Journal of Anthropological Archaeology 46 (2017) 28–39

Contents lists available at ScienceDirect

Journal of Anthropological Archaeology

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

Continuities and discontinuities in the socio-environmental systems of the Atacama Desert during the last 13,000 years

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ARTICLE INFO

Article history:
Received 25 December 2015
Revision received 4 August 2016
Available online 31 August 2016

Keywords:
Atacama Desert
Pampa del Tamarugal
Climate change
Continuities and discontinuities
Human-environment interaction
Hyperarid environments
Water

ABSTRACT

Understanding how human societies interacted with environmental changes is a major goal of archaeology and other socio-natural sciences. In this paper, we assess the human-environment interactions in the Pampa del Tamarugal (PDT) basin of the Atacama Desert over the last 13,000 years. By relying on a socio-environmental model that integrates ecosystem services with adaptive strategies, we review past climate changes, shifting environmental conditions, and the continuities and discontinuities in the nature and intensity of the human occupation of the PDT. As a result we highlight the importance of certain key resources such as water, an essential factor in the long-term trajectory of eco-historical change. Without water the outcome of human societies becomes hazardous.

1. Introduction

To a large extent, the history of humans is the history of a species in constant interaction with and mutual modification of its environment. Understanding how human societies interacted with environmental changes is a major goal of archaeology, human ecology, and other socio-natural sciences. To this end, scholars have been concerned with the causes that led to the collapse or changes in social systems. The debate has confronted environmental causes and social factors. Recently, Roscoe (2014) has emphasized that "anthropological and archaeological research, with its integrative and universalist approach to social analysis" has the potential to improve our understanding of the long-term impacts of climate change (Costanza et al., 2007; Kintigh et al., 2014a,b; Roscoe, 2014). We add that combining both anthropological-archaeological data with ecological and paleoecological records can help characterize and explain past human practices within an eco-historical perspective as well as call attention to possible

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http://dx.doi.org/10.1016/j.jaa.2016.08.006
0278-4165/

future ecological scenarios (Dearing et al., 2015, 2006; Van der Leeuw and Redman, 2002; Verstraeten, 2014).

Widespread desertification can affect large human populations and particularly socio-economically vulnerable communities and indigenous peoples, as it has been occurring in the African Sahel (Anderson et al., 2006; Geleta, 2014; Palmer and Smith, 2014). Alternatively, human practices can alter and transform the landscape considerably by means of several social, subsistence and ritual activities that produce, distribute and consume goods and services in order to maintain social and biological life. Today, there is growing consensus that major structural transformations in human societies, often documented as dramatic changes in the archaeological record such as regional abandonment, can be triggered by multifactorial internal and external factors (Aimers, 2007; Kohler et al., 2012; Rowland, 2008).

The goal of this paper is to present and discuss major trends in the long-term history of human-environment interactions in the Pampa del Tamarugal (PDT), located in the hyperarid core of the Atacama Desert in northern Chile. Using an eco-historical perspective, we focus on determining the social, economic, and technological, continuities and discontinuities that developed during key cycles of water availability, as inferred from archaeological and paleoenvironmental records during the entire span of human presence in the region.

2. The Atacama Desert

The Atacama Desert is a key region for examining how humans coped with climate change in environments considered extreme. Arid regions such as the Atacama cover more than a third of the planet and are very sensitive to climate change (Holmgren et al., 2006; Jimenez et al., 2011; Le Houerou, 1992; Ortega et al., 2012). Large variations in rainfall and temperature can drive large swings in productivity on inter-annual and even longer timescales (Noy-Meir, 1973). Like other subtropical arid regions (IPCC-AR4, 2007; Sheffield and Wood, 2008; Wang, 2005), the Atacama is predicted by regional models to become even more extreme (Minvielle and Garreaud, 2011; Urrutia and Vuille, 2009; Vuille, 2013), expecting substantial decreases in precipitation (20–30%) and increases in temperature (rising up to 3 °C) and frequency of extreme hot events. In sum, the future is uncertain but past ecological and archaeological records are key sources of information to attempt to model how human societies respond to significant changes in resource availability.

Our specific study area is known as the Pampa del Tamarugal (PDT) basin and is situated in the hyper-arid core of the Atacama Desert (Fig. 1). The PDT basin is surrounded by five ecosystems: (a) the Pacific coast and Coastal Cordillera to the west, (b) the quebradas that drain the Andes to the east, (c) the Altiplano in the high Andes to the east, (d) the exorheic valleys to the north, and (e) the Loa river and the Salar de Atacama basin to the south. These ecosystems were part of the broader landscape of the groups that inhabited the PDT throughout time.

The little water available in the PDT occurs in seasonally activated streams and springs and depends, almost exclusively, on summer rainfall occurring in the western slope of the Andes (e.g. Houston, 2006; Magaritz et al., 1990; Muñoz et al., 2007). These events feed the desert ecosystem through underground aquifers and superficial runoff (Briner, 1985; Gajardo, 1994; Luebert and Pliscoff, 2006; Villagrán et al., 1999). Precipitation variability has had a strong impact on the availability of water resources for various ecosystems at different timescales, from the last 13 millennia to the last several centuries, as revealed by diverse array of proxy records (Latorre et al., 2003; Mujica et al., 2015; Nester et al., 2007; Quade et al., 2008).

