incremental adjustments and economic redundancies delay local stakeholder
524 awareness of agroecosystem vulnerabilities (van Apeldoorn et al., 2011). All stakeholders do not
share the same capacity to access social and territorial resources, or to activate multiple options of
526 economic redundancies. The poorest families with the lowest social capital also are the most
disadvantaged in competition for new croplands. In this context, livelihood diversification further
528 increases social inequity among families. An undesirable system could thus emerge in which
household adaptability generates a trap that could threaten social equity and ecological sustainability.

530 To face such complex issues, development NGOs, state or private services offer their expertise.
Indeed, the rationality of local populations is no longer the only one that applies in the Bolivian
532 altiplano: new foreign actors introduce divergent opinions and practices, which increases the quinoa
socioecosystem complexity. Now, complexity also can cause unsustainability (Fisk and Kerherve,
534 2006). Some of the new foreign actors promote short-sighted interests and irreversible technological
innovations like irrigation or certified seeds, with a lack of integrative vision which has great potential
536 to worsen the situation. These actors reinforce the command-and-control approach to natural resource
management (Briggs, 2003; Holling and Meffe, 1996). If this approach is followed, local societies
538 would become increasingly dependent on risky technologies, bank credits, and rationales external to
the local social and environmental context. Southern Altiplano populations are fluent with foreign
540 markets and different cultures, as part of their inherited lifestyle based on active mobility and trade
exchange (Stern, 1995). Yet, the unprecedented magnitude of these emerging socioeconomic
542 interactions raises concerns (Lennox and Gowdy, 2014). Local policy-makers and stakeholders should

cautiously evaluate these new forms of interference and dependence before making decisions that
544 bind the region and its inhabitants to a future they may not desire. Such a loss of autonomy would
challenge the goals of good living and food sovereignty recently integrated into the Bolivian
546 constitution (Cockburn, 2013; Kerksen, 2015; Mercado et al., 2016).

5. Conclusion

548 This study reminds us that panarchy is more than just the adaptive loop of a specific subsystem: a
panarchy is essentially a *dynamic hierarchy of several subsystems*—environmental and human—that
550 interact over nested scales of time and space. Using this multi-dimensional and dynamic perspective,
we were able to elucidate part of the sustainability of quinoa production in the southern altiplano of
552 Bolivia during the last four decades, firstly by identifying the characteristics of the households, the
environment, and the communities at stake. Then, by examining interactions between these nested
554 components, we found that the adhesion of local populations to self-governance and the tradition of
temporary migration, instead of causing social stagnation, had indeed stimulated the rapid
556 transformation of their territory. This is explained by processes operating at different scales: a limited
social control in the initial phase of crop expansion, the interdiction for foreigners to access land
558 resources in the communities, and household's pluriactivity as a continued risk-coping strategy despite
the boon of the quinoa trade.

560 While nested hierarchies of scales may be relatively trivial to detect (household, community, state,
etc.), their driving interactions are less obvious because the underlying dynamics often require time to
562 develop and become apparent. Conceptual efforts should be made to enrich the typology of these
interactions and discover new cross-scale connections beyond the well-described configurations of
564 revolt or memory (Walker and Salt, 2006) (**Fig. 1B**). The synchronous alignment of nested
subsystems in reorganization phase (α) found in this study is an example of such critical
566 configurations (**Fig. 4A**). It reveals a situation open to innovations, chance events, and regime shifts
cascading across subsystems. This alignment pattern within a complex socioecosystem may provide
568 an early-warning indicator, a form of intrinsically cross-scale transition signal (Scheffer et al., 2009).
Despite such conceptual advances, scholars and decision makers should accept that no panacea
570 exists for modeling or governing socioecosystems (Anderies and Janssen, 2013; Brock and
Carpenter, 2007; Ostrom, 2007). These are controlled simultaneously by fast and slow variables, and
572 go through incessant co-adaptation processes that continuously change their structure, function, and
interrelationships, with inevitable dysfunctions (Reynolds et al., 2007; Stafford Smith et al., 2007). In
574 such systems, static equilibria never arise and top-down command-and-control governance fails
(Holling and Meffe, 1996). Instead, continuous adaptive learning and polycentric governance copes
576 with uncertainties and opportunities, particularly in agricultural or natural resource management
(Anderies and Janssen, 2013; Darnhofer et al., 2010). Because panarchy models help identifying
578 people and organizations responsible for the choices and consequences of development policies, an
ethical issue rises up: topics of equity, sustainability, and autonomy of local societies stem from these
580 choices (Vucetich and Nelson, 2010), and thus challenge the social utility of scholarly research
(Thompson, 2008). Agroecosystems offer fertile ground for such ethical questioning in sustainability
582 science.

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862

864 **FIGURE CAPTIONS**

866 **Fig. 1.** Stylized representations of an adaptive loop (A) and a panarchy (B) showing "revolt" and "remember" connections (adapted from *Panarchy*, Gunderson & Holling, eds. 2002)

868 **Fig. 2.** Cropland expansion in the southern Bolivian altiplano from 1963 to 2006. (A) Palaya community. (B) Altitudinal distribution of total cropland area in 6 communities of the southern Bolivian Altiplano.

870 **Fig. 3.** Adaptive loops for the social subsystem (A), household subsystem of quinoa growers (B), and territorial subsystem (C) in the southern Bolivian Altiplano.

872 **Fig. 4.** Quinoa panarchy in the southern Bolivian Altiplano from the 1970's (A) to the present (B). Dotted lines connect the relative positions of the adaptive loops of household economy (E), territorial land resources (T), and social regulations (S) in each time period. Black arrows in (B) indicate changing alternatives in household economy.

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SUPPLEMENTARY MATERIAL CAPTIONS

878 **Supplementary Material A.** The quinoa crop cycle in the southern altiplano of Bolivia.

