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The disappearing desert and the emergence of agropastoralism: An adaptive cycle of rapid change in the mid-Holocene Lake Titicaca Basin (Peru–Bolivia)

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ABSTRACT

The mid-Holocene was an extremely dry period in the Lake Titicaca Basin of South America, when lake levels were at their lowest point in the Holocene. South of the lake, a lack of outflow and very low and irregular precipitation would have created desert-like conditions. This area's 'archaeological silence' seems to reflect an effective lack of population. This situation changed drastically as lake levels rose suddenly in the centuries following 3540 cal BP. As the desert disappeared, a flux of migrants filled the landscape, probably from the population concentration in the basin's western highlands. They imported and developed new technologies and economic practices and reorganized them into an agropastoral lifeway. The emergence of agropastoralism was both rapid and widespread, as people throughout the Lake Titicaca Basin adopted this practice. This major, regional shift can be productively framed as an adaptive cycle or Holling loop. This approach builds on the robust foundation of complexity theory, emphasizes the integrated nature of humans and their environment in a single system, highlights how systems fluctuate between slow and accelerated change, and is useful for developing hypotheses. Cascading feedback loops in climate, ecology, and cultural practices generated the emergence of agropastoralism. This resilient system is still in use today and is currently facing major climate changes, which makes understanding its origins especially relevant.

1. Introduction

The mid-Holocene was a period of significant climate and cultural change in many parts of the world (Anderson et al., 2007). Large parts of South America were also affected (Grosjean et al., 2007) including the Lake Titicaca Basin (Baker et al., 2001, 2005; Fritz et al., 2006; Ledru et al., 2013). The extensive altiplano (high plain) south of Lake Titicaca was especially dry, where desert-like conditions would have dominated. Precipitation was scarce and highly variable in space and time (Theissen et al., 2008). The end of this regime marked a sudden, widespread change. The mid-Holocene desert disappeared as precipitation quantity and regularity abruptly increased. At the same time, the lake rose past its outflow level and water began flowing south for the first time in millennia (Rigsby et al., 2005).

The environmental change is correlated with cultural change, as hunter-gatherers transitioned to herding and farming. One view describes this as 'a long process' (Stanish, 2003, pp. 99–101) but a recent surge of research and radiocarbon dates support an alternate interpretation, that this was a rapid, emergent episode of coupled cultural and environmental change that took place around 3540–3120 cal BP (Marsh, 2015). This alternative suggests that the mid-Holocene desert was effectively abandoned and then rapidly colonized as conditions improved. Migrants developed, imported, and reorganized economic practices and technologies to create a novel cultural adaptation: agropastoralism (Browman, 1981; Hastorf, 2008). This highly-resilient means of interacting with the environment made it possible to manage risk and climatic uncertainty, which is the reason it continues to be the economic foundation for modern inhabitants of the region (Browman, 1987; Bandy, 2005). Understanding the intimate cultural ties with a fluctuating climate is currently relevant, as the region has been experiencing a steady increase in climatic extremes over the last few decades (Valdivia et al., 2013).

This paper's goal is to advance our understanding of the ways that human–environment interactions shaped a sudden ecocultural change as agropastoralism emerged. This case study addresses

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several of the specific questions among the 'grand challenges of archaeology' (Kintigh et al., 2014) and can make contributions to understanding contemporary socionatural problems (van der Leeuw and Redman, 2002). To better understand this radical reorganization, this paper adopts Holling's (2001) adaptive cycle, which highlights the potential for accelerated change in integrated eco-cultural or socionatural systems (Folke, 2006; Dearing, 2008; Widlok et al., 2012). The adaptive cycle is part of a family of related approaches to non-linear complex systems, which I review in the first part of the paper. Next, I synthesize the cultural and climatic data and recast them in a narrative framed by the adaptive cycle. This cycle provides a much more robust approach than existing models and also is a productive means of generating hypotheses, which are outlined at the end of the paper. I believe this approach has great potential to enrich current debates and orient future interdisciplinary research in the Andes as well as in analogous episodes from around the world (Redman, 2005).

2. Non-linear complex systems

The last few decades have seen a sustained increase in the use of non-linear complex systems to explore the human past (McGlade, 1995; McGlade and van del Leeuw, 1997; Lehner, 2000; Bentley and Maschner, 2003; Bintliff, 2004; Yoffee, 2004; McIntosh, 2005; Kohler and van der Leeuw, 2007; Papagianni et al., 2008; Spencer, 2009; Barton, 2013). These frameworks are based on a family of related approaches such as chaos theory, complexity theory, complex adaptive systems, network models, multi-agent simulations, panarchy, and resilience theory (Kohler and Gumerman, 2000; Holling, 2001; Redman and Kinzig, 2003; Delcourt and Delcourt, 2004; Beekman and Baden, 2005; Folke, 2006; Lane et al., 2009; Mitchell, 2009; An, 2012). Some of these models have surprising similarities to 'eventful' sociology and archaeology and the Annales School of History (Braudel, 1972; Bintliff, 1991, 2004; Sewell, 2005; Beck et al., 2007). Complexity frameworks have potential to bridge the micro–macro gap in the social sciences (Sawyer, 2003), reinvigorate 'the conceptual base of archaeological and anthropological disciplines' (Redman and Kinzig, 2003, pp. 13), and may be the only theoretical position available to archaeologists that 'integrate[s] culture history, processualism, and post-processualism' (Bentley and Maschner, 2007, pp. 245).

Complexity models are powerful because they are generalizable yet flexible enough to accommodate case-by-case variability (see McGlade, 1995; Bentley and Maschner, 2007; Barton, 2013). This makes it possible to compare cases, because the focus is on processes and interactions between elements, not the nature of the elements themselves. For example, in human pedestrian traffic, individuals' decisions generate similar spatial patterns, even though decisions are based on limited, incomplete knowledge (Batty, 2003). The same process explains how a flock of birds forms a V. There is no leader of the flock, but a self-organizing pattern emerges from birds interacting with each other and the wind, making the whole qualitatively different and more than the sum of the parts. At different temporal and spatial scales, the rules of interaction will vary. This makes it possible for larger systems to include smaller, nested systems and hence tie together diverse micro and macro interactions at different scales (Sawyer, 2004; Beekman, 2005; Bradtmöller et al., 2012; Harris, 2014).