3. Theoretical framework

Our general framework for understanding socio-environmental systems and their resulting dynamics is based on a variation of the conceptual model proposed by Marquet et al. (2012) to explain the emergence of socio-cultural complexity in early coastal societies of the Atacama Desert. Given that environmental and social systems are in constant interaction, our model focuses on the interaction between ecosystem services and adaptive strategies to describe socio-environmental continuities and discontinuities (Fig. 2). Specifically, the model integrates: (i) ecosystem services, defined as the available resources and energy provided by the environment and dependent on their own complex interactions (e.g., coastal upwelling drives marine productivity, and aquifer recharge increases freshwater availability), and (ii) adaptive strategies, which correspond to specific behavioral outcomes that together articulate human responses and strategies for appropriating, utilizing and producing the available ecosystem services (e.g. fishing, hunting, farming, exchange, and their combination). Adaptive strategies exist in the space of possibilities for human life defined by the supply of ecosystem services. Some adaptive strategies will fare better in this space, increasing in importance as a result of the interaction between demographic factors (the number of interacting individuals through social leaning), the impact of this number upon the generation of cumulative cultural evolution reflected for simplicity in technological and ideological changes, and their demographic feedbacks (Boyd et al., 2011; Henrich, 2008; Marquet et al., 2012). More formally, the basic components of an adaptive strategy are: (1) demography, including the population parameters that characterize human communities in terms of group size and growth trends (e.g., birth rates, death rates, fertility, etc.), (2) technology, which corresponds to the tools and procedures for extracting, processing and producing resources and energy (e.g., hunting, gathering and fishing instruments and techniques, agricultural terraces and irrigation canals, storage systems, etc.), and (3) ideology, which provides the cognitive and institutional framework that mediates human-environment interactions (e.g. resource sharing, group structure, division of labor, funerary practices, beliefs systems, etc.) and how humans interact among themselves. The nature and extent of ecosystem services available to human societies constrain specific adaptive strategies by means of the intervening components (Boyd and Richerson, 2005). Changes in one component will inevitably lead to alterations in other components, and thus upon the adaptive strategy itself, as well as on the type, rate, scale and intensity with which ecosystem services are used. Moreover, the availability and abundance of ecosystem services (caused by either internal or external factors) will impact the adaptive strategies by means of specific systemic responses in the intervening components. A given adaptive strategy can lead to the eventual under-exploitation, overexploitation or their sustainable use of ecosystem services, by means of regulating access to more resources or using them more efficiently (Ellis, 2015; Smith and Zeder, 2013), but this will depend upon the dominant ideology of the group, their technological means as well as their number. In other words, the nature of an adaptive strategy conditions both the demand of ecosystem services but also the generation of innovations (e.g. Henrich, 2004) to potentially solve the problems that this exploitation could generate, if the dominant ideology thinks it is important to do so.

By linking together social and environmental aspects within an adaptive framework, our model is compatible with other human ecology models that predict demographic and technological change in human societies (Henrich, 2004; Powell et al., 2009). Moreover, following Clarke's (1968) early archaeological modeling work, our systems approach is not deterministic but aims at pro-

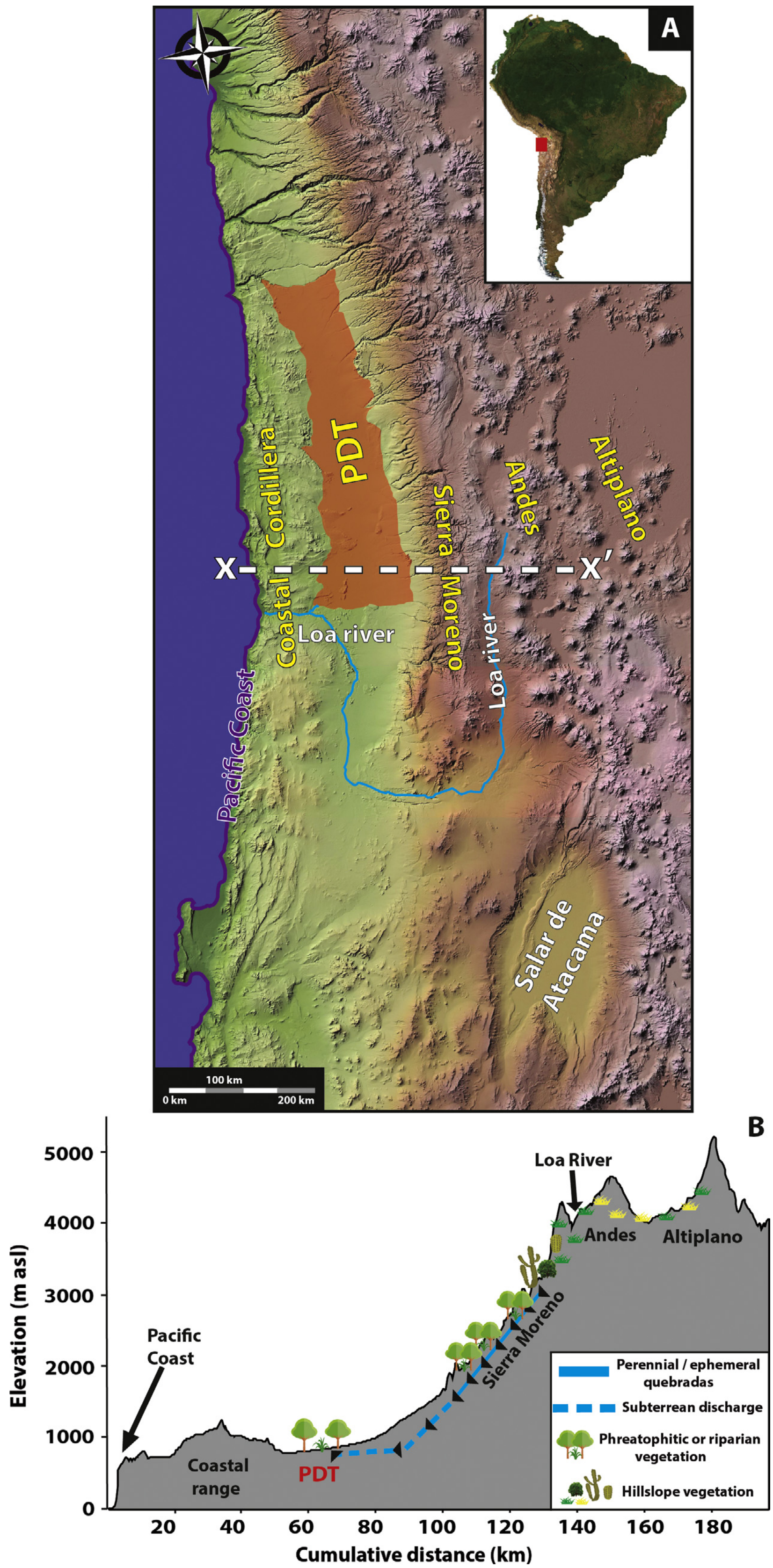

Fig. 1. Study area showing (A) the extent of the Pampa del Tamarugal (PDT) within the Atacama Desert. The dashed line (X-X′) describes the topographic profile with major topographic and vegetation units (shown in B).

