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Zooming out from archaeological discontinuities: The meaning of mid-Holocene temporal troughs in South American deserts

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ABSTRACT

Building on previous research at smaller scales, in this paper we assemble paleoecological data and archaeological time-series for deserts located in three latitudinal bands along the South American Arid Diagonal (16°–41°S, ~1,236,000 km^2 of area). Diverse proxies suggest the existence of arid and extremely arid conditions in large parts of these deserts. Working with a database composed of 914 archaeological dates falling between the first human presence in each region and 3000 years BP, which produce a minimum number of 578 occupational events, we identify a series of patterns at a macro-regional scale: a robust increase in the temporal signal at the beginning of the mid-Holocene (8000–7600 years BP) followed by two troughs (7600–7200, 6800–6400 years BP) during this period. The spatial scope of the data presented provides an opportunity for disentangling processes of spatial re-localization from actual changes in population size. We present a demographic hypothesis at a macro-regional scale, which suggests the existence of mid-Holocene population bottleneck(s). This hypothesis would account not only for the mid-Holocene troughs, but also for the posterior record of an intense and relatively rapid population growth (release) observed in many regions of the arid diagonal. These mid-Holocene events provide the context for independent trajectories of economic intensification based on different sets of resources - marine foods, camelids, and also probably wetland resources-, some of which lead to domestication processes. These cases occur in association with a tendency towards reduced residential mobility in regions that may have acted as refugia during arid periods of the mid-Holocene.

The analysis produces testable expectations for future research at different scales and for different research domains, including human DNA and morphometric evidence. We consider that these issues have a fecund comparative potential, since the analysis of the socio-demographic meaning of archaeological discontinuities in different continents shares a similar conceptual structure.

1. Introduction: building from the local to the continental

Archaeological discontinuities are a multi-layered phenomenon with demographic, informational, economic, technological, and taphonomic interacting dimensions. These levels are inextricably linked in historical processes. Assessing the behavioral, demographic, and evolutionary meaning of archaeological discontinuities is a highly complex endeavor permeated by issues of scale (Bailey, 2007; Holdaway and Wandsnider, 2006). The behavioral and demographic mechanisms invoked to explain discontinuities vary according to the temporal and spatial scale of patterns recorded in the data. Following 'time perspectivism' (Bailey, 2007), we consider that evidence at different scales can reveal the operation of diverse processes that can be hierarchically connected. Thus, zooming out the scale of analysis becomes a powerful tool for envisioning answers otherwise concealed at smaller scales, traditionally used in the archaeological research in South American deserts.

Archaeological radiocarbon databases provide a spatial-temporal proxy reflecting human rates of human discard of datable material (Rick, 1978; Williams, 2012). The use of summed probabilities of radiocarbon dates as a demographic proxy has grown in scope, methodological robustness, and theoretical insight (Bueno et al., 2013; Gamble et al., 2004; Shennan et al., 2013; Surovell et al., 2009; Williams et al., 2015). Some recent debate has focused on the validity of this line of enquiry based on system-

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atic and random sources of bias that question the chain of connection between time-series and reconstruction of human demography (Bamforth and Grund, 2012; Contreras and Meadows, 2014; García Guraieb et al., 2015). Besides specific methodological responses (Timpson et al., 2014), we consider that this method provides a productive approach to explore structure in the data at a multiplicity of scales, helping to produce hypotheses that can be subjected to scrutiny from independent proxies, genomic analyses paramount among them (Gamble et al., 2004; Sundell et al., 2014; Wang et al., 2007).

In this paper we undertake an exploratory analysis of the temporal trajectories of human occupation in desert regions located along the South American Arid Diagonal (SAAD from now onwards). The goal is to explore the behavioral and demographic meaning of archaeological troughs and gaps in human signals recorded for the mid-Holocene (8000–5000 years BP). This period has received increasing attention in South American deserts, in particular regarding the presence of archaeological hiatuses, initially termed 'archaeological silence' by Núñez and Santoro (1988; see also Grosjean et al., 2007). This trough, which was first analyzed through settlement patterns and later on with radiocarbon datasets, was associated with the advent of global and local mid-Holocene climate changes (Anderson et al., 2007; Gil et al., 2005). Increasing arid conditions starting ca. 9000–8500 years BP recorded in diverse paleoclimatic archives in the Andes and nearby areas (Lamy et al., 1999, 2004; Latorre et al., 2003) have provided the frame for studying human responses to climatic change and resource degradation (Méndez et al., 2015; Neme and Gil, 2009). Volcanic eruptions have also been suggested to operate at local and regional scales (Durán et al., in press).

The analysis presented here is based on a compilation of radiocarbon databases recently published for the following regions (Fig. 1): (a) '*Low latitudes of the SAAD*' (16°–25°S), usually referred to as the South Central Andes, which include northern Chile, southern Peru and western Bolivia (Gayo et al., 2015; Grosjean et al., 2007; Marquet et al., 2012); (b) '*Mid latitudes of the SAAD*' (29°–35°S), integrating Cuyo region of Argentina and North Central Chile (Méndez, 2013; Méndez et al., 2015; Neme and Gil, 2009); and (c) '*High latitudes of the SAAD*' (35°–41°S), corresponding to northwestern Patagonia in Argentina and Southern Chile (Barberena et al., 2015; Campbell and Quiroz, 2015).

Enhanced aridity in already dry regions would increase environmental unpredictability and the associated costs of use of marginal lands (Mandryk, 1993). The most immediate response by mobile hunter-gatherers to increased risks would be spatial reorganization and/or relocation (Garvey, 2008; Méndez et al., 2015), which could lead to abandonment of regions in different spatial scales and for varying amounts of time. So far, working at local and regional levels, evidence of local abandonments and spatial re-locations has been presented for a number of desert regions along the Andes (Marquet et al., 2012; Neme and Gil, 2009; Núñez et al., 2002; Yacobaccio, 2013). While providing the basis for an assessment of the impact of climate change in local populations, this scale of analysis does not allow estimation of the overall demographic trajectories in the South American deserts and neighbor areas. The question in hand is whether the coincidence of multiple discontinuities in neighboring areas is evidence enough of a demographic decrease, which may display seemingly divergent local archaeological trajectories. Our core methodological suggestion is that, by augmenting the analytical scope, we can disentangle processes of spatial re-localization and/or reorganization of mobility from significant demographic changes at the level of metapopulations (i.e., significant increase or decrease in the numbers of people inhabiting a given unit of space). On this basis, we can then explore the behavioral and demographic basis of archaeological discontinuities.

2. South American Arid Diagonal: ecology and paleoecology

Large-scale patterns in the climate of southern South America are related to major atmospheric circulation patterns. The interaction of two large climatic systems that control precipitation patterns, the tropical easterlies and the southern westerlies, and the orographic (rain-shadow) effect of the Andes, results in the major climatic and biogeographic boundary of the SAAD, an arid NW-SE continuous area which extends from Peru to southern Argentina (Figs. 1 and 2) (Abraham de Vazquez et al., 2000; Bruniard, 1982; Villagrán and Hinojosa, 1997). The SAAD, which originated during the Pliocene (Villagrán and Hinojosa, 1997), has remained relatively stable since then, but global and regional climate change during the Late Quaternary has had important changes in the distribution of plants, animals, and human populations (Betancourt et al., 2000; Grosjean et al., 2003; Latorre et al., 2013; Marquet et al., 2012; Méndez et al., 2015).