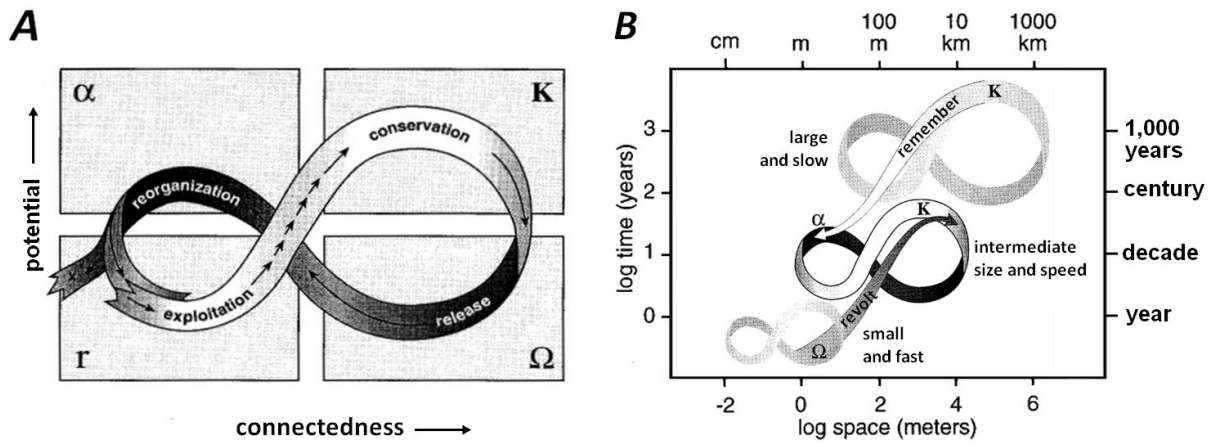
Supplementary Material B. Mobility and migration among quinoa growers.

880 **Supplementary Material C.** Localisation and cropland area in six communities of the southern altiplano of Bolivia from 1963 to the 2000's.

882 **Supplementary Material D.** The Vulnerability Scoping Diagram.

FIGURES

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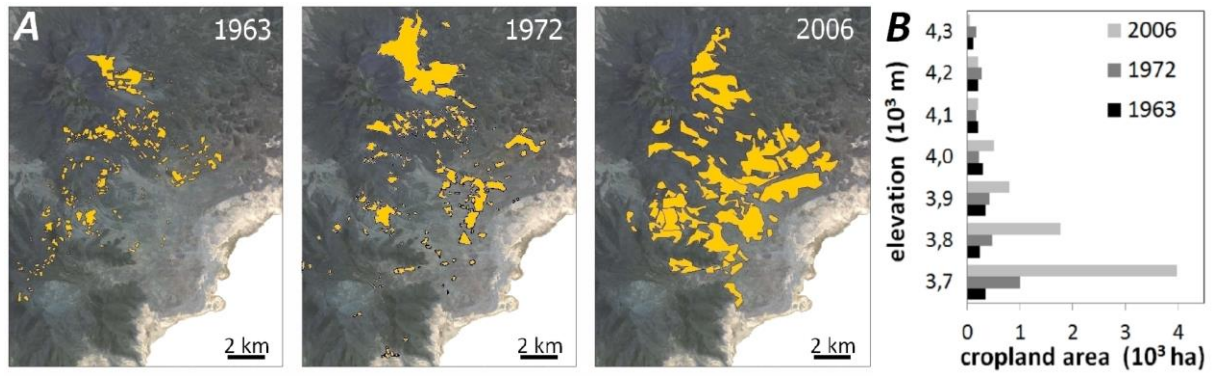
888 **Fig. 1.** Stylized representations of an adaptive loop (A) and a panarchy (B) showing "revolt" and
 890 "remember" connections (adapted from *Panarchy*, Gunderson & Holling, eds. 2002).

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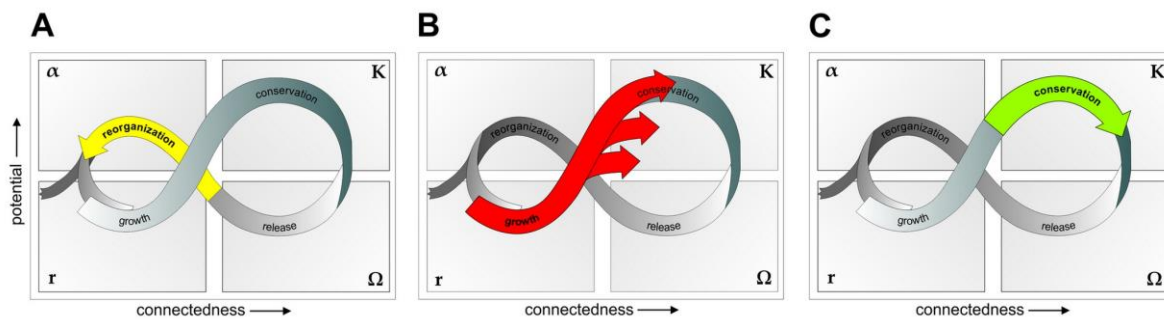
FIGURES

894



896 **Fig. 2.** Cropland expansion in the southern Bolivian altiplano from 1963 to 2006. (A) Palaya
898 community. (B) Altitudinal distribution of total cropland area in 6 communities of the southern Bolivian
900 Altiplano.