Complex systems are fields of variable interaction densities with a few high-density nodes. For example, water holes are landscape features that attract webs of human, plant, and animal interactions. Interactions result in long-term impacts that are beyond the life span of a single individual, often resulting in unintended consequences. Interaction-based networks have an inherent temporal component, making them a robust means of describing changes over time. Punctuated episodes of rapid change can be generated by dense webs of interactions between larger numbers and more diverse elements. At these interaction hot spots, potential emergent episodes are driven by a cascade of accelerated changes via feedback loops at multiple scales (Sawyer, 2004). Emergent episodes generate new, qualitatively different elements that subsequently contribute to increasingly complex systems (Archer, 1982; Doran, 2000; Beekman, 2005). Finally, these systems are subject to the butterfly effect, making each one historically unique and formally unpredictable. An apparently insignificant event may spark a wide-spread chain reaction; likewise, a major event may

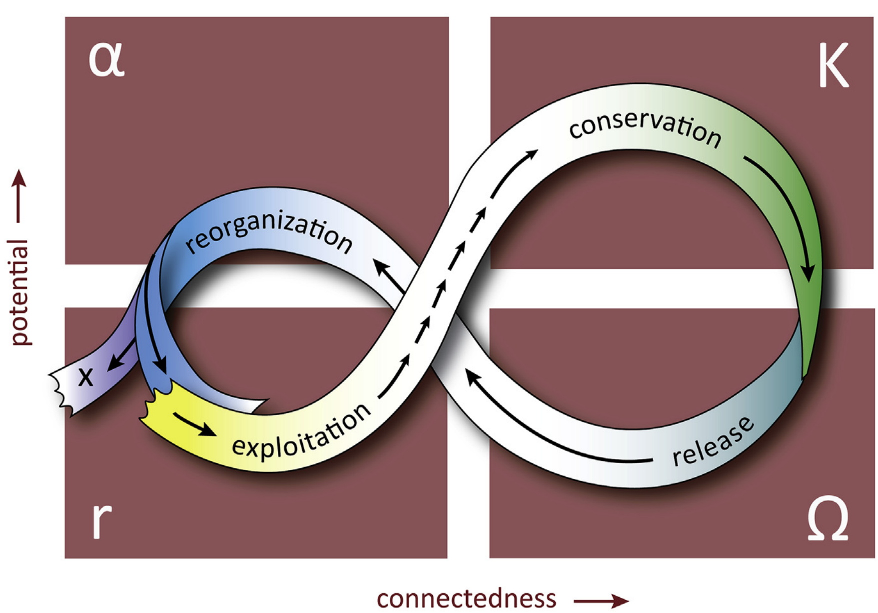

Fig. 1. The Holling loop's sequence of four ecosystem stages (r, K, α, Ω), redrawn from Holling (2001, Fig. 4). As in the original figure, shorter arrows indicate gradual change and accumulation while longer arrows suggest more rapid change. Moving along the y- axis indicates changes in potential, while the x- axis indicates changes in connectedness. Following the last of the four stages (α or reorganization), potential can leak away toward a less productive and less organized state (×) or be harnessed toward even greater levels of potential and connectedness in the exploitation stage (r).

have no effect in the long run. This makes complexity models robust alternatives to deterministic, top-down, or elite-centered models, in part because they consider interactions at all levels.

2.1. Holling loops and the adaptive cycle

This paper focuses on one complexity model, Holling's (2001) adaptive cycle (Fig. 1), This heuristic metaphor tracks systematic changes though a four-phase sequence: growth, conservation, release, and reorganization. Originally proposed for ecology, it has recently been gaining traction in archaeology (Redman, 2005; Dearing, 2008; Bradtmöller et al., 2012; Schmidt et al., 2012; Widlok et al., 2012; Zimmerman, 2012). There a number of reasons for choosing this model, principally because it treats environmental and archaeological data as a single system at a regional scale. As an ecologically-tested model, it provides archaeologists with a robust means of describing the tightly-knit interaction of environmental and cultural elements in ecocultural systems (McGlade, 1995; Redman, 2005; Folke, 2006). It is also attractive because it is based on interactions and relationships, like other non-linear frameworks. It can accommodate different scales as nested cycles, each of which may have their own interaction rules. For example, meteors or solar flares may be responsible for planetary climatic fluctuations, to which humans must respond – there is little that humans can do to affect such events. At a smaller scale, this relationship is reversed – a single human planting a vegetable garden can irrevocably alter a few square meters of the earth. An effective framework should allow for multiple scales with different rules, which is a means of moving beyond stale, polarized debates that insist on either environmental determinism or human agency at all scales.

Holling's adaptive loop also recognizes the importance variable tempos of change, which are indicated by short and long arrows (Fig. 1). Exploring variable tempos in specific cases requires refined environmental and archaeological chronologies at compatible scales. As part of the family of complexity models, the adaptive cycle is a robust yet general scheme for understanding change over time, making it useful for generating hypotheses and exploring the potential of other complexity frameworks. Hence the adaptive cycle is an effectively means of undergirding an understanding of eco-cultural changes over time, for example, the rapid emergence of agropastoralism in the Lake Titicaca Basin.

3. The emergence of agropastoralism on the altiplano

Lake Titicaca and the surrounding altiplano are located in the Andes of South America along the border between Peru and Bolivia (Fig. 2). At around 4000 masl, Lake Titicaca is flanked by the eastern and western Andean chains of snow-capped peaks that reach above 6500 masl. Days are sunny and hot but the temperature plummets at night. Regional vegetation is dominated by grasses, low shrubs, and a stark absence of trees. There is a marked fluctuation in precipitation between wet and dry seasons. The lake has an important influence on the climate; areas near the lake have much greater and more regular precipitation. Farther from the lake, precipitation is