The three latitudinal bands considered here present striking topographic, climatic, and ecological contrasts. In Fig. 2 we reproduce their main eco-physiographic properties. In Fig. 3 we present an overview of some settings. In the '*Low latitudes of the SAAD*' space is subdivided in: (a) coastal Atacama region, (b) inland Atacama region, and (c) Bolivian Altiplano region (Gayo et al., 2015). In the '*Mid latitudes of the SAAD*', space is stratified in: (a) Pacific coast, (b) western valleys, (c) West Andes, (d) East Andes, (e) Eastern foothills, (f) Eastern lowlands (Méndez et al., 2015). Finally, for the '*High latitudes of the SAAD*' space is subdivided in: (a) Pacific coast, (b) Valleys, and (c) Western Andes, (d) Eastern Andes, (e) Eastern steppes (Barberena et al., 2015; Campbell and Quiroz, 2015).

In Fig. 4 we present an overview of dominant climate trends since the late Pleistocene onwards for the three latitudinal bands considered. These tendencies are assessed in detail below.

2.1. Low latitudes of the SAAD (16°–25°S): South Central Andes of Chile, Peru, and Bolivia

After widespread humid conditions during the late Pleistocene-early Holocene (Betancourt et al., 2000; Latorre et al., 2002, 2003; Maldonado et al., 2005; Sylvestre et al., 1999), extreme arid conditions were established in the South Central Andes around 9500 years BP, peaking at 9000–7000 years BP (Betancourt et al., 2000; Grosjean et al., 2003; Latorre et al., 2003; Maldonado et al., 2005), although the timing of this arid phase varies from site to site. After this arid phase, still more extreme arid conditions characterized the mid-Holocene, but the onset of this environmental condition is a matter of discussion (Grosjean, 2001; Quade et al., 2008). On one hand, wetland and rodent midden-associated plant macro-remains records suggest that less arid conditions would have occurred since 8000–7000 years BP (Betancourt et al., 2000; Latorre et al., 2003; Rech et al., 2002). On the other hand, and in agreement with our view, lake sedimentary records and alluvial deposits from the Altiplano and the Salar de Atacama suggest that the arid phase would have lasted until 4000–3000 years BP, interrupted by a moist pulse around 6000–5000 years BP (Bobst et al., 2001; Grosjean, 2001; Grosjean et al., 2003). Pollen records from rodent middens at 21°S indicate the termination of the arid phase around 3300 years BP, supporting the second alternative (Maldonado and Uribe, 2015). During the late Holocene, highly variable environmental conditions at centennial-to-millennial scales occurred in the South Central Andes, but under less dry scenarios than those of the mid-Holocene. A series of moderate humid phases were recorded at 21°S in the highlands between 2400–720 years BP peaking at 2000 and 1000 years BP (Maldonado and Uribe, 2015), and in the lowlands at 2245–2230, 1615–1350, and

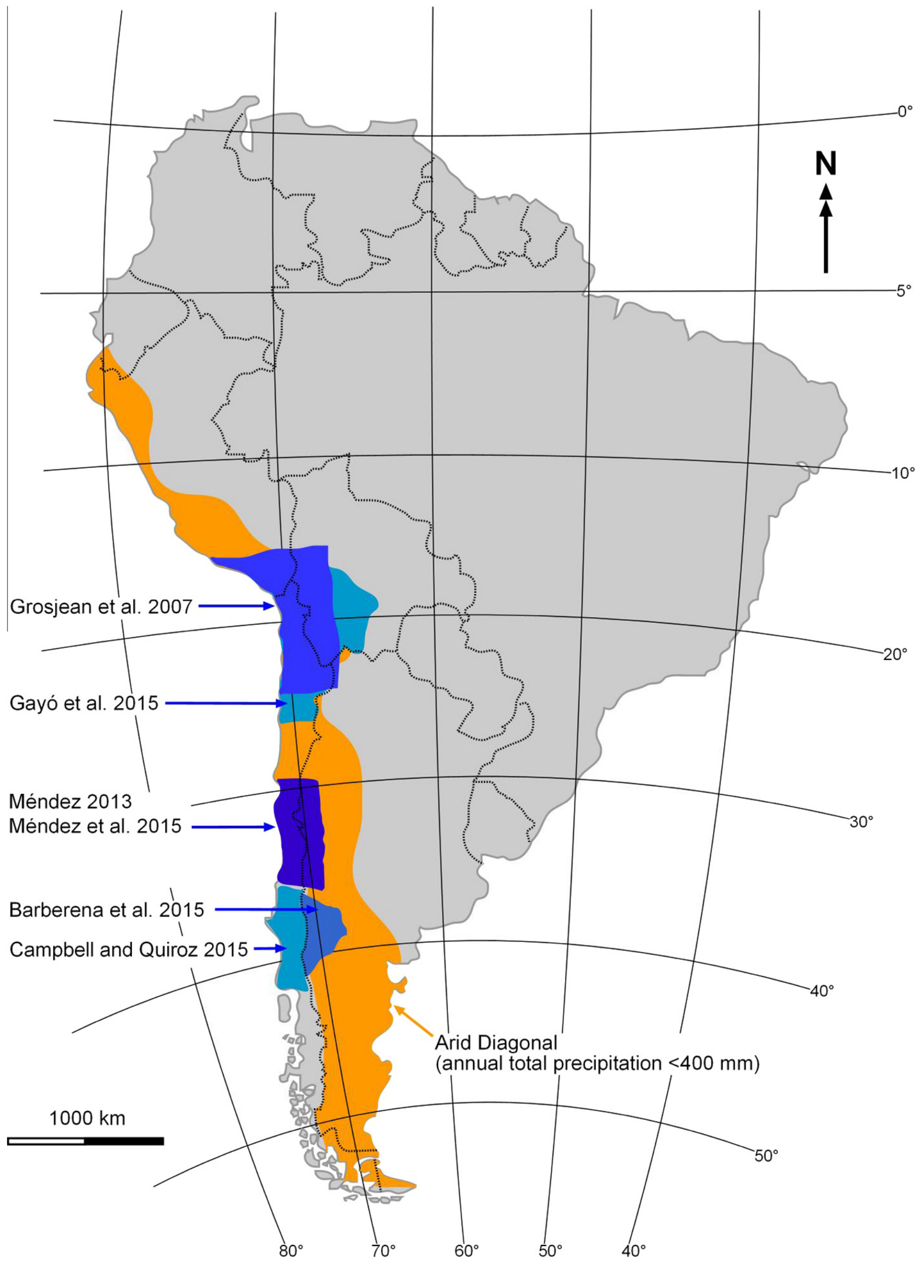

Fig. 1. South American Arid Diagonal and study areas.

1050–650 years BP (Gayo et al., 2012). At the Central Atacama Desert (22°–25°S), humid phases occurred between 1700–1000 years BP (22°30′S; Latorre et al., 2003), 1500–600 years BP (25°30′S; Maldonado et al., 2005), and 1000–500 years BP (24°S; Latorre et al., 2002). It is possible that the onset of the late Holocene moisture increase in the Central Atacama Desert began around 1700 years BP, presenting a peak by 1500 years BP so as to be recorded in the most arid areas.

2.2. Mid latitudes of the SAAD' (29°–35°S): Cuyo region of Argentina, North Central Chile and Norte Chico

During the Pleistocene-Holocene transition (ca. 11,500 years BP), a change from humid and cold conditions to similar to modern conditions occurred (Villagrán and Varela, 1990) in Central Chile and Norte Chico. Then, most of the records suggest early Holocene humid conditions interrupted by an arid phase centered at 9200 years BP represented as an expansion of xerophytic scrubland taxa and a decrease of local humidity indicators (Jenny et al., 2002; Maldonado and Villagrán, 2006). Starting in 8500 years BP, the mid-Holocene was characterized by widespread and extreme arid conditions particularly accentuated between 7800 and 6200 years BP (Jenny et al., 2002; Maldonado and Villagrán, 2002, 2006; Valero-Garcés et al., 2005; Villa-Martínez et al., 2003). Following the mid-Holocene arid conditions, swamp-forests and terrestrial pollen records show a gradual trend towards increased humidity started, peaking at 4500 years BP, which was recorded as a dramatic decrease of Chenopodiaceae percentages in lake records (Valero-Garcés et al., 2005; Villa-Martínez et al., 2003) and a rise of local moisture taxa indicators in swamp forests (32°S; Maldonado and Villagrán, 2002, 2006), whereas marine core records indicate a gradual decrease of temperature (Kim et al., 2002; Lamy et al., 1999).