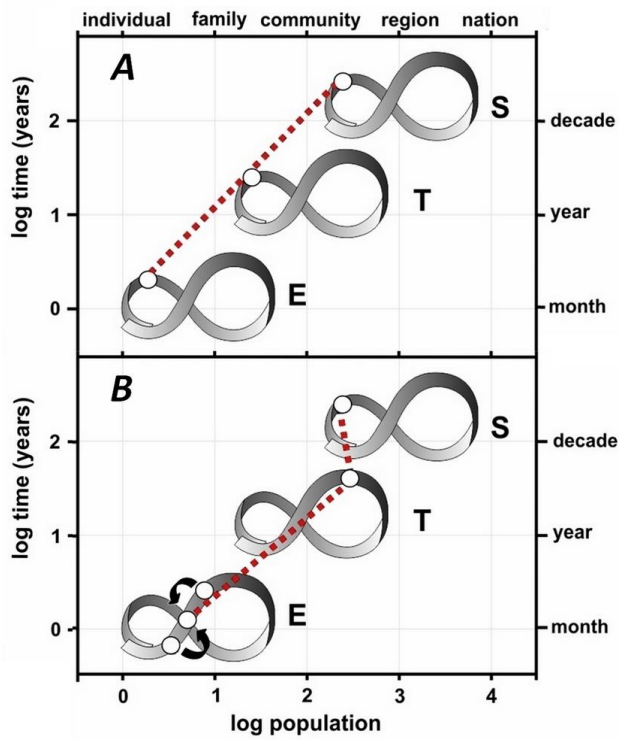
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Fig. 3. Adaptive loops for the social subsystem (A), household subsystem of quinoa growers (B), and territorial subsystem (C) in the southern Bolivian Altiplano.

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914 **Fig. 4.** Quinoa panarchy in the southern Bolivian Altiplano from the 1970's (A) to the present (B).
 Dotted lines connect the relative positions of the adaptive loops of household economy (E), territorial
 916 land resources (T), and social regulations (S) in each time period. Black arrows in (B) indicate
 changing alternatives in household economy.

918

SUPPLEMENTARY MATERIAL

920

Supplementary Material A. The quinoa crop cycle in the southern altiplano of Bolivia

922 Cultivation in that region has to cope with two major climatic constraints: a large frost period from April
 924 to October and a short rainy season between December and March. In fact, frost events may occur
 926 even during the rainy season, and the mean annual rainfall (lower than 250 mm) does not cover the
 water requirements of a complete quinoa crop cycle. Thus, the quinoa crop cycle necessarily takes
 place over a two year period including a long period of plowed fallow with bare soil.

928 The crop calendar begins in Year 1 with the plowing of the land area planned to be harvested
 930 in Year 2. Plowing is done in January-February in order to facilitate rainfall infiltration and refilling of
 the soil water reserve. Nowadays, in the plains, this work is most often mechanized. During the austral
 winter (from May to August), soil evaporation is reduced. Soils are generally sandy, and soil moisture
 932 in the subsurface soil layer in late August is sufficient for early sowing and seed germination (R. Joffre,
 unpublished data). Early sowing is advantageous as it allows for harvesting the crop before the March-
 April frost period, but it is also risky as the probability of a severe frost event damaging the quinoa
 934 seedlings in September-October is non-negligible. Quinoa seeds placed on the humid soil layer at a
 10-20 cm depth germinate and fastly develop deep rooting (Alvarez-Flores et al., 2014a; Alvarez-
 Flores et al., 2014b). The growing season lasts till March-April in Year 2 and the harvest has to be
 936 done before the main frost period (corresponding to the austral autumn-winter). During the post-
 938 harvest period, a large part of the soil surface remains without any vegetation cover.

	Year 1												Year 2											
Month	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
Climate																								
rainy season																								
main frost risks																								
Land use	plowed field						cultivated field						fallow											
Vegetation	bare soil						5 – 40%						< 10%											
Cropping																								
plowing																								
sowing																								
crop growth																								
harvest																								

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948

Supplementary Material B. Mobility and migration among quinoa growers

950 This section shows patterns of mobility and pluriactivity among quinoa growers from the southern
952 Altiplano of Bolivia. We considered several types of spatial mobilities: (i) the migration of individuals,
defined as a temporary or permanent change of residence, including mobility of bi-residential migrants,
(ii) the seasonal and circular mobility of migrants linked to the agricultural activity in their community.

954 A socioeconomic survey was conducted in two years (2007, 2008) on 149 households from 5
956 rural communities (San Juan, Chilalo, Otuyo, Candelaria, Palaya). Using interviews and livelihood
958 stories, we reconstructed the residential and professional trajectories of 170 members of quinoa
grower families (Vassas-Toral, 2011, 2015a, b, c). The results show (i) the extension of the migration
960 area of 139 migrants people between 1934 and 2008 (Fig. B-1) and the diversity of the activities
practised by male and female migrants in this period (Table B-1) , (ii) two cases illustrating the
962 individual trajectories of migrant people from these communities (Figs. B-2, 3), (iii) two cases
illustrating the circular mobility trajectory linked to the agricultural activity (Fig. B-4, 5). To preserve
confidentiality, the names of the interviewed people have been changed.