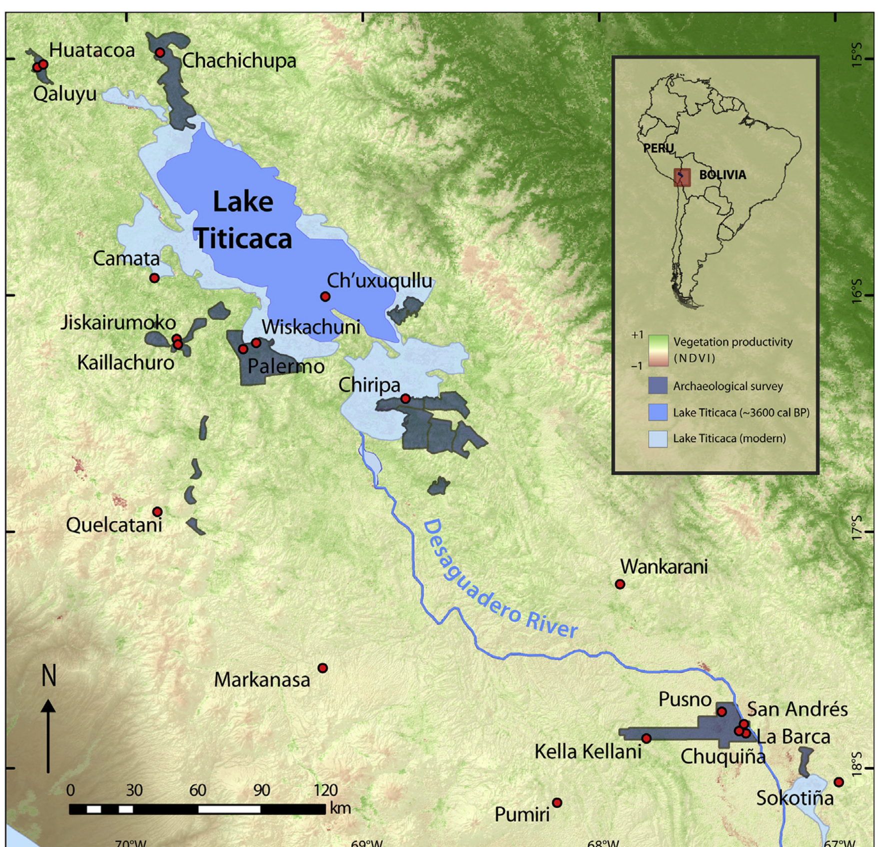

Fig. 2. The Lake Titicaca Basin and central altiplano, showing 20 sites with radiocarbon dates (red dots) and 15 full coverage surveys (shaded gray). Light blue lake areas indicate current shorelines; the darker blue area is the approximate extent of Lake Titicaca until ~3600 cal BP, 90 m below its current 3810 masl (based on D'Agostino et al., 2002, Fig. 14). Two overlapping layers show (1) topography, as hillshading of an ASTER Digital Elevation Model and (2) vegetation productivity, estimated as the Normalized Difference Vegetation Index (NDVI), based on 32-day composite MODIS imagery, February–March 2001. Satellite data courtesy of NASA and the US Geological Society, accessed through the Global Land Cover Facility. Modified from Marsh (2015, Fig. 1). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

much lower and temperatures oscillate much more (Roche et al., 1992).

3.1. Foraging during the Archaic Period

The human history of the altiplano begins with the Archaic period. Foragers occupied the area for the first time around 11,000 cal BP (Aldenderfer, 1998).[1] They established stable and enduring hunting and gathering practices. Mobility was crucial to their success and they probably moved with herds of guanacos, a principal prey item. Mobility would have allowed both humans and guanacos to adapt to smaller-scale temperature and humidity fluctuations.

The region experienced an arid extreme in the mid-Holocene. At this time, Lake Titicaca was as much as 100 m lower than it is today (Wirrmann and Oliveira Almeida, 1987; Wirrmann and Mourguiart, 1995; Seltzer et al., 1998; Cross et al., 2000; D'Agostino et al., 2002). This led to increased climatic instability as most of the altiplano would have become an area with few, unreliable resources. The effect was especially marked south of Lake Titicaca, which did not receive water from the lake for thousands of years because it was below its outflow level.

Archaeological data are sparse, so it is difficult to conclusively describe how people on the altiplano responded to increased aridity. However, the balance of data suggest that foragers eschewed the drier part of the altiplano in favor of the moister highlands to the west and north of Lake Titicaca (Marsh, 2015, pp. 19–20). South of the lake, 11 full-coverage surveys have covered 1432 km^2 and only documented 52 sites from the 6500-year Archaic period, and most are small lithic scatters that probably represent short-term camps (Fig. 2; Albarracín-Jordan, 1992; Mathews, 1992; Stanish et al., 1997; Bandy, 2001; Lémuz Aguirre, 2001, 2011; Janusek and Kolata, 2004; Stanish and Bauer, 2004; McAndrews, 2005; Calla Maldonado, 2011; Capriles et al., 2011). These data group sites from the entire Archaic because it is difficult to reliably make temporal distinctions in surface assemblages. While Archaic sites are undoubtedly underrepresented (Aldenderfer and Flores Blanco, 2011, pp. 536–538), current data suggest a very reduced human occupation (Marsh, 2015: 19–20, Table 4). It is likely that there was some occupation south focused at a few ecorefugia (Capriles, 2011, pp. 60–80; Ledru et al., 2013).

In contrast, four surveys north and west of Lake Titicaca reported 392 Archaic sites, even though they covered a much smaller area of 573 km^2 (Fig. 2; Aldenderfer, 1996; Tripcevich, 2002; Klink, 2005; Cohen, 2010; Cipolla, 2005; Plourde, 2006; Stanish et al., 2014). This region was much more densely occupied, with an Archaic site found every 1.46 km^2, an order of magnitude greater than south of the lake, where an Archaic site was found every 27.5 km^2. In one detailed survey in west of the lake, the frequency of temporally-sensitive projectile points shows a sharp increase in the Late Archaic (Craig, 2011, pp. 372–375). The regional trend is consistent with the ecological expectation that human occupation was spatially tethered to resource availability and reliability (Aldenderfer, 1998).

3.2. Lake level rise and the emergence of agropastoralism

In the centuries following 4000 cal BP, a variety of climate proxies agree that there was a major climate change marked by increasing quantity and regularity of precipitation (Abbott et al., 1997a, 1997b; Mourguiart et al., 1998; Seltzer et al., 1998; Cross et al., 2000; Paduano et al., 2003; Tapia et al., 2003; Baker et al., 2005). The precipitous rise of Lake Titicaca was as much as 10 m in four centuries (Abbott et al., 1997a, pp. 176) resulting in a significant increase in lake volume and regional precipitation (Rowe and Dunbar, 2004; Theissen et al., 2008). The net increase would have been more dramatic south of the lake because it had been so dry in the mid-Holocene. At the same time, this area began receiving outflow for the first time in millennia (Rigsby et al., 2005). The precise timing of this change can be estimated with a Bayesian chronological model of four lake cores (Abbott et al., 1997a), which estimates that the lake began rising at 3545 ± 52 cal BP (Marsh, 2015, pp. 16). This dates the beginning of one of the region's most pronounced Holocene climate changes. The human response to this change was nothing less than the most dramatic ecocultural reorganization in the region's history. The development of agropastoralism was a watershed shift in cultural practices and interactions with the environment, which was in turn affected by increasingly large populations. This is documented with radiocarbon dates associated with archaeological evidence such as plant remains, ground stone, ceramics, projectile points, domestic camelid bones, sunken courts, the founding of new sites, agricultural hoes, and raised fields (see summary and citations in Marsh, 2015, pp. 24–25).