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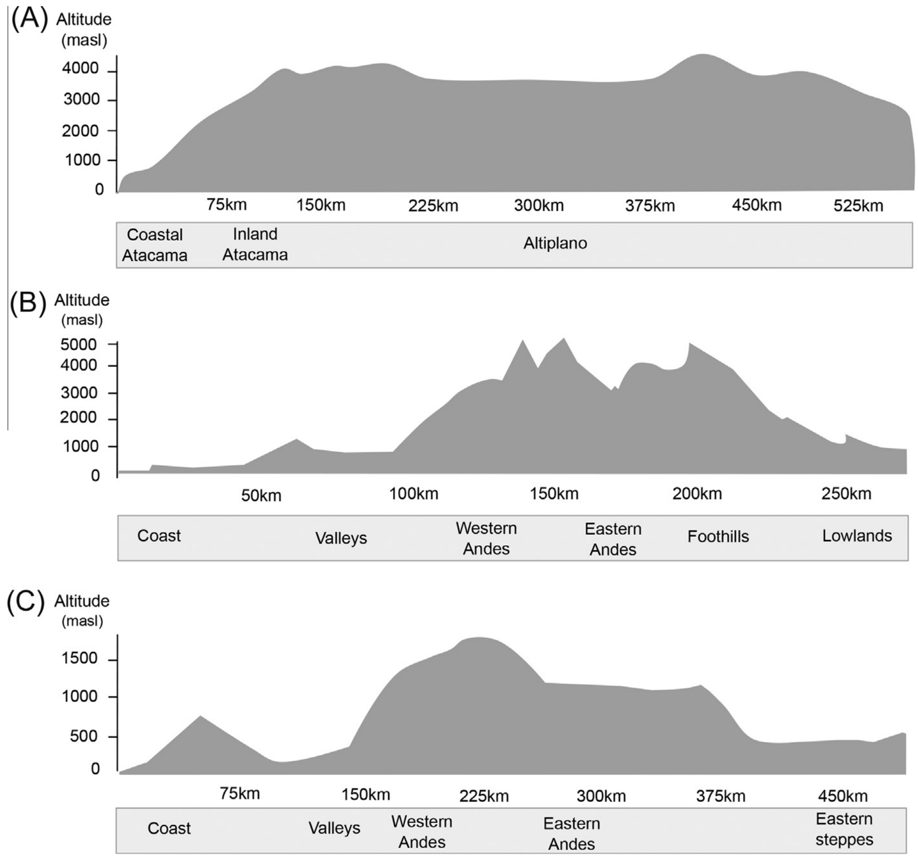

Fig. 2. Eco-physiographic areas in the three latitudinal bands considered. References: (A) Low latitudes, (B) Mid latitudes, (C) High latitudes.

On the contrary, the scarce records located eastwards of the Andes point out humid conditions between 6400 and 5000 years BP. Thus, the presence of Patagonian shrub communities that develop today 100–500 m up slope the Laguna El Sosneado location and a maximum fire frequency and magnitude suggest high fuel availability and, therefore, high water availability during this period (Navarro et al., 2012). On the other hand, Neoglacial advances that occurred between 6400 and 4800 years BP at the Río Valenzuela basin (35°S), strongly dependent on precipitation (Espizúa and Pitte, 2009), suggest humid conditions (Espizúa, 2005). During the late Holocene, most SAAD records show high climatic variability under similar-to-present conditions related to an increased frequency of El Niño Southern Oscillation (ENSO from now onwards) events during the last 2000 years (Rein et al., 2005). Laguna El Sosneado record shows, however, a trend towards drier conditions up to present ones (Navarro et al., 2012).

2.3. High latitudes of the SAAD' (35°–41°S): northwestern Patagonia in Argentina and South Central Chile

Most records between 41° and 42°S along the western Andes show abrupt increases and dominance of the thermophilous Valdivian trees *Eucryphia/Caldcluvia* between 11,500 and 7000 years BP (Abarzúa et al., 2004; Jara and Moreno, 2014; Moreno, 2004; Moreno and León, 2003; Villagrán, 1990), whereas between 38 and 39°S, a *Nothofagus obliqua*-dominated forest developed (Abarzúa, 2009; Heusser, 1984). This dramatic vegetation change in the Late Glacial plant communities suggests the establishment of peak interglacial warmth (multi-millennial warm/dry phase) and a substantial reduction in precipitation driven by a regional weakening of the westerly winds. Since 7000 years BP, a gradual expansion of the north Patagonian forest between 41 and 42°S indicates overall cool-temperate conditions associated to a precipitation increase compared to the early Holocene, brought on by an equator-ward shift/intensification of the southern Westerlies (Heusser, 1966; Jara and Moreno, 2014; Vargas et al., 2008). At 38–39°S, changes in the forest composition reveal wetter conditions but still presenting thermophilous elements, therefore suggesting warm scenarios up to 2000 years BP (Abarzúa, 2009). Coupled with cooler conditions, enhanced fire activity prevailed over the region during the mid-Holocene, pointing out high climatic variability mainly related to ENSO (Jara and Moreno, 2012).

A well-defined west-to-east vegetation gradient developed eastward of the Andes during the late Pleistocene-early Holocene (Iglesias et al., 2014; Markgraf et al., 2009; Whitlock et al., 2006). Then, no major vegetation changes were recorded during the mid-Holocene given that their dynamics mainly involved millennial- and centennial- trade-offs between trees and shrubs that were likely brought about by shifts in water availability. At 39°S, a high diversity of the steppe recorded in Mallín Vaca Lauquen between 12,000 and 8000 years BP was interpreted as increased precipitation and temperature, though below present values (Markgraf et al., 2009). Based on the later, it was hypothesized that the existence of opposite precipitation patterns west and east of the Andes (dipole) would have been the result of an anomalous component of the upper level flow. However, the development of open *Nothofagus dombeyi* forest supporting substantial amounts of steppe and scrubland elements associated with recurrent fires in Laguna El Trébol (41°S) between 11,400 and 6000 years BP was interpreted as a signal of drier than present conditions (Whitlock et al., 2006). In synthesis, Laguna El Trébol record supports the arid conditions recorded in those sites on the leeward

Fig. 3. Different areas of the SAAD: (A) Camarones 14 site (mid-Holocene) at low latitudes, (B) Ñagué site (early Holocene) at mid latitudes, (C) Cueva Huenul 1 site (late Pleistocene-late Holocene) at high latitudes.

side of the Andes and does not match the climatic inferences (precipitation dipole) proposed by Markgraf et al. (2009). During the last 5000 years, higher effective moisture promoted the development of modern vegetation likely as a response to the continued northward shift/strengthening of the southern westerlies, as well as the strengthening of ENSO-related climate variability (Lamy et al., 2004; Markgraf et al., 2007, 2013).