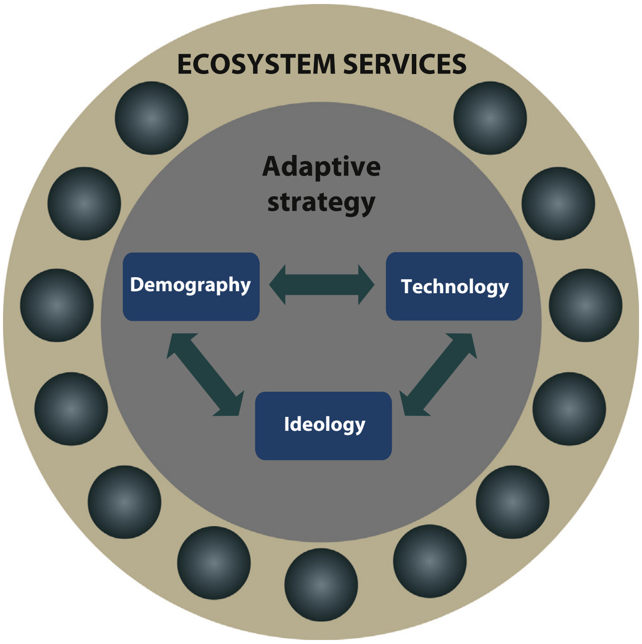

Fig. 2. Graphical depiction of our theoretical framework to understand the emergence of adaptive strategies. First, adaptive strategies emerge in the space of ecosystem services, and capitalize on particular resources provided by the ecosystem. These strategies involve the interaction between demographic, technological and ideological factors that jointly modulate the demand and use of the services provided by ecosystems. In a given ecosystem, different strategies are likely but only one become dominant, at least in a given time frame.

viding a conceptual framework to understand the emergence of adaptive strategies understood as a way of being in the world for a particular group of humans in the space of ecosystem services (Millennium Ecosystem Assessment, 2005) or the services that ecosystems provide to sustain human life.

In the context of this framework, social continuities and discontinuities are seen as a result of the interaction between a given adaptive strategy and the environment wherein it is embedded. An example of the latter is the collapse of local farming communities in the Samaca basin of southern Peru (Beresford-Jones et al., 2009) as a consequence of large flash floods linked to intensive ENSO events and enhanced by the overexploitation of the local *Prosopis* forests, that previously ameliorated the impact of flooding. Moreover, since our case study corresponds to the Atacama Desert, the most critical resource for engaging and transforming the socio-environmental systems was water (Núñez and Grosjean, 2003; Núñez et al., 2010).

Based on the modern relationship between hydroclimate, coastal upwelling of nutrient-rich cold waters, and the ecosystem productivity of the Atacama Desert and the adjacent Altiplano (Jaksic, 2001; Muñoz and Bonacic, 2006; Squeo et al., 2006; Thiel et al., 2007; Washington-Allen et al., 2008), we could expect changes in past availability of ecosystem services as well as proportional adaptive responses throughout a series of hypothetical cascade effects (Fig. 3) (Gayo et al., 2014; Williams et al., 2008). Since environmental variability of terrestrial and marine systems from the western Andean slope is driven by the same mechanisms (i.e. El Niño Southern Oscillation), an orchestrated demographic response (in timing or direction) should be detected in both areas. That is, enhanced (weaken) summer rainfalls above 2200 m above sea level (asl) in the western Andes can led to positive (negative) anomalies in hydrological patterns (e.g. increased runoff, groundwater discharge) in the PDT basin, which in turn amplified (reduced) the extension of fertile oasis for human activities across the Atacama inland and Altiplano. Similarly, enhanced (weakened) upwelling of cold nutrient-rich waters along western coast of South America driven by strong (weak) southerly winds can result in amplified (reduced) bioproductivity of the coastal ecosystems along the Atacama Desert littoral.

The long-term population dynamics of the region has been recently reconstructed using summed probabilities of calibrated radiocarbon dates from coastal and inland archaeological sites (Gayo et al., 2015; Williams et al., 2008). Here we use this sequence (Fig. 4) to make inferences about population trends over the past 14,000 years. Moreover, under our working cascade effect hypothesis, we expect low (high) probability values in the summed probability distribution during intervals of reduced (enhanced) bioproductivity in terrestrial and coastal ecosystems.

Much of the long-term population dynamic in the Atacama Desert arises from coastal and inland paleodemographic reconstructions based on the distribution of summed probabilities of archaeological radiocarbon dates. Specifically, we considered unbiased inferences of population trends reconstructed by Gayo et al. (2015) and Williams et al. (2008) for the western Andean slope over the past 13,000 years. Hence, under our working cascade effect hypothesis, we could expect low (high) probability values in the summed probability plots of radiocarbon data through intervals of reduced (enhanced) bioproductivity in terrestrial and coastal ecosystems. We agree with Timpson et al. (2014) that the invalidation of the method arisen from a simulated historical time-series (last 800 years) is inadequate because it spans the most problematic interval for any calibration curve (see the Introduction section for further details). These authors also stress the use of the trimming technique to hamper the impact of such spurious calibration effects in long-term reconstructions, which was applied to our reconstruction (see Gayo et al., 2015).