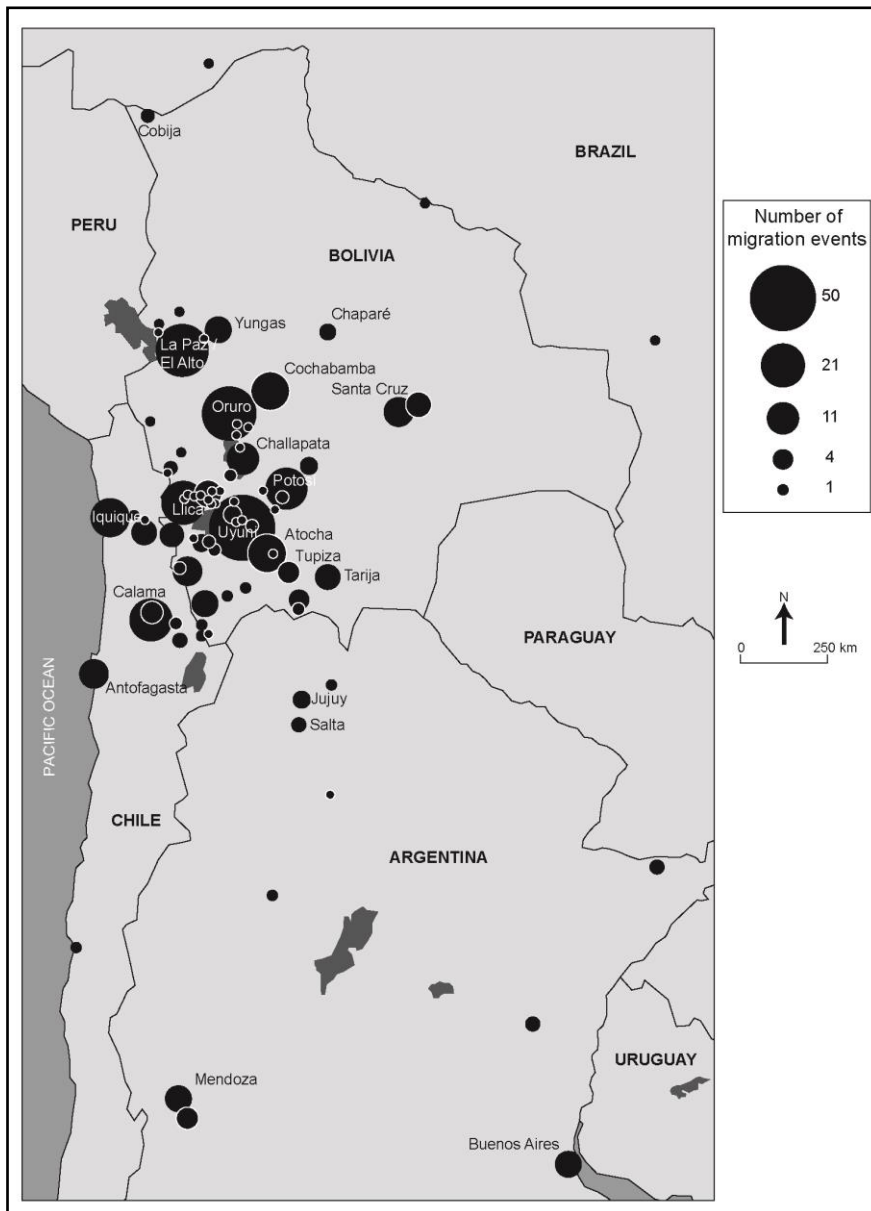


Fig. B-1. Extension of the migration area of 139 migrant people from 5 rural communities of the southern altiplano of Bolivia between 1934 and 2008.

Source: Interviews and livelihood stories, 2007-2008. Elaboration: A. Vassas-Toral and S. Coursière.

992 The mapping of the migrations of the 170 surveyed individuals (139 of them effectively
 993 migrating) reveals more than 400 events between 1934 and 2008, with urban and rural destinations in
 994 Bolivia, Chile and Argentina (Fig. B-1). In 2008, the main destinations of migration were big cities of
 995 Bolivia (La Paz, Oruro, Cochabamba) and Chile (Iquique). **Table B-1** (below) shows the professional
 996 activities practised by 139 migrating people, differentiating male and female migrants (data are
 percent of interviewees who declared having practised the activity in at least one of their migrations):

Economic sector	Division	Status and activity	Males (%)	Females (%)
primary	agriculture	informal sector employee: farmhand, lumberer	31	6
		self-employed worker: farmer, tractor driver	10	14
	mining	informal sector employee: miner	44	0
secondary	building industry	informal sector employee: mason, carpenter, electrician	29	0
		self-employed worker: foreman, carpenter	6	0
	textile and craft industries	informal sector employee: dressmaker, cabinetmaker, brickwork, quinoa food processing	15	12
		self-employed worker: dressmaker, baker, musician	2	2
tertiary	trade and restaurant industries	informal sector employee: grocer, ironmonger, caretaker, waiter	14	10
		self-employed worker: street fooding, clothing trade, restaurant	14	37
	car services and transportation	informal sector employee: mechanic, welder, minibus driver, truck driver, railway worker	10	0
		self-employed worker: mechanic, bodywork, welding, minibus or truck business	4	0
	domestic work	informal sector employee: daytime or fulltime servant	0	50
	administration	civil servant and assimilated workers: nursing, rural professor, policeman, administrative officer	16	0

998 Source: Vassas-Toral (2015c)

1000 As illustrated below (Figs. B-2, 3), many people practise a temporary migration and a circulation
 1002 between these different places and their community. These practices attest to the maintaining of
 1004 personal links with the rural place of origin and a strong territorial anchoring, which facilitated the
 return of emigrated people to their communities during the period of quinoa expansion.