Quinoa was initially domesticated prior to the climate change. In the western highlands, it was first used around 3690 cal BP[2] and on the lakeshore at 3670 cal BP. After the beginning of the climate change, domestic quinoa spread rapidly to the southern shore by 3430 cal BP, and hundreds of kilometers farther south by 3220 cal BP (Browman, 1989a; Eisentraut, 1998; Bruno and Whitehead, 2003; Whitehead, 2007; Langlie et al., 2011). Other plants were domesticated at the same time, including potatoes, as plant resources use became more diverse and ground stone use became more intensive (Rumold, 2010).

As quinoa cultivation spread south, ceramics were invented around 3440 cal BP, according to a Bayesian model of 191 dates from 20 archaeological sites (Marsh, 2015, pp. 21). Stratigraphically, ceramics appear slightly posterior or contemporaneous with domestic quinoa. Remarkably, all groups in the region began using ceramics within around 160 years. The earliest dates for ceramics are at newly founded sites south of the lake, where this new technology was developed by innovators in migrant communities. This technology was subsequently adopted at previously-occupied sites near the lake and in the southern altiplano.

Hunting strategies and prey choices also changed as lithic darts became common. Bow-and-arrow technology was probably invented just prior to the lake level rise, after which it became ‘heavily integrated’ (Klink and Aldenderfer, 2005). Some darts were made with obsidian, much of which arrived as the result of growing social networks that facilitated long-distance obsidian exchange (Burger et al., 2000; Craig, 2011). Also prior to the climate shift, foragers domesticated llamas and alpacas from their wild cousins, guanacos and vicuñas, respectively (Rick, 1980; Browman, 1989b; Kuznar, 1990; Bonavia, 1999; Mengoni Goñalons and Yacobaccio, 2006). By 3500 cal BP, bones from domestic camelids were present at sites in the northern and southern Lake Titicaca Basin (Kent, 1982; Warwick, 2012).

[1] For that sake of readability, I use median dates calibrated with IntCal13 (Reimer et al., 2013) in the text. See Marsh (2015) for details. It should not be forgotten that ^{14}C chronologies have error ranges that can affect our understanding the past. Bayesian models were run in OxCal 4.2 (Bronk Ramsey, 2009).

[2] This date is based on data from the highland site of Jiskairumoko, where 97 percent of Late Archaic and Early Formative Chenopodium seeds had characteristics consistent with domestic quinoa (Murray, 2005: 83, Table 3). They are associated with at least nine radiocarbon dates (Craig, 2011, Table 3). A single-phase Bayesian model of these dates indicates a starting boundary of 3690 ± 64 cal BP, which is statistically identical to the lakeshore date.

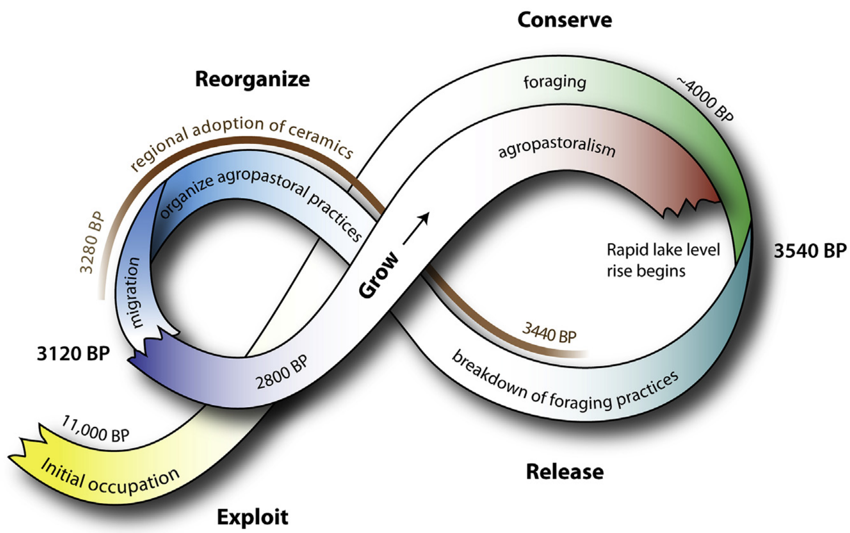

Fig. 3. Holling loop or adaptive cycle of major changes in the Lake Titicaca Basin. After the initial human occupation of the region (yellow), a long period of growth began as potential and connectedness increased (green). This broke down around 3540 cal BP (based on Bayesian models in Marsh, 2015), leading to accelerated release (teal) and reorganization (blue), which include the appearance and spread of ceramics (brown curve line, 3280–3440 cal BP). By around 3120 cal BP, agropastoral practices were in place over a large region and connections and potential began to grow again (purple). This remains the dominant human–environment relationship today (red). Agropastoralism's long-term effectiveness at managing environmental risk suggest it continues in the conservation phase. It may be a long time before the next major system breakdown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

These data indicate a new focus on agriculture and pastoralism that downplayed but did not abandon hunting and gathering. Perhaps the most significant innovation was integrating and coordinating these practices with the altiplano's marked seasonality. Labor scheduling would have been a major challenge that was solved by rapidly growing and more sedentary populations (Bandy, 2001, 2005). Living in larger villages, groups built the region's earliest sunken courts around 3350 cal BP, which were likely temples with used for ceremonies and ancestor veneration (Hastorf, 2003; Cohen, 2010, pp. 33).

Demographic growth and migration were major features of the emergence of agropastoralism, which is documented by survey data south of the lake. The number of sites per millennium jumped from 4 to 178 in the Archaic and Formative periods, respectively (Marsh, 2015, pp. 19). The site sizes increased by an order of magnitude. In one survey that focused on identifying Archaic sites, there were six Late Archaic sites with an average size of 0.02 ha; in the Formative, there were 15 sites with an average size of 0.45 ha, including a 5 ha village (Calla Maldonado, 2011, Tables 5.4 and 6.1).