4. The first human occupations in the Atacama (13–10 ka)

During the glacial-interglacial transition at least two extended periods of increased rainfall, together termed the Central Andean Pluvial Event (CAPE I: from 17.5 to 14 ka and CAPE II: from 13 to 10 ka) (Quade et al., 2008), dramatically accelerated the regional hydrological cycle. Both events created vast 'paleolakes' in the Uyuni basin (Placzek et al., 2009, 2006; Sylvestre et al., 1999) and other smaller basins in the Altiplano (Giralt et al., 2008; Grosjean et al., 1995, 2001; Moreno et al., 2009), and enhanced groundwater discharge rates toward the Pacific lowlands (Quade et al., 2008; Rech et al., 2003, 2001, 2002). Such hydroclimatic conditions affected the latitudinal and altitudinal distribution of many plant species in northern Chile as evidenced by downslope displacement of the Subnival and High Andean steppe vegetation belts about 1000 m and the expansion of the Puna belt and Pre-Puna annual plants into the absolute desert (Latorre et al., 2006; Maldonado et al., 2005; Placzek et al., 2009; Quade et al., 2008).

In the PDT, CAPE is locally expressed as amplified events that brought about major changes in the availability of ecosystem services. For instance, riparian/wetland ecosystems (mostly composed by *Escallonia angustifolia*, *Schinus molle*, *Prosopis* and *Distichlis spicata* communities) expanded into what is now the hyperarid core of the Atacama in association with increased perennial stream discharge and groundwater tables (Gayo et al., 2012a; Nester et al., 2007). These habitats housed small (rodents and birds) and large-sized (camelids) fauna. The CAPE periods of "bonanza" made the PDT an attractive habitat for hunter-gatherers, and archaeological evidence suggests that they occupied the region by 13 ka and perhaps even earlier. In fact, a number of human

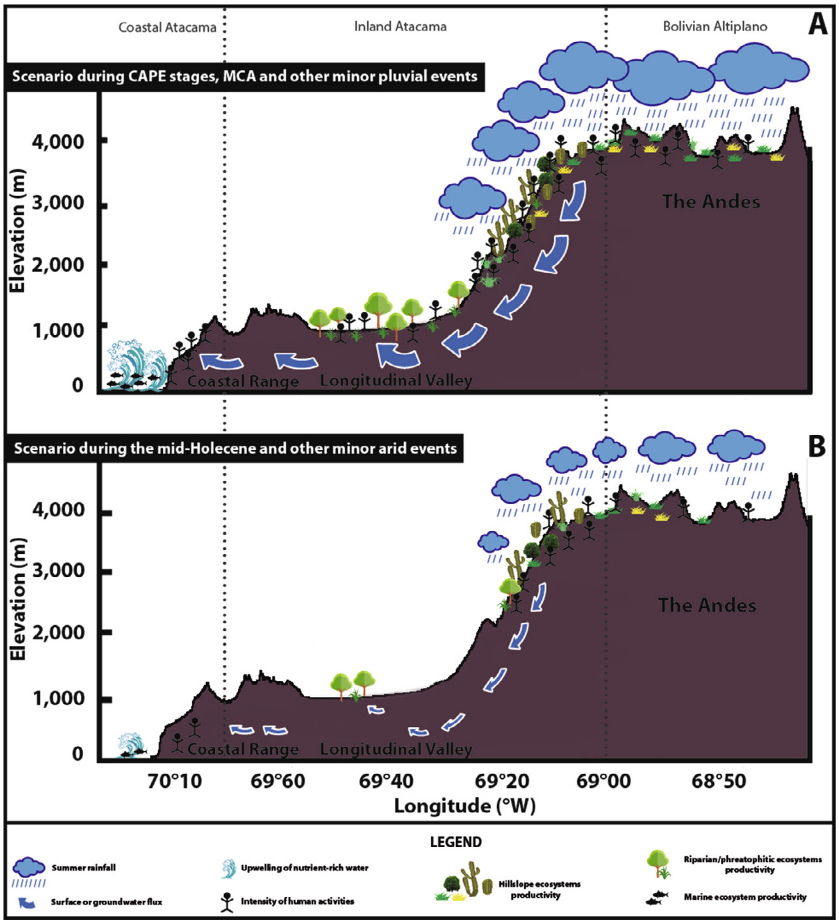

Fig. 3. Hypothesized cascade effect of regional-scale environmental shifts in the Atacama Desert. (A) Fictional period of increased marine and terrestrial productivity brought about by augmented upwelling over the littoral Atacama Desert and positive hydroclimate anomalies in the highlands. (B) Fictional opposite period of decreased marine and inland productivity.

occupations dated between 12.8 and 11.7 ka have been documented in the PDT (Latorre et al., 2013; Santoro et al., 2011a). Excavations at Quebrada Maní 12 (QM12) yielded evidence of a diverse cultural assemblage consisting of abundant lithic tools and debitage, burned and cut bones, small marine gastropods selected for adornment, red pigments possibly for hide processing and cosmetic use, and processed plant and animal fibers (Latorre et al., 2013). The camp, which included features such as prepared fireplaces, was intermittently occupied possibly as a residential base (Latorre et al., 2013; Núñez et al., 2016; Santoro et al., 2011a, 2011b; Ugalde et al., 2012). Our ongoing research in three other contemporaneous open camps, separated by no more than 30 km, suggests that QM12 was part of a complex adaptive system of hunter-gatherers that was successfully taking advantage of the increased ecosystem services available in the PDT during the CAPE II. These sites are also associated with paleowetland deposits including well-preserved tree trunks and other plant remains.

The earliest coastal settlements are situated both to the north and the south of the PDT and include Quebrada Jaguay, Quebrada Tacaguay, La Chimba, and Taltal (deFrance and Umire, 2004; Jackson et al., 2011; Keefer et al., 1998; Llagostera et al., 1997; Salazar et al., 2015, 2011; Sandweiss et al., 1998). Evidence from QM12 demonstrates that the hunter-gatherers that occupied the PDT during the CAPE II maintained contact with the coast, so it is entirely possible that Holocene marine transgressions obliterated late Pleistocene coastal camps.