3. Materials and methods

3.1. Materials

We integrate four radiocarbon databases that have been compiled in previous publications (Barberena et al., 2015; Campbell and Quiroz, 2015; Gayo et al., 2015; Grosjean et al., 2007; Marquet et al., 2012; Méndez, 2013; Méndez et al., 2015; Neme and Gil, 2009). While this combined database does not provide a continuous spatial cover of the SAAD and its ecotones, it allows a first exploration of variation of the mid-Holocene archaeological record in deserts with diverse geographic and ecological features. These databases were selected because they provide some of the largest temporal series available for South American deserts and neighbor areas, and are currently updated. In order to consider both flanks of the Andes in the three latitudinal bands, we decided to include the database recently published by Campbell and Quiroz (2015) for South Central Chile, which lies in a humid setting westwards of the SAAD. This allows for a first step towards integrating the temporal record from deserts with contiguous ecologic zones.

We include dates ranging between the earliest clearly documented human presence in each region and up to 3000 14C years BP. This allows assessing the mid-Holocene chronological trends in a wider temporal frame. With the exception of areas in the high latitude, 3000 years BP further provides a limit for fully hunter-gatherer life-ways in most areas comprised by these regions (Morales et al., 2009). This is important since the key feature of mobile societies is the relocation of residential camps at different yearly time scales (Kelly, 1995), thus providing broad comparability of patterns of interaction with the environment. In addition, 3000 years BP sets a limit for the widespread use of other dating methods, such as thermoluminiscence on pottery, which introduces an additional bias since sample selection and calibration is not fully comparable to radiocarbon dating (Falabella et al., 2015). Since these temporal series have already been fully published as sets, we do not reproduce them here. We excluded dates

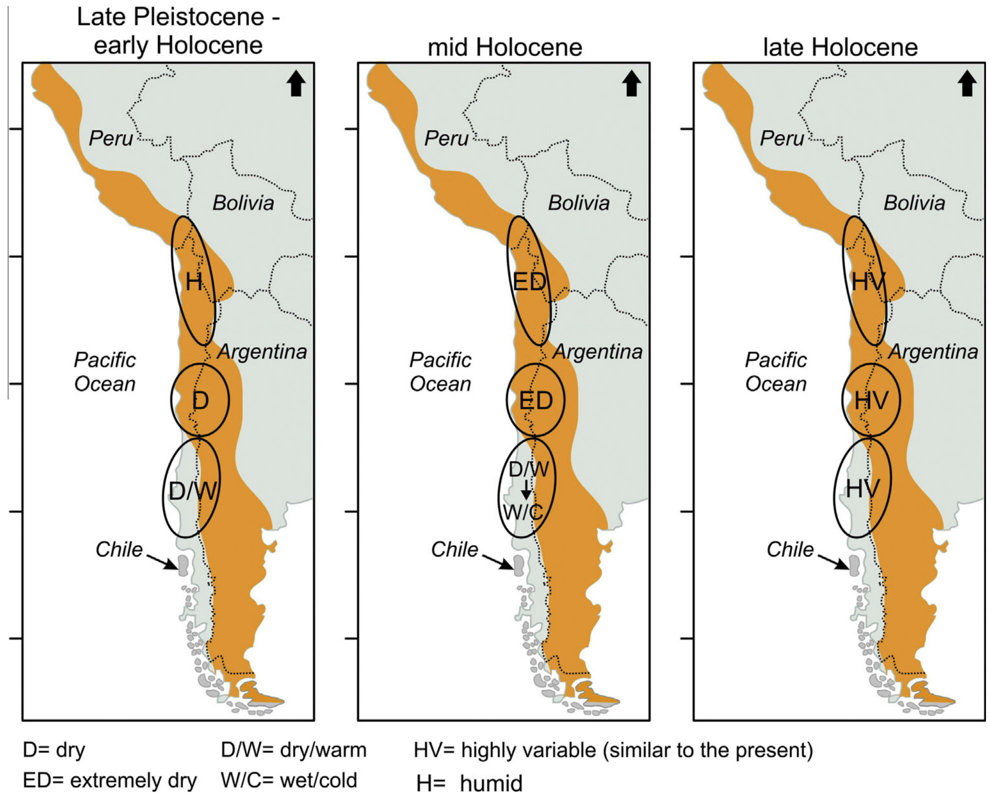

Fig. 4. Map of southern South America showing the SAAD and general climatic conditions during key periods.

showing standard deviation larger than 250 years, since they introduce imprecision in the analysis (Jull et al., 2013). On the other hand, we also excluded dates obtained from marine organisms, since there is no precision on the magnitude of the "aging" of the 14C signatures due to local reservoir effects in these different areas and also through time (Ortlieb et al., 2011). This improves the precision of the analysis, though may certainly introduce some bias in coastal records. Nevertheless, preliminary comparisons between time series with and without shell dates at North Central Chile show that overall trends are not altered, while peaks and troughs in the radiocarbon record are enhanced when these are excluded (Méndez et al., 2015). Unless specifically stated otherwise, the radiocarbon ages mentioned in the text are calibrated and expressed as years BP.

3.2. Methods

The radiocarbon samples were calibrated with Calib 7.1 (Reimer et al., 2013), using the calibration curve for the southern hemisphere (SHCal13, Hogg et al., 2013). The basic analytical units in this paper are the occupational events at the site scale. These events were calculated by averaging the dates at sites with multiple ^{14}C measurements that are statistically undistinguishable (Shennan and Edinborough, 2007). Dates were sorted in ascending order and two or more dates were averaged whenever their differences were not significant (at <0.05) according to a *t*-test (Ward and Wilson, 1978). The number of occupational events that results from these operations must be considered a "minimum number of events" (Méndez, 2013; Peros et al., 2010; Wicks and Mithen, 2014).

As a first step, we use summed probability plots at two-sigma confidence level to assess comparative trends in the different regions. Then, dates are assigned to 200 years-bins based on their medians. Following Peros et al. (2010), this bin-size was selected since it is considerably larger than double the median ^{14}C error of 64 year for the full dataset (Table 1). The resulting histograms are plotted with a moving average trend line of 400 years that helps removing the most important effects of the calibration process, such as artificial troughs associated to the presence of plateaus in the calibration curve (Michczynski and Michczynski, 2006; Williams, 2012).

Taphonomic bias is among the main factors influencing the results of ^{14}C time series analysis since, other things being equal, the older an archaeological event is, the less likely it is to be preserved. As Surovell et al. (2009) suggest, this time-dependent taphonomic destruction may mimic a signal of population growth. To address this issue we utilize the taphonomic correction equation suggested by Surovell et al. (2009) with the correction introduced by Williams (2012). We do not differentiate samples in terms of their context (open air vs. shelters). Aiming at an assessment of the changes introduced by the taphonomic correction, we compare the original and corrected curves.

4. Results

4.1. Macroregional scale

The database is comprised of 914 dates that produce a minimum number of 578 occupation events distributed across the three latitudinal bands (Table 1). The regions considered here present very different research histories that lead to unequal sampling intensities. Northern Patagonia, particularly on the western watershed of the Andes, is under-sampled. With this exception, the density of occupational events per km^2 is relatively even, with a mean value of 0.46 event per km^2. The standard deviations for the different regions have median values between 50 and 72 years with a global median for the 578 occupational events of 64 years (Table 1).

Table 1
Numbers of dates and occupational events for the regions considered.

Region	N of raw dates	Minimum N of occupation events	Median of standard deviations	Area (km^2)	Events per km^2	Reference
Low latitudes	515	323	64	~760,000	0.42	Gayo et al. (2015)
Mid latitudes	258	160	60	~205,000	0.78	Méndez (2013), Méndez et al. (2015) and Neme and Gil (2009)
High latitudes west (Chile)	65	38	70	~163,000	0.23	Campbell and Quiroz (2015)
High latitudes east (Argentina)	76	57	52	~108,000	0.53	Barberena et al. (2015)
Total	914	578	64	~1,236,000	0.46	

The combined chronological database for the three latitudinal bands represents a total of ca. 1,236,000 km^2, integrating areas such as the South Central Andes -northern Chile, southern Peru, and western Bolivia-, Central Argentina and Chile, and northern Patagonia (Fig. 1). This provides a glimpse of a number of South American deserts with diverse topographic, climatic, and biogeographic features. In Fig. 5 we present the summed probability curve for the three latitudinal bands combined, a histogram with the frequency of dates per time interval of 200 years and a 400 years-moving average, and the frequency of occupation events corrected for taphonomic destruction (following Williams, 2012).