The timing and magnitude of this major demographic change can be estimated with a summed probability distribution of the region's radiocarbon dates (Fig. 3). These distributions can reflect large-scale regional changes in population, but can suffer from significant methodological issues, many of which also apply to the small set of dates from the Late Titicaca Basin (Surovell et al., 2009; Bamforth and Grund, 2012; Williams, 2012; Contreras and Meadows, 2014). Despite these issues, these distributions remain useful when major trends are supported by other lines of evidence such as survey data and Bayesian models (Marsh, 2015). The relative change in this distribution is especially notable when comparing the periods before and after the climate change. The summed probability distribution of dates from the Lake Titicaca Basin (Fig. 3) shows steady, low populations both west of the lake (dark red) and in the rest of the basin (orange) until around 4200 cal BP, when population west of the lake increases around 3700–3600 cal BP. Next, population west of the lake drops as population in the rest of the basin begins to increase. Over the next few centuries, this trend continues and intensifies. By 3200 cal BP, population west of the lake has returned to previous levels while in the rest of the basin, a very large area, population is much greater. This population boom is one of the most significant demographic changes in the region's entire history.[3]

The best known site from the western highlands is Jiskairumoko, which was abandoned around 3360 cal BP after thousands of years of continuous occupation, a pattern that agrees with survey data (Craig, 2011, pp. 374). South of the lake, Chiripa was founded around 3400 cal BP on the new lakeshore, which was created by the rising lake (Hastorf, 2008). The most parsimonious explanation is that people migrated from the western highlands to the south in the generations that immediately followed the initial increase in lake level. However, alternative explanations cannot be disregarded such as the rapid growth of a yet-undetected Archaic population (see Stanish, 2003, pp. 101; Marsh, 2015, pp. 21–22).

To date the beginning and end of the emergence of agropastoralism, dates associated with agropastoral practices were modeled with Bayesian statistics (Marsh, 2015, pp. 23, Table 6). A composite model of 14 sites suggests that the earliest agropastoral practices were around 3540 $\pm$ 87 cal BP and statistically simultaneous with the lake level rise. The end of this emergent episode was around 3120 $\pm$ 87 cal BP, by which time all groups in the region had integrated agropastoral practices.

3.3. Herding and farming in the Formative Period

By around 3120 cal BP, the entire region had integrated agropastoral practices, the hallmark of the Formative Period. Once these practices were established, they began to increase in scale. Plant communities also appear to have completed their transition as

[3] This western signal is dominated by dates from Jiskairumoko (with 26 of 35 dates). Likewise, the signal from the rest of the basin is dominated by dates from Chiripa (27 of 73 dates). However, both sites are very well documented and for now are treated as representative of their respective regions, the moist highlands and the arid south. The starting and ending dates for these two sites are from the ending and starting boundary of single-phase Bayesian models, which are detailed in Marsh (2015).

arboreal species declined in abundance. There were more open areas on the landscape and fewer trees, as indicated and by more abundant open-ground weed species, a change in Poaceae grain sizes, and charcoal quantities (Paduano et al., 2003). This is correlated with a pattern of ‘intensifying land use leading to a progressive loss of forest cover and eventual lack of fuelwood’ from 4000 to 2600 cal BP (Paduano et al., 2003, pp. 274). These anthropogenic impacts on the landscape were probably unintended results of wide-spread herding and farming.

Agriculture was expanded. Hoes became increasingly common after 3200 cal BP, including a large-scale movement of olivine basalt hoes beginning around 2800 cal BP (Bermann and Castillo, 1995; Steadman, 1995; Bandy, 2001; Rigsby et al., 2003; Janusek and Kolata, 2004). Some crops were planted on raised fields, an agricultural system that reduces drisk of loss and improves yields, which eventually transformed 1200 km^2 of the landscape (Erickson, 2000; Stanish, 2003; Bandy, 2005). Increasing agricultural activity is also reflected in quinoa and amaranth pollen, which reached a maximum after 2600 cal BP (Paduano et al., 2003).

Villages continued to grow as the landscape was filled in. Community ties were continually rebuilt during a ‘florescence in the type and amount of ritual activity’ (Cohen, 2010, pp. 305). Serving ceramics became more common and elaborate, and the Yaya-mama stone sculpture style was used throughout the region (Chávez and Mohr Chávez, 1975; Bandy, 2001, pp. 156–157; Hastorf, 2008).

Agropastoralism's success was due to its ability to manage risk in an unpredictable environment (Bandy, 2005). The foundations of this economic practice are still in place today, even though the region has since undergone major upheavals such as the rise and fall of the Tiwanaku state and the invasion of the Inca and Spanish empires. Most recently, market capitalism and globalization have had marked impacts on the region's people and environment, yet for millions of modern inhabitants, agropastoral practices continue to be effective lifestyles for families and villages. The millennial resilience of the system gives added relevance to understanding its emergence and the role of intimately-linked ecological and cultural interactions (Valdivia et al., 2013). This sequence of changes can be conceptualized as an adaptive cycle.

4. Discussion: the adaptive cycle of Lake Titicaca's ecocultural system

The *longue durée* of Lake Titicaca's human history is an excellent example of a complex ecocultural system. Human–environment interactions have been at the heart of the region's dynamics since humans first explored this area 11,000 years ago. At this temporal scale, there have been two principal states of ecocultural stability: foraging and agropastoralism. The change between the two can be described a revolutionary episode of emergence that was triggered by large-scale climate change. In turn, the human response to this led to extensive transformations of the landscape. This section tracks changes according to the Holling loop phases as a loop (Fig. 4) and a time line, which integrates the probability distribution curves as a demographic proxy and key dates from Bayesian models (Fig. 5).

4.1. The adaptive cycle of the emergence of agropastoralism

In terms of the adaptive cycle, the region was first occupied during a phase of reorganization, shown as the yellow tail in bottom-left part of Fig. 4. Humans initially entered an unknown region led by explorers and pioneers. Connectedness was very low as they adapted to a new and distinct environment. Not all strategies would have worked and not all colonists would have survived. Enough did, though, to allow for human groups with effective strategies to grow.

4.2. Growth and conservation of foraging

In the growth phase, moving up the temporal ribbon toward the green part of Fig. 4, effective foraging practices became widespread as populations became more stable. Capital was gradually accumulated – cultural capital in the form of the necessary knowledge to live well – as well as biomass, that is, a demographic increase west of Lake Titicaca (Fig. 5). This part of the adaptive cycle moves slowly and conservatively, fostering incremental changes.