5. Socio-environmental discontinuity during the early and middle Holocene (10–3 ka)

So far, the PDT has revealed more substantial evidence for early and sustained peopling of the region than other adjacent (and potentially more attractive) ecosystems such as the coast and the highlands (but see Capriles et al., 2016). Nevertheless, after the CAPE II, exacerbated arid conditions prevailed between 10 and 3 ka, in the Atacama Desert, which underwent a severe and protracted period of aridity and ecological stress (Fig. 4A). The intensity, geographical extent, and timing of this arid phase is a matter of discussion (Betancourt et al., 2000; Grosjean et al., 2003; Latorre et al., 2003; Ledru et al., 2013; Maldonado et al., 2005). In the PDT, extreme arid conditions prevailed and drastically reduced the availability of ecosystem services (Betancourt et al., 2000; Latorre et al., 2003; Ledru et al., 2013; Rech et al., 2002).

Under new climatic conditions, archaeological data suggest that important transformations occurred in settlement patterns and cultural behavior, producing a phenomenon of socio-environmental discontinuity that has been conceptualized as the "*silencio arqueológico*" (archaeological silence) (Núñez et al., 2002, 2013). To cope with long periods of widespread environmental uncertainty and reduction of ecosystem services imposed by the prolonged and intense aridity, people either abandoned the region, possibly migrating towards the coast and highlands (see below), or

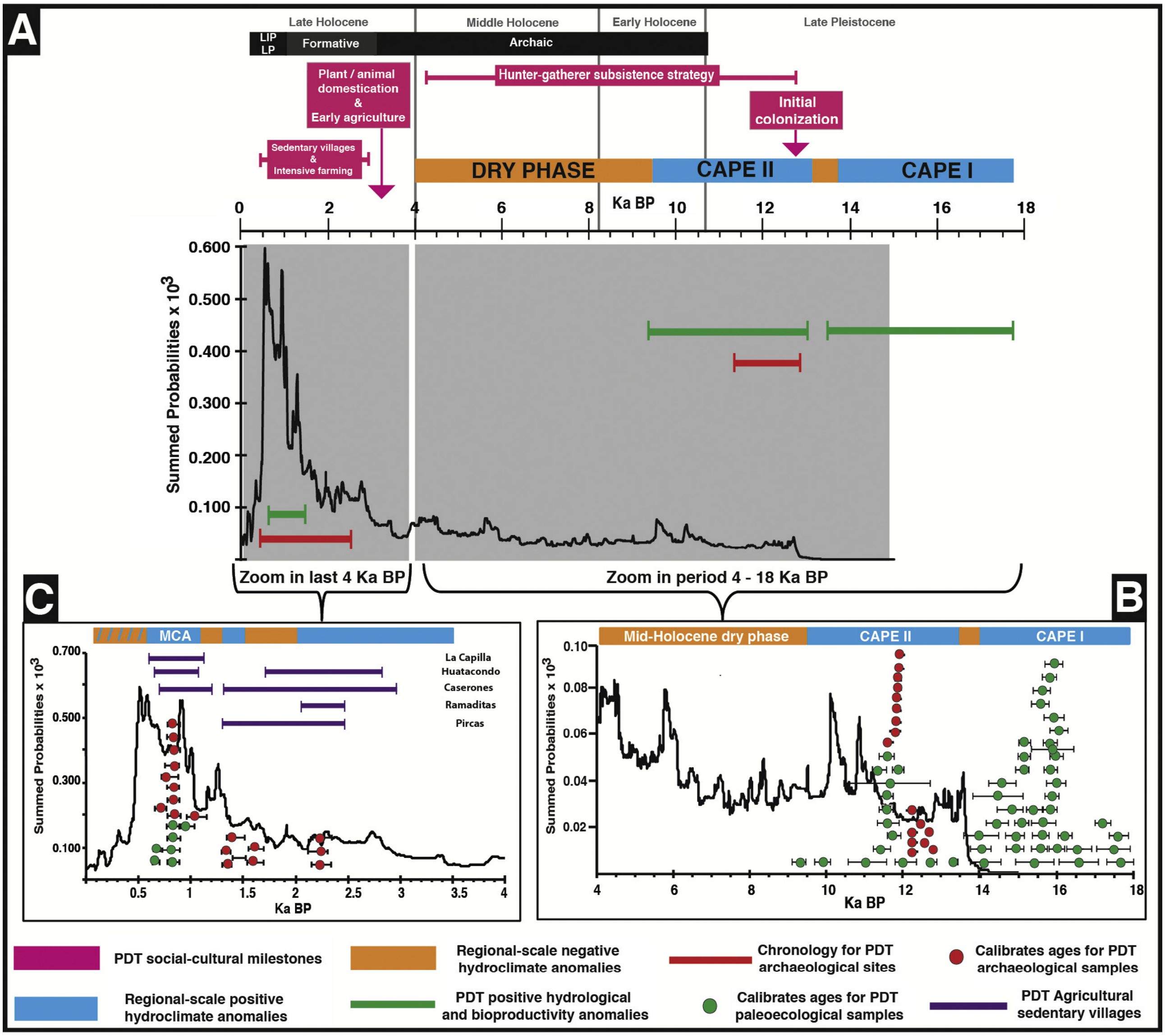

Fig. 4. Synthesis of socio-environmental changes in the PDT over the last 13,000 years based on (A) summed probabilities of calibrated radiocarbon dates (modified from Gayo et al., 2015), and including geological epochs, archaeological periods, and socio-cultural milestones in the Atacama Desert. Details of paleoenvironmental variations during the oldest (B) and youngest portions (C) of the sequence are also provided. LIP: Late Intermediate Period. LP: Late Period. CAPE: Central Andean Pluvial Event. MCA: Medieval Climate Anomaly.

settled near the few and very localized sources of permanent water (i.e., "ecological refuges") (Aldenderfer, 1988, 1998; Aldenderfer and Flores Blanco, 2011; Cartajena, 2013; de Souza, 2004; Grosjean et al., 2005, 1997, 2007; Núñez et al., 2013, 1995; Núñez and Grosjean, 1994; Santoro et al., 2016; Santoro and Núñez, 1987).