The earliest widely accepted date for human presence in South America is 14,600 years BP at Monte Verde II (Dillehay, 1997), included here in the high latitudes assemblage. This initial human signal is not repeated in other areas of the SAAD. The most widespread human presence appears consistently at 13,000 years BP and generates an initial peak in the time-series, lending support for the existence of demographically viable hunter-gatherer populations (Méndez, 2013; Steele and Politis, 2009) in the SAAD. This early peak should be regarded with caution in view of a possible bias towards dating the first human appearances in stratified sites. During the early Holocene, variable increases in dates produce a series of peaks that are different for each latitudinal band herein discussed. The early troughs recorded at high latitudes of the SAAD should also be treated with caution, since they are likely artifact of low research intensity.

The beginning of the mid-Holocene at 9000–8500 years BP is marked by an augment in the density of the probability curve, and then followed by two distinct troughs occurring respectively between ca. 7600–7200 and 6600–6400 years BP, separated by a period of intense density of summed probabilities between 7200 and 6600 years BP (Fig. 5). Overall, this temporal structure is replicated in the different analyses conducted: summed probability (Fig. 5a), frequency of dates per 200 years intervals and 400 years moving average (Fig. 5b), and frequency of dates corrected for taphonomic destruction (Fig. 5c). The only noteworthy difference is observable between the series corrected for taphonomic destruction against the others, since the correction increases the intensity of the signal during the Early Holocene to levels that are similar to those recorded for the late Holocene.

4.2. Regional scale

In Figs. 6–8 we present the time series for the low latitudes (16°–25°S), mid latitudes (29°–35°S), and high latitudes (35°–41°S) databases respectively.

Despite minor differences, the structure of the mid-Holocene probability curves is remarkably similar in the three latitudinal

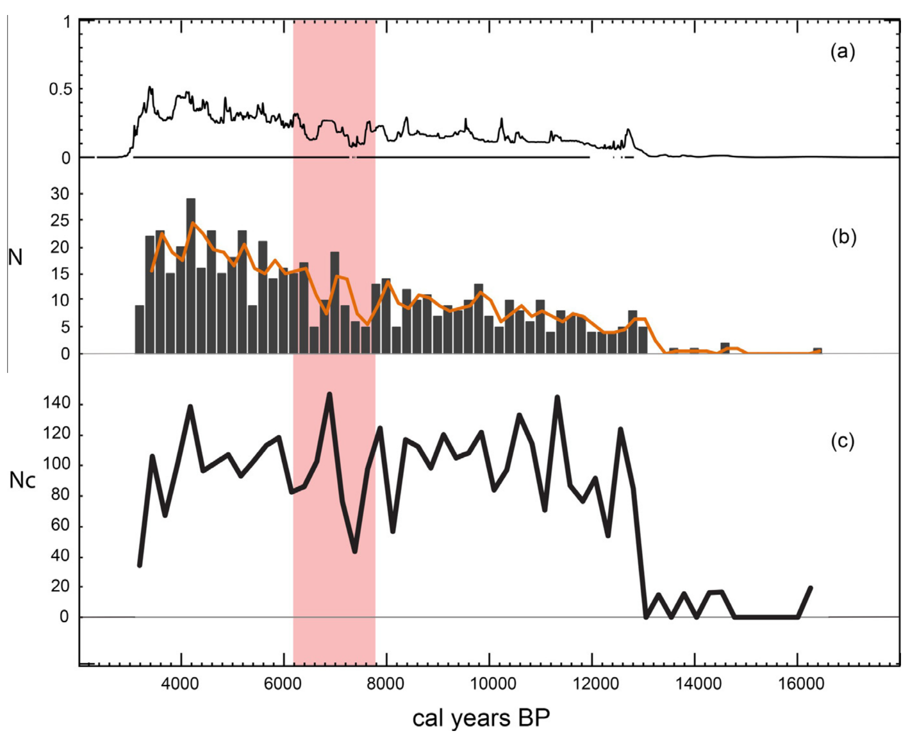

Fig. 5. Time series for the three latitudinal bands of the SAAD: (a) summed probability; (b) frequency of dates per 200-interval and 400 years-moving average; (c) frequency of occupation events corrected for taphonomic destruction (Nc).

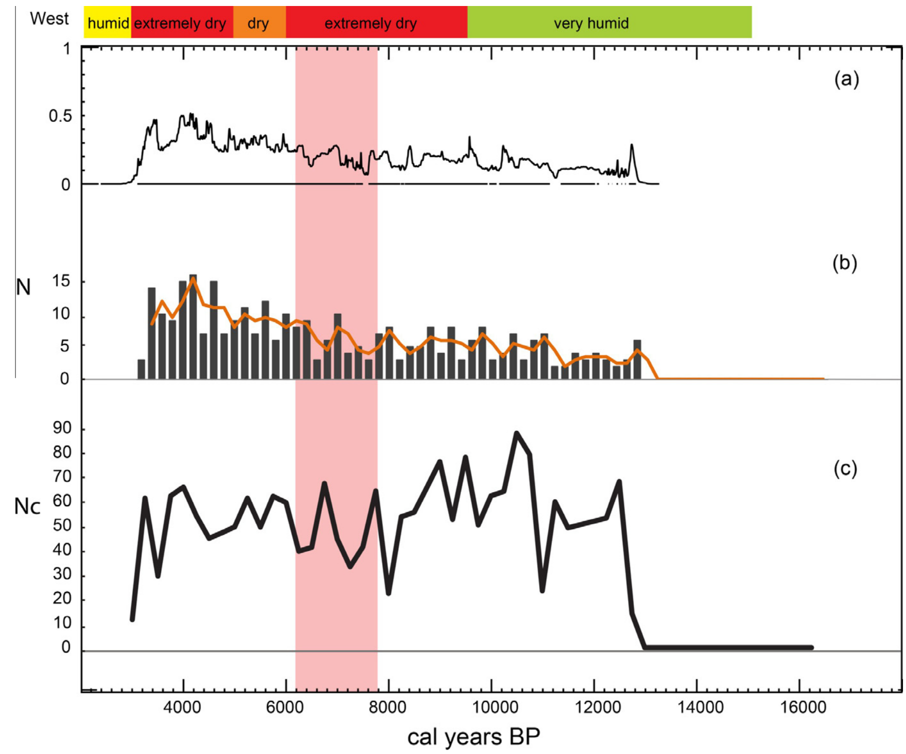

Fig. 6. Time series for the low latitudes of the SAAD: (a) summed probability; (b) frequency of dates per 200-interval and 400 years-moving average; (c) frequency of occupation events corrected for taphonomic destruction (Nc).