An excellent example of this may be the domestication of camelids, a long, poorly-documented process (Yacobaccio, 2004). Guanacos were the choice prey for hunters for millennia, and over time, hunters would have had increased contact with them. Growing populations would have transformed this into a resource to be managed. Groups may have followed movements of specific guanaco and vicuña herds. Humans probably intended to regulate prey by hunting fewer animals and specifically targeted older or younger animals, a herd-management technique that would later be important to herders. The seasonal movements of hunters probably followed camelids, which are quite similar to the annual rounds of modern domestic animals and their herders (Kuznar, 1993).

A high degree of interaction and connectedness may have eventually led to tamer animals and the unintended consequence of domestication (Yacobaccio, 2004). This process could have occurred simultaneously in adjacent valleys as well as other distant regions, as recent data have begun to suggest that domestication may have taken place at multiple locations throughout the Andes (Gasco, 2013). This narrative for domestication depends more on models than data, which remain few. Data may be reflecting a gradual, unintentional, and piecemeal process that happened in slightly different ways in neighboring regions. Especially in the case of camelids, there are varying degrees of ‘domestication’ and even modern llamas are remarkably similar to their wild ancestors.

Camelid domestication was probably closely linked to quinoa domestication. Kuznar (1993) convincingly argues for the camp-follower hypothesis, as domestic llamas preferred food is quinoa's wild ancestor. This pioneer species grows in trash pits near human settlements and would have been propagated by domestic animals' grazing preferences. This mutualism suggests that camelids would have been domesticated prior to quinoa, which is supported by more recent radiocarbon dates and pollen studies (Fig. 4, Paduano et al., 2003, Fig. 4; Marsh, 2015). These unintentional, mutualistic changes are best seen as an dynamic web of plant–animal–human–environment interactions (van der Veen, 2014).

At the same time, animal hunting shifted away from big game, as suggested by the appearance of small darts and the bow and arrow that are more apt for hunting smaller animals. This implies more interactions with a greater diversity of wild and domestic animals as plants were domesticated and processing because more intensive (Rumold, 2010; Craig, 2011). This marked trend of diversifying resources was related to increased resource competition and population.

Population was increasing, but only west and north of the lake (Fig. 5). As population rose, mobility decreased, and the region's first domestic architecture appeared with a greater focus on storage, typical of longer-term residence (Craig, 2011). These high-altitude foragers' activities were probably similar those of other ‘small-scale food producers’ (Smith, 2001). At the same time, long-distance obsidian exchange was increasing, signaling denser and

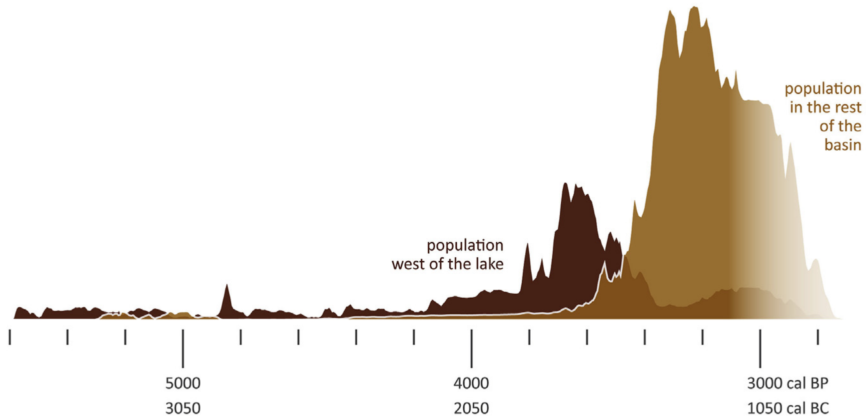

Fig. 4. Major trends in population for the Lake Titicaca Basin, based on summed probability distributions for radiocarbon dates from west of the lake (4 sites, n = 35, δT = 55), in dark red, and for the rest of the basin (16 sites, n = 73, δT = 75) in orange. The curve fades out to the right as it reaches the end of the sample (all available dates from 2800 to 4800 radiocarbon years BP), not a drop in population. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

farther-flung social networks, including obsidian from the Chivay source, 275 km to the northwest (Burger et al., 2000).

These centuries were marked by increasingly dense and over-connected networks, principally in the humid areas north and west of the lake. The dry south may have acted as an ecological barrier that constrained an ecological space with growing populations, over-exploited resources, and increasing population pressure. This was likely a factor in growing social and economic complexity, as suggested by ethnographic patterns (Keeley, 1988).

The earliest experiments with ceramics may have been during these centuries, but this possibility is only supported by a single questionable date from Quelcatani, 90 km east of Lake Titicaca (Eisentraut, 1998, pp. 64, 175; Stanish, 2003, pp. 102). All other dates from early ceramics fall shortly after the major climate change. Climate data also indicate that human-induced landscape change began as early as 4000 cal BP (Baucom and Rigsby, 1999; Rigsby et al., 2003; Paduano et al., 2003). Future research with high-resolution chronologies will be necessary to detail interactions in the centuries leading up to the major lake level rise.

In synthesis, the ecocultural system in the Lake Titicaca Basin had moved into the conservation phase of the Holling loop. It was becoming an increasingly large and interconnected system. There were widespread increases in mutualistic interactions between humans, camelids, and quinoa. According to the adaptive cycle, these networks had dense connections and interdependencies that created a brittle system that became 'an accident waiting to happen' (Holling, 2001, pp. 394).

4.3. Catastrophic change

Along the right edge of the Holling loop, the system experienced a rapid episode of 'creative destruction' (Schumpeter, 1994, pp. 81),