A possible location for ecological refuges includes the quebradas of Sapiga (the northern drainage of the PDT) and Tiliviche, where the sites of Aragón and Tiliviche 1 are situated respectively (Núñez, 1986; Núñez and Zlatar, 1976). The occupation of these sites begins ca. 9.5 ka and continues, albeit discontinuously, throughout the early and middle Holocene, containing both inland and marine food remains, suggesting that the locally available ecosystem services had to be complemented by coastal resources.

5.1. What happened along the coast?

In contrast to the PDT, the coast shows a strong sequence of continuous occupation beginning approximately 9 ka (Marquet et al., 2012). The coastal settlements found at several locations such as Punta Pichalo, Punta Patillo, and Caleta Huelén show the development of a specialized technology focused on the exploitation of marine resources including abundant hooks, harpoons, fishnets, etc. (Andrade et al., 2016; Bird, 1943; Standen et al., 2004). Between 7 and 4 ka coastal settlements became more abundant although with regional variation possibly tied to fresh water availability and marine upwelling. Maritime communities increased their technological specialization by creating a full range of tools that included watercrafts, harpoons for hunting marine mammals, hooks made of cactus spines and shells, sea lion ribs (*chope*) for collecting and processing gastropods, and plant fiber bags for collecting shellfish (Andrade et al., 2016; Olguín et al., 2014; Standen and Arriaza, 2016).

The coastal peoples also introduced complex ideological innovations, which included sophisticated procedures to transform and preserve their dead by means of artificial mummification (Arriaza et al., 2005; Standen, 1997). The way that corpses were intervened involved the selection, procurement, and transformation of different raw materials (i.e., clay, wood, vegetable fiber, pigments, animal skins and human hair) (Arriaza, 1995a,b; Llagostera, 2003; Rivera, 1995; Standen, 1997). Artificial mummification possibly arose within a dynamic process that involved population growth related to increased and stable ecosystem services (i.e., high marine productivity and water availability) and an increase of naturally mummified remains (Marquet et al., 2012).

5.2. Colonization of the high Andes

A series of rodent middens collected at 21°S and above 4000 m asl suggests that during the early and middle Holocene, the Altiplano east of the PDT was comparatively more productive (de Porras et al., 2015). Archaeological data supports that, although preceded by exploratory and logistical incursions, hunter-gatherers were recurrently occupying the highlands after 10 ka (Albarracin-Jordan and Capriles, 2011; Capriles and Albarracin-Jordan, 2013; Herrera et al., 2015; Moreno et al., 2009; Osorio et al., 2011). Moreover, archaeological evidence supports cultural connections between the first inhabitants of the PDT and the later extensive settlement of the Altiplano. For instance, Patapatane projectile points, which may have originated in the PDT, became widespread in the Andean highlands as people improved and adapted to a hunting and gathering social system in the higher but more vegetated terrain. The distribution of these artifacts is also wider and persisted longer in time (Capriles et al., 2011; Klink and Aldenderfer, 2005; Maldonado and Uribe, 2015; Núñez and Santoro, 1990; Santoro, 1989; Santoro and Núñez, 1987). However, it is worth noting that the factor that caused the hyper aridity in the PDT also caused decreased precipitation in the highlands (Gayo et al., 2012b; Nester et al., 2007). In Antofagasta de la Sierra in northwest Argentina, Pintar (2014) has suggested less vulnerable environments above 4000 m asl attracted people during a dry period beginning around 8000 years cal ago. Similarly, in the eastern Bolivian Altiplano (16°S) Ledru et al. (2013) have hypothesized that ‘‘ecological refuges" were key for sustaining hunter-gatherers in the highlands (~3750 m asl) during the arid middle Holocene.

6. The return to the PDT during the late Holocene (3–0.5 ka)

After 3 ka major socio-environmental changes are observed in the archaeological record of the south central Andes, which have been related to an increasingly humid climatic regime (Baker and Fritz, 2015; Baker et al., 2001; Binford et al., 1997; Fritz et al., 2012; Pintar, 2014). The changes continued to develop over the next millennia causing the increase of available ecosystem services within the Atacama Desert. Paleoecological and archaeological archives support that wetter conditions in both superficial and groundwater gradually increased in the PDT during the late Holocene (Gayo et al., 2012b; Maldonado and Uribe, 2015). Three positive moisture anomalies (~2.5–2.0, 1.6–1.3, and 1.1–0.68 ka) increased local phreatic levels and stimulated the natural vegetation coverage of non/woody and woody taxa (for instance *Prosopis* cf. *strombocarpa*) across the PDT. The forests certainly created distinct fertile landscapes that favored hunting and gathering as well as silvo-agropastoralist systems. In this regard, some *algarrobo* species with edible pods (i.e. *Prosopis alba*, *P. flexuosa*) that occur for the first time during this period could have been introduced from the eastern Andes (McRostie, 2013, 2014). The same might be true of the agricultural complex that included *Arachis hypogaea*, *Chenopodium quinoa*, *Lagenaria*, *Phaseolus lunatus*, *P. vulgaris*, and *Zea mays* (García et al., 2014) as well as plants introduced for foraging purposes (e.g., *Euphorbia amandi*, *Junellia* sp.) (Gayo et al., 2012b).

6.1. The Formative Period in the PDT

This new phase of ‘‘bonanza" is coeval with the Formative Period (2.5–1.5 ka), which in the PDT is characterized by the emergence of complex communities that engaged in dynamic scenarios for social congregation, experimentation, and innovation. Large dispersed and concentrated villages with monumental public spaces founded during this period include: Pircas, Caserones, Ramaditas, Guatacondo, and La Capilla, among others (Adán et al., 2013; Cabello and Gallardo, 2014; Urbina et al., 2012; Uribe, 2006b, 2009; Uribe and Vidal, 2012) (Fig. 4C). A wide range of economic, social and technological innovative arrangements were added to the traditional hunting and gathering systems. The village communities of the PDT also engaged in textile production, wood and shellfish carving, pottery and basketry production, among other manufactures, indicating a growing demand for everyday consumption and public exposure. A landscape of social effervescence seems to have emerged within the PDT villages and its associated ceremonial places such as the cemetery Tarapacá 40 (Uribe et al., 2015). Population size in the PDT increased during this period (Fig. 4, Gayo et al., 2015) and local communities developed sophisticated technologies for managing surface water including the construction of water dams, irrigation canals, well-drained cultivation plots, and wild resources (González-Silvestre et al., 2013; McRostie, 2014; Núñez and Santoro, 2011; Rivera, 2005; Rozas, 2014; Urbina et al., 2012; Vidal et al., 2015).