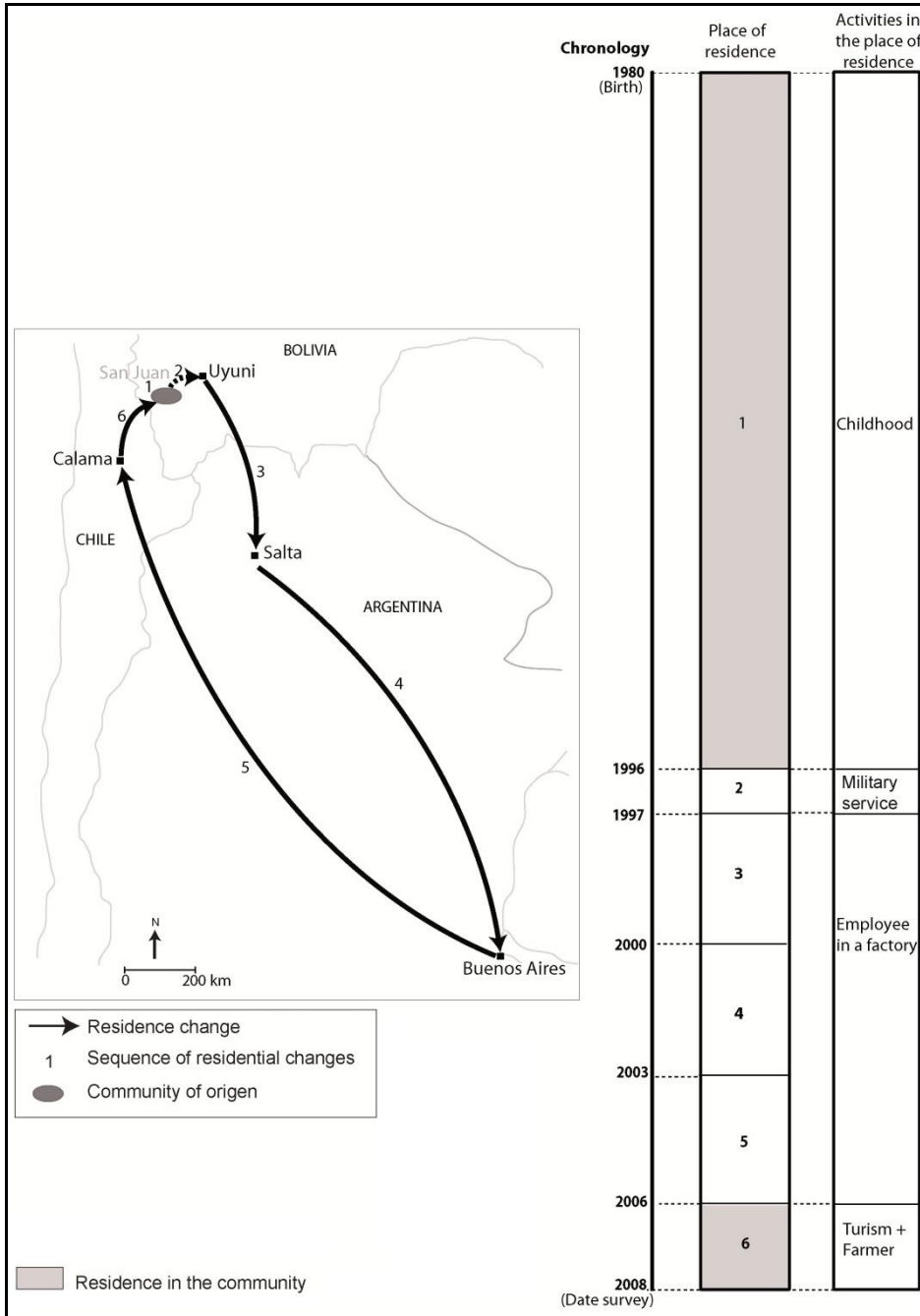


Fig. B-2. Trajectory of residential mobility of Calixto, 28 y old, native of San Juan de Rosario, with residence in that community in 2008.

Source: Vassas-Toral, interviews and livelihood stories, 2007-2008.

1006 The trajectory of Calixto is typical of many young people who emigrated for a long time in
 1008 Argentina and Chile, before returning in their community to produce quinoa. After 1 year in Uyuni to complete his military service, and 9 years as a factory worker in Salta, Buenos Aires and Calama (1996-2006), Calixto returned in 2006 to San Juan where he is now living from quinoa production and touristic activities.