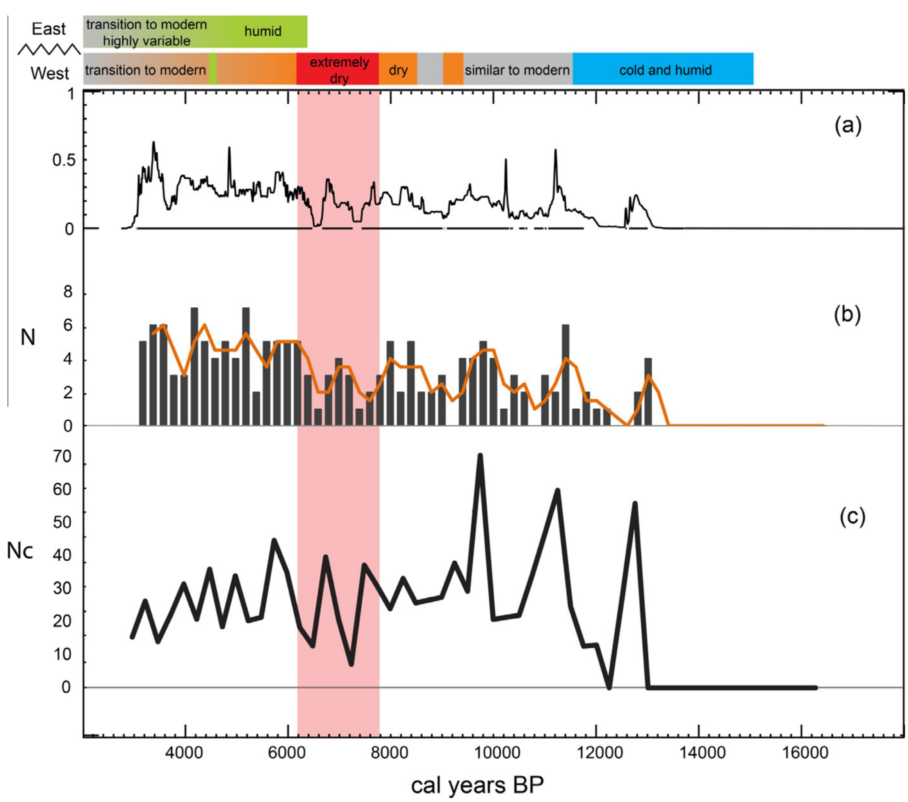

Fig. 7. Time series for the mid latitudes of the SAAD: (a) summed probability; (b) frequency of dates per 200-interval and 400 years-moving average; (c) frequency of occupation events corrected for taphonomic destruction (Nc).

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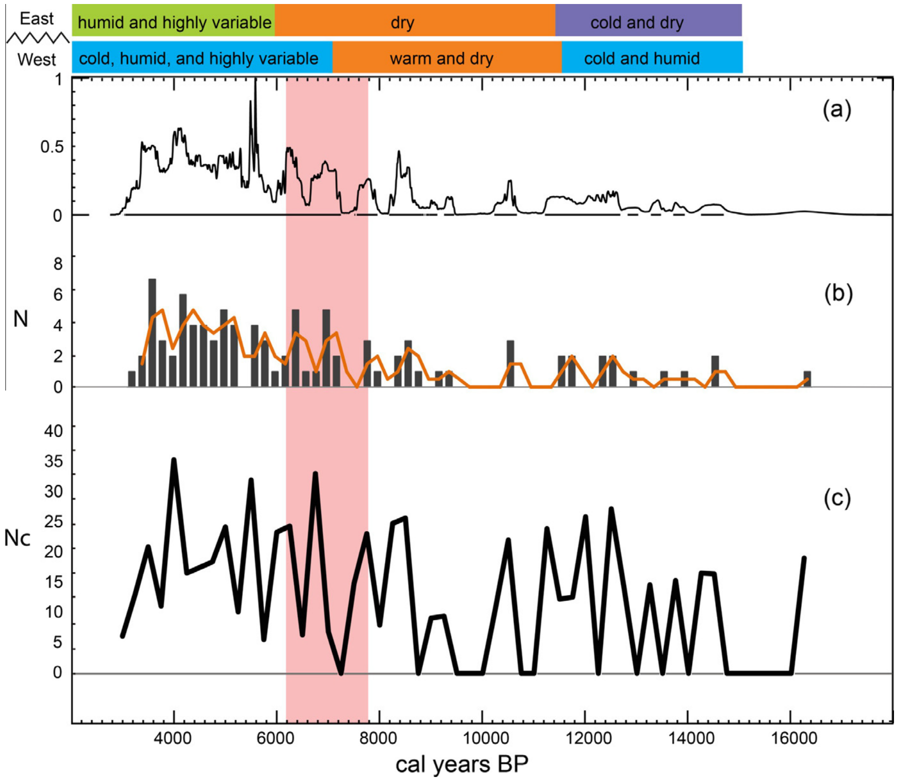

Fig. 8. Time series for the high latitudes of the SAAD: (a) summed probability; (b) frequency of dates per 200-interval and 400 years-moving average; (c) frequency of occupation events corrected for taphonomic destruction (Nc).

bands of the SAAD, as can be seen in the summed probabilities, the frequencies of minimal occupational events, and the 400 years-moving average lines, which would soften peaks and troughs. This overall similarity includes an increase in the signal at the beginning of the mid-Holocene that is followed by the two troughs referred above for the full dataset (Fig. 5). This is most visible in the mid (Fig. 7) and high latitudes (Fig. 8), where the temporal signal is fully interrupted at times. In the case of the low latitudes band (Fig. 6), the troughs are still present, tough in a less marked fashion (Fig. 6).

The series based on the data corrected for taphonomic destruction homogenize the time series for the full dataset, as well as for the individual latitudinal bands, by producing an increase in the intensity of the signal for the early Holocene when compared to the late Holocene. Interestingly, the mid-Holocene troughs are still recorded in these corrected series.

5. Discussion

5.1. Alternative explanations for the temporal patterns

When attempting to extract information on intensity of human occupations to infer aspects of paleodemography, we face three main sources of bias: sampling limitations, taphonomic destruction, and artificial products of the calibration curve (Campbell and Quiroz, 2015; Gayo et al., 2015; Méndez et al., 2015; Shennan et al., 2013; Williams, 2012).

Biases stemming from deficiencies in sampling can be minimized by zooming out and increasing spatial scale. In the three regions considered here, teams with diverse research traditions, aims, and field sampling strategies have produced the radiocarbon record during the last decades, minimizing systematic bias due to research decisions and contributing to provide an averaged chronological signature for the macro-region. We do not consider that research decisions would have the capacity to artificially produce the troughs recorded on a macro-regional scale.

We cover a region large and diverse enough to include multiple taphonomic modes that would not have been affected by sources of taphonomic bias acting in a similar fashion, so as to produce taphonomic biases at a macro-regional level.

In addition, the presence of an intense -though variable- early Holocene signal in association to different taphonomic modes from the three latitudinal bands weakens taphonomy as the main explanation for the mid-Holocene patterns recorded.

Admittedly, the series corrected for taphonomic destruction provide only a preliminary assessment, since we have not discriminated samples in terms of their context of deposition (open air vs. sheltered sites). In the three regions, it is evident that the correction produces an over-representation of the early Holocene record, which shows levels comparable to the late Holocene, a consideration that is not supported by quantitative nor qualitative data from these regions. This would be due to the inclusion of the samples coming from rock shelters and caves, indicating that an assumption of time-dependent taphonomic loss may not be valid for samples deposited in these contexts (see Goldberg et al., 2016; Williams, 2012), at least as modeled by the correction equation. Interestingly, the mid-Holocene troughs are not obscured by the likely artificial changes introduced by the taphonomic correction to the early Holocene section of the curve, remaining as distinctive low points within the series. We suggest that this highlights the robustness of the pattern in the full dataset of the SAAD and in the three individual regions.