Regional hydroclimate was still variable during the late Holocene and droughts of diverse duration occurred. Important gaps in the paleoecological record during 2.0–1.6 and 1.3–1.1 ka at the PDT suggest that these aridity events were characterized by reduced productivity brought about by negative hydrological budgets (Gayo et al., 2012b; Fig. 4C). Although the effects of these short-term droughts caused population relocation and disaggregation, the adaptive strategies were successful enough to sustain socio-cultural continuity.

6.2. Socio-environmental systems during late prehistoric period

Late Holocene droughts detected in the PDT could have provoked abandonment and migration in agricultural villages such as Ramaditas and Guatacondo. Likely, these extreme events resulted in massive population migrations to upstream areas and the establishment of new settlements around sectors where water resources were much more abundant and predictable (Maldonado and Uribe, 2015). The observed shift of villages towards the highlands or ‘‘sierra" during the Late Intermediate and Late periods (1–0.6 ka) was possibly caused both by sociopolitical turmoil as well as climatic deterioration (Uribe, 2006a; Uribe et al., 2007; Zori and Brant, 2012). Multiple communities in higher oases, quebradas, sierra, and Altiplano established new systems of agriculture (terraces and irrigation canals), defensive arrangements, and land management within their increasingly circumscribed territories. For instance, the inhabitants of Tarapacá Viejo, one of these higher valley communities, chose diverse risk reduction strategies to minimize both shortage of resources and conflict induced-risk (i.e., increased trade, agricultural diversification and intensification, farming in strategic enclaves, building defensive features, and ritual exchange expressed in rock art) (Zori and Brant, 2012).

During the last millennium, environmental conditions in the PDT were strongly influenced by the Medieval Climate Anomaly (1.1–0.6 ka) (Holmgren et al., 2008; Latorre et al., 2006, 2002; Maldonado et al., 2005; Morales et al., 2012; Mujica et al., 2015). Regional-scale amplified water budgets in the highlands produced positive hydrological balances that increased recharge rates of Andean aquifers and episodic flashfloods in the PDT (Rech, 2001; Rech et al., 2003, 2001). Important population aggregations supported by farming, herding, and foraging developed in highland sierra valleys (above 2400 m) such as Camiña and Mamiña (Adán and Urbina, 2010; Maldonado and Uribe, 2015; Mendez-Quiroz and Uribe, 2010; Pestle et al., 2015; Urbina and Adán, 2006; Uribe et al., 2007). At the same time, the mostly abandoned PDT, was transformed in an inter-nodal territory crossed by trains of llama caravans communicating the highlands with the coast, and only, occasionally used opportunistically by farmers following flashfloods episodes that inundated sections that made fields temporarily productive (Briones et al., 2005).

Archaeological evidence suggests that mining was one of the regional economic activities that developed during the late prehistoric period in the Atacama Desert. Although smelting and mineral extraction took place in Tarapacá since at least 3 ka, mining tasks were tightly connected to the production of prestige goods and tied to inter-regional trade networks (Zori et al., 2013). During the apogee of the Inca State (0.5–0.4 ka), copper and silver mining became important and the scale and organization of mining exploitation and metal production was restructured (Zori and Tropper, 2010). Later, as the economic emphasis of the Andean region was restructured by silver mining, some traditional activities (i.e., agriculture, herding and foraging) became gradually abandoned or deteriorated. Silver was a highly profitable resource in economic terms, as well as a metaphor for wealth, access to power and enhancement of social status (Castro et al., 2012; Gluzman, 2007).

7. Mining and capitalism in the Desert at the dawn of the Anthropocene (0.5–0 ka)

Arid conditions prevailed in the region over the last five centuries (Latorre et al., 2003; Placzek et al., 2001), intercalated by short-lived wet pulses (Christie, 2009; Holmgren et al., 2008; Kuentz, 2012; Morales et al., 2012; Mujica et al., 2015). Nevertheless, the Spanish conquest of the Andes brought new political, technological, demographic, and land use conditions that drastically changed the socio-environmental systems of the Atacama Desert. Demographically, strong transformations occurred, especially along the Pacific Coast, where the Spaniards settled their first colonial cities. This socio-environmental discontinuity persisted until the second part of the 19th century, when an extensive reoccupation of the Atacama Desert took place, as part of the boom in the exploitation of the saltpeter. Unlike previous periods, the colonial occupation of the PDT no longer responded simply to subsistence strategies and socio-environmental transformations occurred despite the desert's physical constrains. As such, the consequences of the new social and political strategies prompted by the new economic model were significant and its impact in the desert landscape is still visible today.

During colonial times, taking advantage of socio-political conditions already established by the Inca conquest, the Spaniards focused – and intensified – the exploitation of some of the desert's mining resources (Zori and Tropper, 2010, 2013). Throughout colonial and, mainly during republican times, mining became increasingly significant for the regional and burgeoning global market economy. With the advent of the anthropocene brought by the industrial revolution, the demands for the mining resources, as well as the technology employed for acquiring them, marked a clear distinction in the dynamics of the human-environmental relationships (Crutzen, 2002).

One of the major consequences of the extractive mentality that soon characterized the modern economy imposed by market capitalism is related to the environmental changes occurred in the last century. By rendering different territories as marginal and empty spaces, this particular narrative was part of the colonial gaze that legitimated the occupation of places. This new way to conceive the Atacama historically involved the displacement of their inhabitants and the imposition of a rationale of progress and modernity (Angelo, 2010; Haber, 1999).