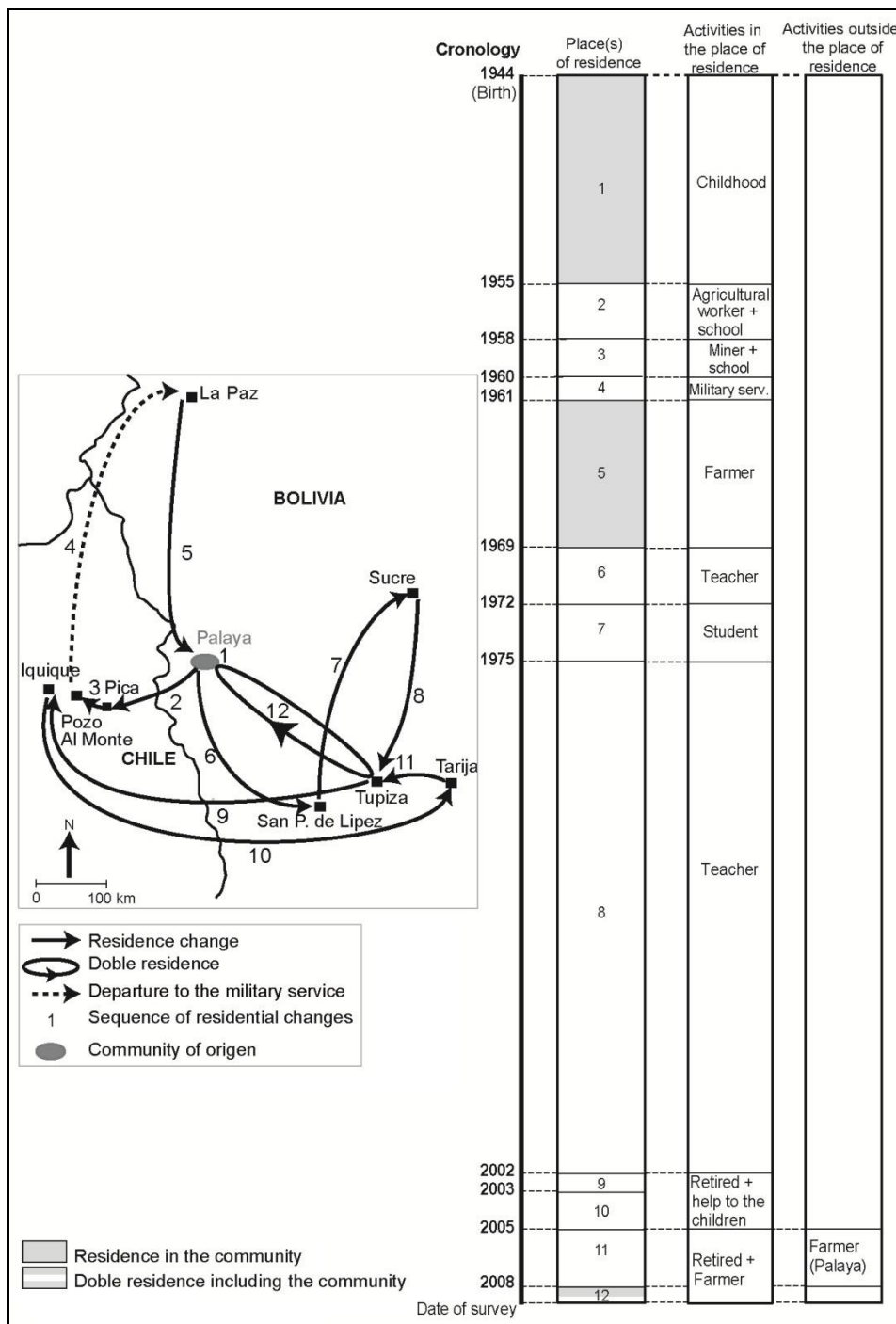
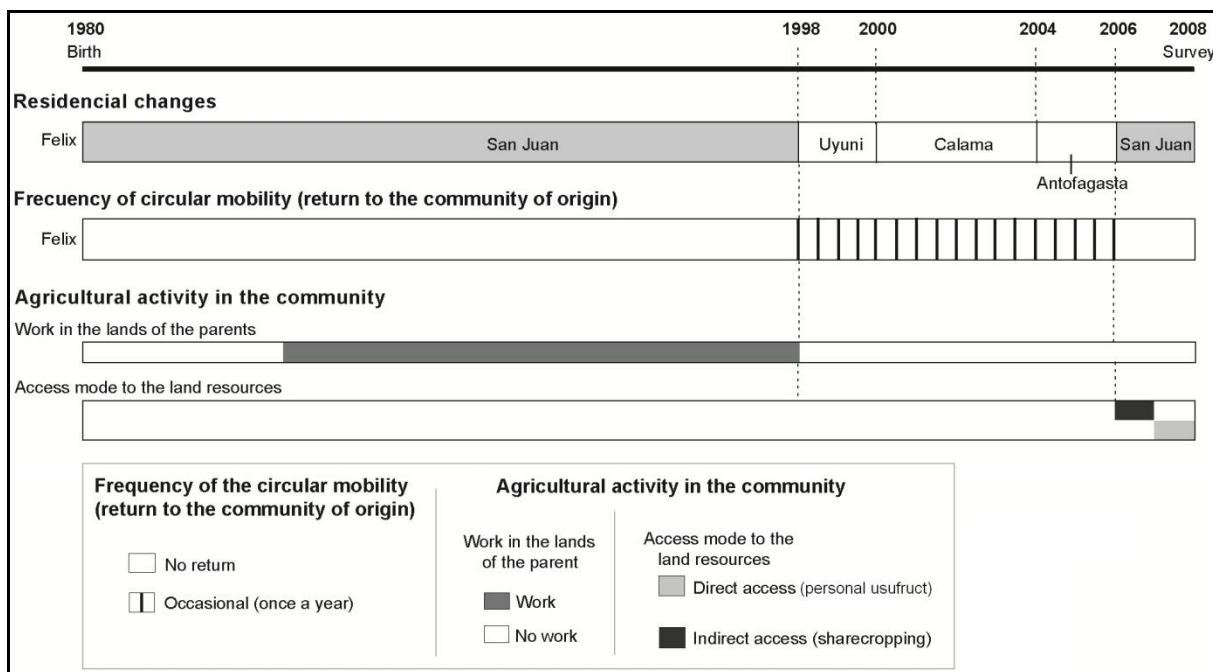


Fig. B-3. Trajectory of residential mobility of Benedicto, 64 y old, native from Palaya, with doble residence in Palaya and Tupiza in 2008.

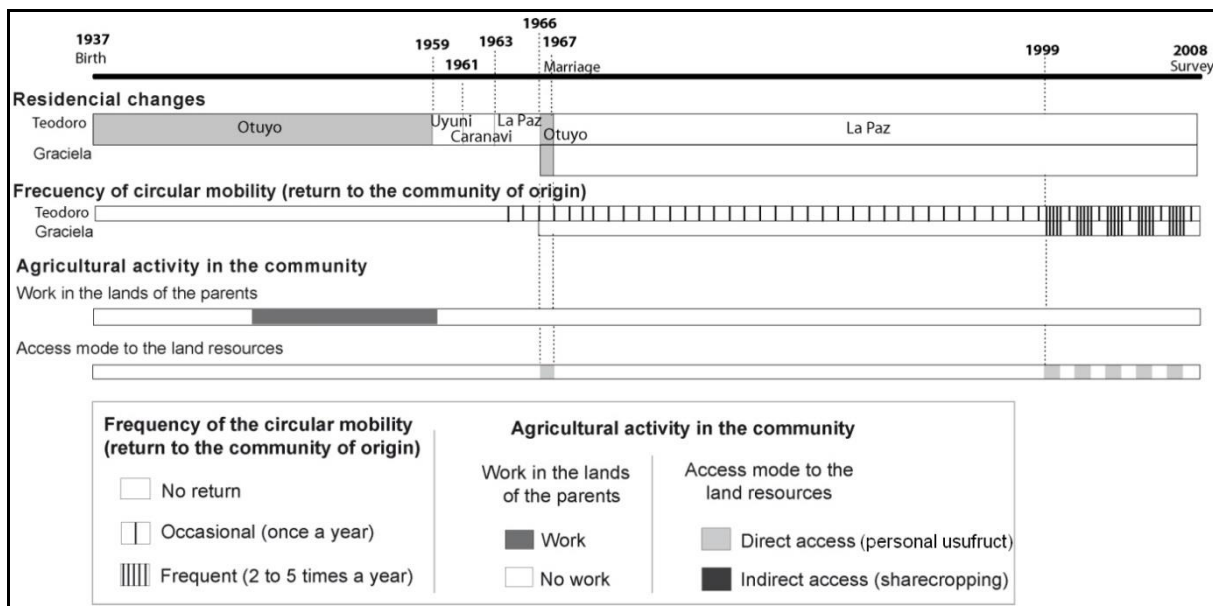
Source: Vassas-Toral, interviews and livelihood stories, 2007-2008.