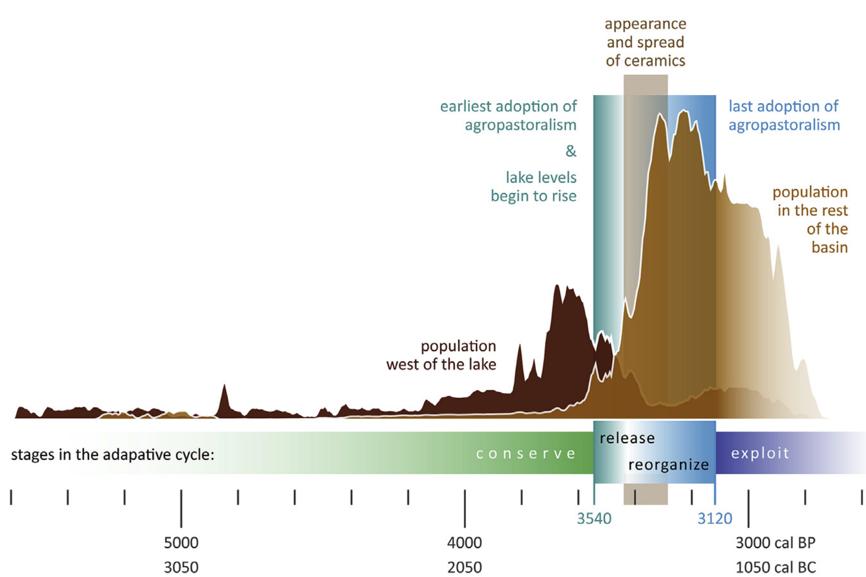

Fig. 5. Graphical synthesis of the emergence of agropastoralism based on summed probability distributions (Fig. 3), changes through the Holling loop (Fig. 4), and dates estimated with Bayesian models (Marsh, 2015). The bottom bar shows stages in the Holling loop stretched along a time line, using the same color scheme as Fig. 4. First there was 1) a long period of low population (conservation), 2) the initial rise of lake levels around 3540 cal BP (inciting release), 3) the simultaneous first expression of agropastoralism, 3) the brief span from the initial appearance of ceramics to their wide-spread use (light-brown vertical bar), and 4) the last adaptation of agropastoral practices in the region around 3120 cal BP (end of reorganization). Overlaying the summed probability distributions curves (Fig. 3) shows that populations migrated from west of the lake to occupy the rest of the basin at the same time as lake levels began to rise (release), a major demographic increase that coincided with the spread of pottery (the beginning of reorganization), ended by the time agropastoralism had spread throughout the basin (end of reorganization), and then regional connections began to grow anew with much greater population density and a new economic system (exploitation). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

one of the most significant events in the ecohistory of the Lake Titicaca Basin. Lake levels and regional precipitation increased rapidly beginning around ~3540 cal BP, where the loop twists from green to teal in Fig. 4. Lake-core data indicate an abrupt and significant change from the previous regime (Abbott et al., 1997a). This major climate amelioration creatively destroyed the southern desert and inspired a holistic reorganization of millennial traditions of Andean foraging (Aldenderfer, 1998).

4.4. Release and reorganization

The lower-right part of the curve represents release, when bonds broke and connectedness dropped precipitously. Change accelerated into the reorganization phase in the upper-left part of the curve. The high speed of change seems to be inversely proportional to the extended period of the slow growth period. Current archaeological data cannot clearly distinguish these phases, and the speed of these change highlights the need for extra care when excavating and dating material from this period.

Foragers renovated earlier practices and developed new technologies as they organized themselves around agriculture and herding. People began to leave their homes and migrate south of Lake Titicaca as connectedness dropped. The lowest point may have been at the inflection point between the population curves for west of the lake and the rest of the basin (Fig. 5). This took place very close to the initial appearance of ceramics and may have been when the system transitioned from release to reorganization. The speed of change in the system tracked the speed of migration – people scattered over hundreds of kilometers within a few centuries. It is not clear if people brought camelid herds with them or if they followed wild camelids herds, which also probably expanded rapidly into the area. It is not clear if they imported the new set of agropastoral practices or developed them as they established new settlements.

The best evidence for reorganization is the founding of new sites throughout the region within a few centuries. The earliest levels of these sites include the material remains of agropastoral practices. Choosing to move and establish new sites in new ecological settings is a clear indication of novel human relationships with the surrounding environment on local and regional scales. New settlements would have created ideal ecological settings for mutualistic interactions between camelids and quinoa (Kuznar, 1993). These new sites also include the region's earliest ceramics, a key technology developed by innovators in migrating communities.

New inventions began to take hold in rapidly changing social networks. Ceramics spread throughout the region in less than two centuries, coincident with a major demographic boom (Fig. 5; Marsh, 2015, pp. 21). This technology and way of life was so effective that it led to a regional realignment – all foragers in the region quickly adopted these practices, and have since maintained them for over three thousand years. Perhaps the most significant innovation was coordinating the annual round of productive activities with marked seasonality and inter-annual instability in precipitation.

There was a corresponding shift among plant and animal communities. Flooding of previously dry areas would have led to ecological realignments (Abbott et al., 1997b; Mourguiart et al., 1998; Paduano et al., 2003). The lakeshore was remodeled and the drainage to the south suddenly filled with water after being dry for thousands of years (Rigsby et al., 2005).

Reorganization ended around 3120 cal BP, shown in the figure as a break in the loop. By this time, substantial migration had wound down and all of the characteristic features of agropastoralism were in place. The pace of the demographic rise slowed (Fig. 5). People were widely dispersed in new environments and experimenting with new ways of interacting with changing resources. The lake level rise steadied as the region's ecology adjusted to the new precipitation regime.

4.5. Exploitation

The beginning of exploitation stage (around 3120–2800 cal BP) is indicated in purple (Figs. 4 and 5). Rapid change continued as the scale of successful practices and settlements rose rapidly. Villages were stable and growing faster than almost any other time in the history of the Lake Titicaca Basin (Bandy, 2001, pp. 105). Existing villages continues to grow and many new ones were founded, probably as groups responded to social stresses and fissioned (Bandy, 2001, pp. 280–283).

This new lifestyle involved a major demographic surge (Fig. 5). Having larger families would have become advantageous, as in other agricultural societies. Increasing productive output made it possible to feed larger groups. The improved means of managing risk also made it more viable to feed larger populations. Most of these groups were in new, unoccupied areas that were ripe for colonization, another factor favoring population growth.

This same period was associated with major changes in plant communities. Arboreal species began to decline as open-ground weeds become more common, which likely reflects human-driven climate change (Paduano et al., 2003). Environmental changes to the altiplano were probably a result of a humans expanding agricultural fields and herds of domestic camelids, in addition to wild camelids that more intensively occupied areas that were once desert-like.

4.6. Growth

There is no clear cut division between exploitation and growth, but significant changes began happening around 2800 cal BP, when the adaptive cycle had turned the corner (as the purple fades out in Fig. 4's loop).

One major change was the scale of agriculture. The initial reorganization and migration included domestic plants, but on a scale relative to pioneering populations. As villages grew, crops were grown on larger scales and cultigens were diversified (Bruno, 2014). This period saw the beginning of raised fields, terraces, and a major increase in the quantity of agricultural hoes. These significant modifications to the landscape would continue for thousands of years.