Properties inherent to the southern hemisphere calibration curve may produce 'artificial' outcomes in the summed probabilities, biasing the macro-regional temporal patterns. Steep segments of the calibration curve for the southern hemisphere (Hogg et al., 2013) produce artificial concentration of dates within certain time periods that simulate temporal peaks, while plateaus in the calibration curve may produce troughs in the temporal series (Michczynski and Michczynski, 2006; Prates et al., 2013). Due to their susceptibility to methodological factors, we do not give accentuated peaks a role in the development of our discussion. By augmenting analytical scale, the use of the 200 years-intervals coupled with a 400 years-moving average minimizes the incidence of these effects (Williams, 2012). Importantly, the mid-Holocene troughs are recorded in the different analyses applied to the temporal data. In addition, we refer to the thorough analysis published by Gayo et al. (2015) for the calibration curve of the southern hemisphere showing that, when calibrating samples at two-sigma, there are no major plateaus in the mid-Holocene, as opposed to two significant ones detected between 5381–4973 and 4675–4207 years BP (Gayo et al., 2015, Table S4). In addition, there is no overlap between steep sections of the calibration curve with the areas of high density of summed probability in the plot for the SAAD during the mid-Holocene (Gayo et al., 2015, Table S5). In sum, the temporal tendencies recorded for the mid-Holocene in the three latitudinal bands of the SAAD would not be an artifact of the calibration process.

As already mentioned, the degree of consistency in the patterns recorded across regions with diverse taphonomic modes and research histories do not lend support to taphonomy or sampling decisions as the main source for this pattern. On this basis, we suggest that the main troughs recorded for the mid-Holocene represent periods of decreased human occupation in multiple regions of the SAAD and neighbor ecological zones (among others, see Araujo et al., 2005–2006; Gil et al., 2005; Goldberg et al., 2016).

5.2. Climate change and landscape fragmentation in macro-regional scale

In the context of considerable spatial and temporal variation, the paleoecological information reviewed above suggests the predominance of dry conditions during the mid-Holocene in large parts of the SAAD. This is particularly clear in the records from the low (Fig. 6) and mid latitudes (Fig. 7), with periods characterized as 'extremely dry' on the basis of several proxies (Grosjean et al., 2007; Latorre et al., 2003; Maldonado and Villagrán, 2006; Maldonado et al., 2005), while the fragmentary information available for northern Patagonia (Fig. 8) indicates the establishment of a well-defined west-to-east humidity and vegetation gradient developed eastward of the Andes since the late Pleistocene-early Holocene (Iglesias et al., 2014; Markgraf et al., 2009; Whitlock et al., 2006). It is also evidently clear that, despite the existence of predominantly arid conditions, humid pulses of varying extent and intensity also characterized the mid-Holocene across the latitudinal range considered (Bobst et al., 2001; Grosjean et al., 2003). The exploratory nature of this paper, plus the large scale of analysis utilized, prevent us from attempting to correlate temporal trends in the archaeological record with paleoclimatic proxies in a high temporal resolution. Rather, we are interested in exploring the effects of enhanced and prolonged aridity on resource availability for human populations.

Different proxies from the three latitudinal bands indicate that enhanced aridity in these already dry settings would have produced an increase in landscape fragmentation, expressed as large parts of the landscape taking the character of temporary or continuous barriers for humans (Veth, 1989). The persistence of arid conditions in annual, decennial, and centennial time scales would produce a progressive desiccation of the landscape with cumulative consequences for forager societies (Marsh et al., in press). The occurrence of short wetter pulses interspersed between dry periods would ameliorate, but not reverse, prevailing ecological conditions. The barrier-character implies infrequent human use associated to elevated risks involved in traversing or occupying dry and unpredictable areas (Fitzhugh et al., 2011; Mandryk, 1993). In ecologically extreme cases, this could also produce the abandonment of large regions (Gil, 2006; Manning and Timpson, 2014; Núñez et al., 2002; Schlanger and Wilshusen, 1993).

5.3. Refugia in archaeological scale

There is abundant paleoecological and archaeological evidence for the existence of favored tracts of the landscape of the SAAD during the mid-Holocene. These may be considered analogous to Veth's (1989) 'islands in the interior' of the Australian Desert, Yacobaccio's (1994) 'zones of nutrient concentration' of northwestern Argentina, or Núñez et al. (1999) 'opportunistic refugia' of Atacama. We explore a few cases that play a qualitative role in our argument, by indicating places that may have had a key role in terms of demographic persistence (Smith, 1989) and, in some cases, socio-economic change. These cases can be considered potential refugia during the mid-Holocene, and may have acted as buffer zones allowing to cope with the higher risks that prevailed during adverse climatic pulses (Lanata and Borrero, 1994).

In the low latitudes of the South Central Andes, some tracts of the Pacific coast did not only have continuous human occupation, but also experienced demographic growth and social elaboration leading to the astounding Chinchorro cultural complex (Arriaza et al., 2005). As Marquet et al. (2012:14756) indicate, "the resulting [temporal] curve indicates that human populations increased dramatically at 7 ka BP and peaked by 6 ka BP". This demographic node is associated with a process of economic intensification based on marine foods (Santoro et al., 2012).

Also located in the low latitudes band, high areas of the Puna plateau presented scattered oases-like settings in association to springs or river valleys (Latorre et al., 2006; Ledru et al., 2013; Núñez et al., 1999; Yacobaccio, 2013). Núñez et al. (1999, 2002) acknowledged these contexts first at the Puripica locality in northern Chile, where water availability was controlled by local factors. Recent interdisciplinary research suggests that these settings experienced the first experiments of guanaco (*Lama guanicoe*) 'herd protecting strategies' leading to domestication (Cartajena et al., 2007; Yacobaccio, 2004). Based on extensive Andean databases, Yacobaccio and Vilá (2013) suggest that this process should be framed as a trajectory of gradual economic intensification on wild camelid populations in the context of reduced residential mobility.

In the mid latitudes-band, we have the record of the Tagua Tagua wetlands in Central Chile (34°S), which remained as a key and persistent wetland ecosystem during mid-Holocene (Valero-Garcés et al., 2005). Yielding an initial occupation at 13,000 years BP (Núñez et al., 1994), the most redundant archaeological assemblages in the Tagua Tagua area appear to be of mid-Holocene age. Though only published on a preliminary basis, this locality is known to present a mortuary record indicative of recurrent human burial in particular sites, such as Cuchipuy and Santa Inés, during the mid-Holocene (Jackson et al., 2012; Kaltwasser et al., 1983). The Cuchipuy site is a key early burial and residential site in Central Chile showing a minimum number of ca. 50 individuals (E. Aspillaga, pers. comm. to C. Méndez, 2015) excavated on a continuous stratigraphic feature contained between ca. 8000 and 5800 years BP (Jackson et al., 2012; D. Jackson, unpublished data; Kaltwasser et al., 1983). The archaeological record at this particular ecological site suggests the attraction and role of stable freshwater resources, a suggestion that is substantiated by preliminary stable isotope determinations for the site (Sanhueza and Falabella, 2010).

Summing up, despite their different ecological and historical dynamics, low-latitude localities, such as coastal Atacama and some Puna oases, and mid-latitude contexts, such as the Tagua Tagua wetlands, preserve an intense and unique mid-Holocene signal with behaviors suggestive of reduced mobility and incipient economic intensification that is based in different sets of resources. In the macro-regional context of aridity and increasing landscape fragmentation that is indicated for segments of the mid-Holocene, these localities can be satisfactorily conceived as refugia. Some of these refugia witnessed initial processes of economic intensification during the mid-Holocene, such as marine specialization in the Chinchorro complex of northern Chile (Marquet et al., 2012; Santoro et al., 2012) and camelid herd-protecting strategies ultimately leading to llamas (*Lama glama*) and alpacas (*Vicugna pacos*) in the South Central Andes (Cartajena et al., 2007; Stahl, 2008; Yacobaccio and Vilá, 2013). The mid-latitudes in Central Chile may have witnessed human adaptations emphasizing low mobility and broad-spectrum diets focused on wetland resources.