1010 The migration trajectory of Benedicto is a complex one. He left alone the community of Palaya
 1012 when he was 11 years old and, while going to the school, began working in Chile as an agricultural
 1014 worker (*peon*) on the farm of a family member, and then as a miner. After completing his military
 1016 service at the age of 17 in La Paz, he settled in Palaya for 9 years, cultivating his own lands. However
 1018 the income of agriculture was insufficient for the family to live. So Benedicto decided to leave his
 1020 community and began a long migratory trajectory as school profesor in urban centers: Sucre, Tupiza,
 Iquique, Tarija, and again Tupiza. In 2008 Benedicto retired. After 24 years of absence, he returned in
 his native community to dedicate himself to quinoa production on the lands of which he had retained
 usufruct. Like numerous quinoa growers in the southern Altiplano, he practices now a circular mobility
 with double residence between the countryside and the city.



1022 **Fig. B-4.** Trajectory of circular mobility linked with the agricultural activity of Felix, 28 y old, native of
 1024 San Juan de Rosario with residence in that community in 2008. Source: Vassas-Toral, interviews and
 livelihood stories, 2007-2008.

1026 The trajectory of Felix is representative of numerous young people who contributed to the
 process of appropriation of lands in the southern altiplano. When he was 18 years old, Felix moved
 1028 from his native community to Uyuni, then to Chile (Calama and Antofogasta) to work in the building
 sector. During eight years, he returned to his community every year to visit his parents. The link
 1030 maintained with the community allowed him to move back in San Juan in 2006. However, having no
 direct access to cropland, Felix cultivated at first in sharecropping (*al partir*), before being able to clear
 some plots in the collective pasture lands, gradually becoming usufructuary of five hectares.



1032 **Fig. B-5.** Trajectories of circular mobility linked with the agricultural activity of Teodoro and Graciela,
 1034 both 71 y old, native of Otuyo with residence in La Paz in 2008. Source: Vassas-Toral, interviews and
 livelihood stories, 2007-2008.

1036 In 2008, Teodoro and Graciela were simultaneously residents in La Paz (the capital of Bolivia)
and quinoa growers in their native community of Otuyo, more than 500 km away. Their trajectories
1038 show a continuous circular mobility between the city and the community during more than twenty
years of migration (1963-1999). During this period, they didn't cultivate their lands any more but they
1040 returned once a year to their community to participate in local festivities, thus maintaining the right of
usufruct of their lands. From 1999 on, when Teodoro and Graciela decided to cultivate their lands
1042 again to produce quinoa for trade, the frequency of their circular mobility increased. They return three
or four times a year to cultivate their fields. The case of Teodoro and Graciela illustrates the
1044 emergence of "urban farmers" as a significant social group in the southern altiplano.

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Supplementary Material C. Localisation and cropland area in six communities of the southern
 1062 altiplano of Bolivia from 1963 to the 2000's.

1064 Latitude and longitude are in decimal degrees. Cropland areas were calculated using aerial
 photographs (1963), EROS satellite images (1972), and SPOT satellite images (2005-2008).

1066

Community	Altitude (m)	Year		
		1963	1972	2005-2008 ¹
Chacoma	3700	0.0	0.0	0.0
	3750	20.1	46.6	450.0
latitude S	3800	21.1	43.0	581.6
-19.71	3850	54.4	107.0	306.9
longitude W	3900	69.3	79.5	166.5
-68.49	3950	109.0	124.1	180.3
	4000	31.8	27.6	53.3
	4050	26.0	21.6	22.9
	4100	25.4	27.7	3.6
	4150	0.0	5.0	0.0
Candelaria	3700	21.5	108.8	870.1
de Viluyo	3750	50.2	123.6	540.8
	3800	7.0	41.8	104.4
latitude S	3850	0.6	3.2	1.6
-19.68	3900	0.0	0.0	10.2
longitude W	3950	0.0	0.0	9.8
-67.16	4000	0.0	0.0	7.4
	4050	0.0	0.0	3.0
	4100	0.0	0.0	0.0
Capura	3700	0.0	0.0	0.0
	3750	1.0	2.5	15.1
latitude S	3800	14.9	40.7	247.6
-19.49	3850	2.6	4.6	0.8
longitude W	3900	0.0	1.8	0.0
-67.28	3950	0.0	0.0	0.0
Chilalo	3700	9.7	65.4	109.2
	3750	16.0	14.4	1.6
latitude S	3800	17.5	10.5	8.7
-19.8	3850	9.6	9.8	17.0
longitude W	3900	16.0	5.2	8.4
-67.81	3950	12.4	6.2	3.0
	4000	10.0	4.9	10.9
	4050	5.2	1.8	6.5
	4100	3.8	0.0	4.8
	4150	9.2	1.2	0.0
	4200	1.6	0.7	0.0

(continued)

¹ 2006 in Chacoma and Palaya, 2008 in Candelaria de Viluyo, 2005 in Capura, Chilalo, and Otuyo.