There was a contemporaneous 'florescence in the type and amount of ritual activity' in and around sunken courts, which were built at larger sites with growing populations (Cohen, 2010, pp. 305). This period marks the initial appearance of Yaya-mama iconography, elaborate feasting ceramics, and regional exchange system (Bandy, 2001, pp. 156–157), as regional connectedness increased.

Village fissioning slowed as the landscape was filled in by human settlements. This forced groups to form larger villages that resulted in a two-tiered settlement hierarchy. Groups developed new social mechanisms necessary for mitigating social stresses such as feasting and ritual activities, part of increasing social complexity. Over the next few thousand years, these economic and cultural traditions have proven remarkably stable.

4.7. Generating hypotheses

One of the advantages of using an adaptive cycle is to generate hypotheses. For now, the entire narrative presented here and the models it is based on (see Marsh, 2015) can be treated as a hypothesis to be evaluated against alternative explanations. This brings to light more specific hypotheses and possible directions for future work.

1. In the conservation phase of foraging, it seems like growth was focused in the highlands west of the lake. This implies weak connections to the region south of the lake, which might have been nearly abandoned, a possibility to be tested with new archaeological data. There is a strong tendency in the data but this may not adequately take into account ecorefugia (Ledru et al., 2013). Ecological reconstructions south of the lake could evaluate whether there were sufficient plant and animal communities for humans to make use of the foraging practices they had developed.
2. If there was a major difference between these two areas within the basin, it may be appropriate to consider them as separate systems with their own adaptive cycles. Doing so will require higher-resolution ecological data that can define the temporal and spatial limits of the apparent desert south of the lake, which remains poorly defined.
3. Additional ecological data are required to better the define the climatic change, especially south of the lake. This narrative argues for desert-like conditions, but this is based on modeled expectations rather than direct data. Moreover, there can be a lag between increasing rains, rising lake level, and ecological shifts, which may have wide implications on the temporal development of the adaptive cycle. These possibilities can be evaluated with higher-resolution temporal and spatial data.
4. The speed of the cultural change seems to be too fast for current data to track, and the sequence of adopting new technologies is not clear. This highlights the need for future research to target these centuries with meticulous excavation, Harris matrices, additional radiocarbon dates, and Bayesian models.
5. In the growth phase of agropastoralism, indicators of agricultural production include starch and ground stone (Rumold, 2010). These very common and important artifacts have not been given their due by archaeologists and could significantly refine the model if used to track the speed and magnitude of increasing agricultural production (see VanDerwarker et al., in press).
6. The transition from foraging to agropastoralism implies radical changes in diet, which could be tracked with stable isotopes and mixing models (e.g., Newsome et al., 2004). We should be able to see diet changes by comparing isotope data from before, after, and during the emergence of agropastoralism. It may be one of the best means for tracking the timing and sequence of changing economic practices, because they would have had an immediate effect on diet. The same bones tested for stable isotopes could be radiocarbon dated, which would provide a high-resolution chronology.
7. Ecocultural adaptive cycles may be useful for redefining archaeological chronologies. These cycles incorporate an entire ecocultural system, as opposed to traditional archaeological chronologies that are usually based a single cultural indicator, decorated ceramics. Local changes in ceramic styles are often difficult to apply to neighboring regions, so using adaptive cycles would help align adjacent ceramic sequences. Adaptive cycles can tack from small to large scales, which is especially relevant as significant environmental shifts often impact areas much larger than the spatial distribution of a single ceramic sequence. Names of the periods might be based on environmental adaptations and interactions rather than the traditional names that can carry evolutionary connotations such as Archaic and Formative. Periodization based on adaptive cycles could stress the alternating between slower exploitation and growth and rapid release and reorganization. For example, macro-regional ecocultural periods in the Lake Titicaca Basin might be:
    1. Foraging Period (slow). 11,000–3540 cal BP (Archaic Period). Within this long period, smaller-scale adaptive cycles could be better defined.
    2. Emergent Episode (fast). 3540–3120 cal BP. This includes release and reorganization.
    3. Agropastoral Period (slow). 3120 cal BP–present
        a. Exploitation. 3120–2800. (Early Formative Period)
        b. Growth. 2800–present (Middle Formative Period–present) Within the growth period, there were other faster cycles begin such as the rise and fall of the Tiwanaku state. Ceramic sequences show significant regional variation, which may also imply the need for smaller, nested cycles to fully describe this period.

5. Conclusion

This paper's goal was to improve our understanding of the emergence of agropastoralism by framing it as an ecocultural adaptive cycle. As the mid-Holocene desert rapidly disappeared south of Lake Titicaca, many elements were reorganized by migrants who expanded quickly across an effectively empty landscape. This macro-scale change closely follows the expectations of both complexity theory and Holling's adaptive cycle. Complexity theory outlines the hypothesis that this was a rapid emergent episode, as an alternative narrative to existing models of slow, gradual change. I argue that this approach better describes extant data and the ecocultural interactions.

This case study and the models used should be useful in other regions, especially as deserts appear or disappear. This can be done in part by turning to the general expectations of complexity models and adaptive cycles. Macro-scale change should alternate between (1) incremental and conservative adjustments during long phases of growth and (2) rapid and revolutionary reorganization. These brief periods of cascading changes must be tracked with refined chronologies at multiple scales, an approach that will make regional complexity models sensitive to local variability in regionally- and historically-specific datasets. Specific cases of expansions of agriculturalists have often involved rapid, large-scale migrations (Rindos, 1984), but so far the Lake Titicaca case has not been compared to other similar episodes (see Marsh, 2015, pp. 25). Comparisons could be facilitated by complexity models.

The emergence of agropastoralism in the Lake Titicaca Basin around 3540 cal BP was one of the region's major Holocene 'events' (Beck et al., 2007). In the centuries prior, interactions between humans, camelids, plants, rocks, and the landscape became increasingly dense and as they approached a breaking point. Regional climate change, best reflected in the rising waters of Lake Titicaca, resulted in a marked and rapid increase in the amount and regularity of precipitation, especially south of the lake, where water flowed for the first time in thousands of years. This would have completely remodeled micro-environments in a previously dry and all-but-unoccupied desertic expanse. Human groups immediately responded and reorganized old and new productive technologies into a remarkable resilient system that combines agriculture, pastoralism, hunting, and gathering. Its success led to rapid demographic growth and major impacts on the environment, such as the construction of expansive terraces and raised fields and the deforestation of the basin. After thousands of years of resilience to cultural and environmental changes, agropastoralism remains capable of adapting to today's climatic fluctuations.

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