While this can be perceived as part of the continuities observed during this final phase, it needs to be emphasized that these land use strategies are not comparable to those observed in previous periods. The depletion of the desert forests for their use as wood and fuel produced a major transformation in the local ecology. More importantly, management of water has become increasingly problematic but the scarcity of this resource has not prevent the thriving of the extractive economy. Today, the technological systems introduced in the Atacama have been taken to the extreme to supply an enormous demand of water for irrigation, mining, and urban consumption. Despite the long-term human and environmental interaction in the Atacama Desert, the colonial discourse, which persists today, is that the desert is a wild and culturally empty space that has to be tamed and domesticated. This situation intensified after the Pacific War conflict (1879–1883), when Chile incorporated the territories of Atacama and Tarapacá and both state and foreign companies strengthened the narrative of the desert as an empty and marginal land to enforce industrial technology and modernization.

8. Discussion

The scale, intensity and continuity of human adaptive strategies in relation to changes in ecosystem services (i.e., hydrological cycles and biological communities) have been diverse and variable throughout the last 13 ka. Major humid periods followed by dry phases impacted three socio-environmental systems. The first developed between 14 and 10 ka when ground and surface water permanently flowed in abundance from the high Andes to the Pacific coast, as a result of a large post-glacial pluvial event (Fig. 4). Social groups with low population densities established a hunting and gathering way of life in the PDT within the core of the Atacama Desert. People maintained connections to highland and coastal patches to obtain, among other products lithic and marine resources. A clear discontinuity in the paleoenvironmental record of the southernmost PDT basin between 10 and 3 ka (with occasional fluctuations) characterized by increased aridity that brought about the lowest water availability of the last 13 ka with an absence of intermittent or even perennial surface discharge and extremely reduced bioproductivity. People were not able to maintain a hunter-gatherer social system that involved permanently living in the desert and therefore, migrated to the north into the coastal exoreic valleys and to the east towards the "sierra" and Altiplano highlands.

Around 3 ka a new, although less abundant cycle of increased rainfall in the highlands reactivated ground and surface water in the hyperarid core of the Atacama. The increasingly available ecosystem services enhanced by the development of complex technologies of water management, and new social and ideological structures featured the resettlement of the PDT. The communities who reoccupied the region transformed the landscape by building complex and ceremonial architecture, managing all sorts of wild and cultivated resources, and constructing extensive agricultural fields around the villages. These changes constitute quantitative and qualitative innovations triggered by internal socio-cultural factors favored by adequate environmental conditions, which were capitalized by the communities in the PDT. The possible introduction into the PDT of several *Prosopis* species, which edible pods were part of the staple food and its wood forms raw material for different purposes. All these innovations allowed people to establish a new socio-cultural circle of life centered in the PDT during the late Holocene.

The wetter period ended around 1.1 ka, causing communities to move to higher oases and sierra where they engaged with different ecosystem services by developing novel systems of land use and management. As water availability fluctuated throughout the subsequent centuries, human communities responded by decreasing the intensity of their permanent presence in the PDT, often moving upstream into the *quebradas* that (only occasionally) drained into the basin. Certainly, these environmental fluctuations cannot explain the full range of complex sociopolitical variability observed throughout the late prehistoric period in the Atacama Desert, but they were a significant constraint affecting how and which decisions were made by people regarding the use of this landscape and its resources.

The Spanish Conquest completely transformed the social and environmental interactions in the entire South American continent and not just the Atacama Desert. The new socio-ecological paradigm involved an extractive mentality that saw the Desert as an "empty" and "wild" territory that needed to be "tamed". Today, the technological systems introduced in the Atacama during the Formative and slightly modified over the following centuries have been taken to the extreme the exploitation of natural resources, and supply an enormous demand for fresh water used for mining, urban development, and agriculture.

As guano, saltpeter and latter copper became attractive global commodities, during the second half of the 19th century, groundwater pumping became necessary to cope with unprecedented increased demand for freshwater for the workforce and extraction operations. Today, the technological systems introduced in the Atacama have escalated well beyond the recharging capacity of the aquifers. These likely formed during the periods of increased moisture of the late Pleistocene and thus constitute nonrenewable resources. Continuing to squeeze water out of the world's driest desert is likely to become unsustainable in the future and reflecting on the long-term trajectory of socio-natural change will become pivotal for establishing current and future management policies.

As a result of the mining intensification through commodity cycles that included guano, saltpeter, and copper, among others, and the ensuing demographic reconfigurations carried out as part of a national policy of modernization, the desert landscape experienced dramatic changes that add up to its socio-environmental history (Bermúdez, 1963; Mujica et al., 2015; Zolezzi, 1993). Thus, even as human occupation of the desert and use of its resources gradually increased since the late Pleistocene, the scale of human influence during its recent history has been unparalleled. Contrary to earlier periods, when environmental changes seem to have been more prevalent in influencing the human-nature interaction of this territory, the effects of the anthropocene during the past two centuries are immense yet remain poorly investigated.

9. Final reflections

Finally, given the complex history of human-environment interactions in the Atacama Desert, but more importantly, the recent history of its overexploitation, we believe that in order to avoid a disastrous socio-environmental discontinuity, presently, human societies must acknowledge that water is a non-renewable resource. Aggressive extraction of fossil freshwater by using the same technological systems that have been applied for over three thousand years is unsustainable and potentially dangerous. In this context, the critical use of water will require new technological solutions to survive, avoid systemic failures, and leave a legacy for future generations. Therefore, we call attention for the need to develop new cultural solutions and institutional paradigms to improve our current management of this landscape as well as to suppress unsustainable practices such as the aggressive pumping of the limited water stored in the PDT aquifers.

Acknowledgements

We thank Chile's CONICYT's Programa de Investigación Asociativa (PIA), Anillo project SOC1405 "Long Term Social Change and Climatic Variability in the Atacama Desert". Basic research behind this study was obtained through FONDECYT Projects 1130279, 11150089, 11150210, 1150763, 1151046, 3140008, 3150638, 3160443, FONDAP 1511009, PII20150081, and UTA Mayor 3714/14.

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