5.4. Is spatial relocation/reorganization a sufficient explanation for the mid-Holocene record? A demographic hypothesis

The primary mechanism that mobile societies employ to cope with increasing aridity and landscape fragmentation would be spatial and/or organizational rearrangements. Depending on human decisions, these spatial changes may take the form of increased residential and/or logistical mobility (Binford, 1991; Veth, 2005) or decreased residential mobility and tethering to favored locales (Garvey, 2008). An enlargement of logistical mobility circuits may also complement the second option (Goñi, 2000). However, ecological and demographic conditions may limit the capacity of these spatial mechanisms to overcome landscape fragmentation. The key issues would be the extent of landscape fragmentation produced by persistent aridity, or the amount of space that takes the character of barriers for humans (Smith, 2013; Veth, 1989; Williams et al., 2013), the carrying capacity of environments suitable for human use, which could be realized by means of economic intensification, and the availability of adequate information and technology enabling it.

As presented in Figs. 6–8 the structure of the time series for the three latitudinal bands is remarkably similar, showing a robust increase in the signal at the beginning of the mid-Holocene, ca. 8000–7600 years BP, followed by two troughs respectively at ca. 7600–7200 and 6800–6400 years BP. The first trough, in particular, indicates the minima in the intensity of the temporal signal in the three latitudinal bands of the SAAD. Accepting the limitations of the currently available database, its spatial scale that covers ~1,236,000 km^2 is an important asset. The concurrence in the timing of the two troughs described, plus their macro-regional spatial scale, lead us to suggest that besides spatial mechanisms of coping with risk, the mid-Holocene record of the SAAD would indicate a large-scale demographic decrease. Recent research by Goldberg et al. (2016, 234) at the scale of South America, with a focus that is not restricted to deserts, suggests that "... population density during the mid-Holocene is in the lower range of estimates for the density of worldwide hunter-gatherer populations". In addition to a decrease in presumable numbers of people, the archaeological record also suggests a 'contraction of range', or space that is systematically occupied by human populations, as the occupational histories of several regions indicate (Barberena, 2015; Núñez et al., 2002; Méndez et al., 2015).

In sum, the combination of two macro-regional troughs occurring at roughly the same periods –though with different intensity – in the three latitudinal bands of the SAAD (low abundance), the absence or near absence of human occupation in several tracts of the SAAD (contraction of range), plus the record of relatively fast increases in the temporal signal following the troughs, *make an excellent case for the existence of population bottleneck(s) in the SAAD during the mid-Holocene*.

The bottleneck scenario implies a *release* or demographic expansion stage following the trough. We consider that this dynamic provides a mechanism that may explain several demographic, economic, and social processes observed after 6000 years BP. The end of the mid-Holocene is marked by a temporal signal that is more intense and continuous than ever before. So far, this macro-regional pattern has been described rather than explained. The expansion mechanisms involved in a bottleneck may contribute to explain these demographic changes at an appropriate spatial scale (Ambrose, 1998; Bennett and Provan, 2008; Sundell et al., 2014). Goldberg et al. (2016, 234) have suggested that the post mid-Holocene record shows exponential demographic growth that would be associated to "the shift to a predominantly sedentary and agricultural subsistence ... between 5.5 ka and 3.5 ka", akin to the demographic transition characteristic of the European Neolithic. While this explanation may account for a fraction of the late Holocene processes of demographic growth, it seems unlikely that it accounts for the full range of processes recorded in South America, particularly if we consider that large parts of the continent did not experience a transition to productive economies until ca. 2000–1000 years BP (e.g., Gil et al., 2014). In addition, other regions that would display a pattern of post mid-Holocene exponential demographic growth, such as the high latitudes band discussed here, plus other areas further south, did not witness the shift to productive economies nor sedentary organization whatsoever (Morales et al., 2009; Morello et al., 2012). In synthesis, we suggest that the release following the alleged mid-Holocene bottleneck(s) and the demographic transition associated to reduced mobility (as suggested by Goldberg et al., 2016) provide complementary mechanisms to account for the late Holocene archaeological record of South America.

6. Conclusions and perspectives

Building on previous research in smaller scales (Gayo et al., 2015; Grosjean et al., 2007; Marquet et al., 2012; Méndez et al., 2015; Neme and Gil, 2009), we have assembled and compared paleoecological data and archaeological time series for three latitudinal bands of the SAAD from 16° to 41°S. Diverse proxies suggest the existence of arid and extremely arid conditions in large parts of the SAAD, though not in a synchronous fashion. We have identified a number of archaeological patterns that are recorded on a macro-regional scale of analysis: a robust increase in the temporal signal at the beginning of the mid-Holocene (ca. 8000–7600 years BP) followed by two troughs (ca. 7600–7200, 6800–6400 years BP). The first trough indicates the minima in the intensity of human occupation in the three latitudinal bands. Though causal relations are far from clear, these mid-Holocene events provide the context for the initiation of independent trajectories of economic intensification based on different sets of resources -marine foods, camelids, and probably wetland resources-, some of which lead to domestication processes. These cases occur in regions that can be conceived as refugia during arid periods of the mid-Holocene, and would share a tendency towards reduced residential mobility (Dillehay, 2014). On the basis of this review, we formalized a demographic working hypothesis at a macro-regional scale, which suggests the existence of mid-Holocene population bottleneck(s) at a macro-regional scale. Though not conclusive, the temporal evidence presented fits well with this suggestion, providing an explanation not only for the occupational troughs, but also for the post-6000 years BP record of intense and relatively rapid population growth observed in many regions of the SAAD, and in South America in general (Goldberg et al., 2016). There is no conclusive evidence regarding the presence of biological discontinuities between populations before and after the mid-Holocene. While this is not part of our current focus, we would tentatively favor an option of biological continuity from a restricted genetic pool modified by random processes.

The spatial scope of the data presented in this paper provides the chance of disentangling processes of spatial re-localization from actual changes in population size. At this exploratory stage of analysis, we are more concerned in presenting a framework with the capacity to guide research on a macro-regional scale, rather than in probing the hypothesis presented. This analysis produces testable expectations at different analytical scales and for different research domains. At a regional scale, work in some of the proposed refugia would be paramount, particularly in the under-researched wetlands of Central Chile (other regions, such as the mesic steppes or the Atlantic coast in northern Patagonia, also hold this potential). The existence of parallel trajectories towards reduced residential mobility should be assessed in a comparative frame. While some of the regions that may have acted as geographical barriers have been thoroughly surveyed, such as parts of the Atacama Desert and southern Mendoza Province, many have not. This should also be the focus of systematic regional work targeting the mid-Holocene period (Garvey, 2012; Durán et al., in press).

This research produces expectations for human genomic and morphometric evidence. There is a robust body of theoretical and empirical DNA research that focuses in assessing the role of population bottlenecks in human history (Excoffier et al., 2009; Sundell et al., 2014), as well as the incidence of random (genetic drift) and selective processes leading to specific relations between genetic and phenotypic features in human populations from South America (Perez et al., 2009). Deciphering the behavioral, demographic, and evolutionary meaning of archaeological discontinuities requires a continental scope.

Setting issues of historical and ecological scale aside, we consider that there is a similitude in the conceptual structure of the debates on the socio-demographic meaning of temporal discontinuities across the southern continents, including the Last Glacial Maximum in the Australian and African deserts (Barham and Mitchell, 2008; Mitchell, this issue; Smith, 2013; Veth et al., 2005, this issue; Williams et al., 2013). These issues hold a great comparative potential at different scales, including an intercontinental level. We will learn a great deal from a comparative take on this matter.

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