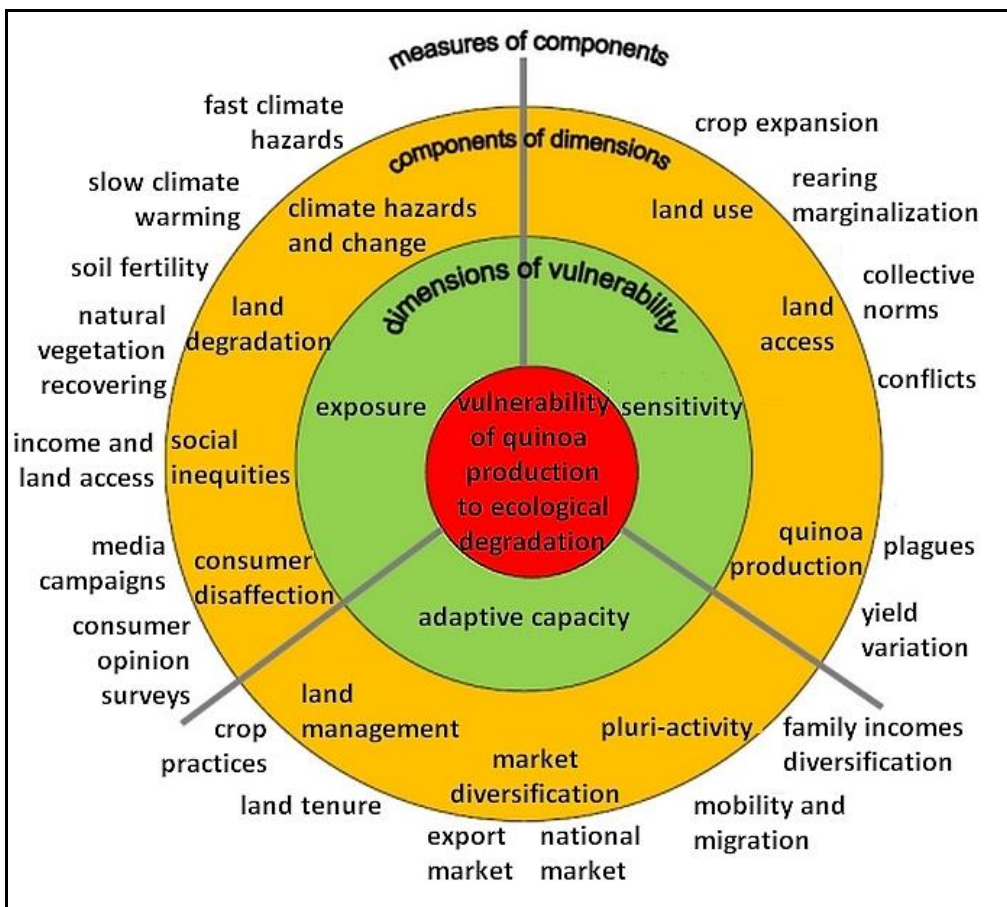
(continued)

	Altitude (m)	1963	1972	2005-2008¹
Otuyo	3700	44.5	23.8	159.1
	3750	35.6	94.8	328.5
latitude S	3800	23.7	24.4	11.4
-19.59	3850	16.2	9.2	0.0
longitude W	3900	8.0	1.0	0.0
-67.76	3950	2.2	0.0	0.0
	4000	0.0	0.0	0.0
Palaya	3700	14.2	242.9	713.8
	3750	130.8	276.3	789.3
latitude S	3800	38.1	104.2	293.7
-19.48	3850	29.8	66.5	197.2
longitude W	3900	60.0	90.4	218.4
-68.08	3950	72.4	112.4	197.6
	4000	106.2	76.8	191.2
	4050	112.0	83.5	214.9
	4100	89.2	63.5	112.1
	4150	81.6	81.5	84.3
	4200	100.2	158.7	108.2
	4250	101.3	103.6	90.6
	4300	61.3	99.1	30.5
	4350	43.8	77.7	12.2
	4400	18.4	46.7	6.4
	4450	7.1	37.8	4.8
	4500	2.6	76.5	6.1

1068 **Supplementary Material D. The Vulnerability Scoping Diagram**

1070 The socio-environmental assessment of quinoa production in the southern Altiplano of Bolivia may
 1072 have different formulations, depending on the structural unit and the process of change under
 1074 assessment. The Vulnerability Scoping Diagram in fig. D-1 synthesizes such an assessment focused
 1076 on the rural community as the exposure unit, and on ecological degradation as the possible source of
 1078 unsustainability for the considered community (an alternative object of assessment could have been,
 1080 for example, the farming unit exposed to the market dynamics). The diagram specifies the
 components of exposure, sensitivity and adaptive capacity identified in the system. In the present
 case, the agrosystem is exposed to real or potential risks related to climate imprevisibility, land
 degradation, as well as increased social inequity or the possible desaffection of part of the quinoa
 consumers. The sensitivity to these risks refers to agrotechnical components, such as the
 management of natural resources and the crop yield. It depends also on social and economic
 components like land access or the dependence towards actors external to the community.

1082 In this context, the members of the community can show their adaptive capacity in different
 1084 components: innovating in their individual and/or collective practices of land management, diversifying
 1086 their markets, realizing pluri-activity with- or without temporary migration. The measures of these
 1088 components can bring sustainability indicators. Examples of such indicators are: quantifying the
 expansion of the quinoa crop in the territory of the considered community, or characterizing the spatial
 and temporal dynamics of the mobility of the community members (Vassas-Toral, 2015a, b), or
 mapping frost risks at a geographical scale compatible with decision making for local crop
 management (Pouteau et al., 2011).



1090 **Fig. D-1.** Vulnerability scoping diagram assessing the vulnerability to ecological degradation in the
 1092 local quinoa production system.

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