Mid Holocene radiocarbon ages in the Subtropical Andes (~29°−35° S), climatic change and implications for human space organization

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ABSTRACT

This article discusses the distribution of radiocarbon age signatures obtained from archeological sites between 29° and 35° S in Central Chile and Midwest Argentina. The goal of this analysis is to establish bases from which to interpret regional trends in the distribution of the archaeological record that connect these areas, which have been traditionally considered to be geographically decoupled. We propose a standardized methodology for selecting ages that provide a reliable human signature. Variations in date frequencies in a regional scale are discussed with the use of summed probability distributions. Radiocarbon voids at the regional level previously identified in Midwest Argentina are explored. Regional chronological information is compared to the available paleoenvironmental records, thereby emphasizing the possible role of climate pulses in the spatial organization of human populations. Significant arid conditions between 7800 and 5700 cal BP are coincidental with a focused occupation of the Andes Mountains, an area which may have offered stable resources and thus was more effectively occupied than other environmental bands.

1. Introduction

Regional radiocarbon (^{14}C) date frequencies provide a significant measurement of human past signatures and an effective tool for discussing occupation trajectories. Rick (1987) initially demonstrated its usefulness as quantitative data for assessing temporal trends in the "Peruvian Pre-ceramic" period. From this analysis, the possibility of indirectly using ^{14}C to measure paleodemographics was indicated because the dates (i.e., auto-dated artifacts) represented human activity at a point in time and space, and could be compared, quantified, and used to indicate the magnitude of human occupation (Rick, 1987). Since then, a series of regional ^{14}C age compilation projects have been conducted with different applications (e.g., Gajewski et al., 2011; Bueno et al., 2013 and papers therein). Furthermore, work has been conducted to refine the

methodology to interpret the data collected (e.g., Williams, 2012). As a result, numerous studies have used radiocarbon records to interpret human responses to changes in the environment, especially with regard to mobile hunter−gatherer archaeological records (Gamble et al., 2004; Williams et al., 2008, 2010).

One of the major environmental changes that affected humans in a recent temporal scale were the advent of arid conditions in several areas of the globe during the mid-Holocene, period between approximately 8000 and 4000 ^{14}C BP or 9000 and 4500 cal BP (Anderson et al., 2007). This situation supposed a series of environmental challenges that humans dealt with through changes in their systems of spatial use, subsistence, and technology. In the Andean area, humans developed different strategies to cope with this adverse scenario, e.g., intensification and complexity along the coast of the Central Andes (Sandweiss and Quilter, 2012) and the settlement relocation that occurred in the Atacama hyper-arid desert (Núñez et al., 2002; Grosjean et al., 2007; Yacobaccio, 2013). These patterns of differential use of space have been recognized for extra-Andean South America on a much wider

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spatial scale through the use of series of regionally categorized ^{14}C ages (Araujo et al., 2005-6).

The area of the Andes between 29° and 35° S provides a key spatial range to evaluate the relationship between the environmental changes and human responses during the mid-Holocene (Fig. 1). In this area, sufficient resolution has been achieved with regard to the environmental changes, their magnitude, and temporal development. Furthermore, it corresponds to an area inhabited by hunter—gatherers during the mid-Holocene, whose most visible response to environmental change was the reconfiguration of their mobility patterns (Zárate et al., 2005; Méndez and Jackson, 2006; Neme and Gil, 2008, 2009). Moreover, the area has significant ecological differences, thereby representing varied environments offering different resources, and thus potential for settlement complementarity, as suggested by previous works (Gambier, 1993; Jackson, 2002; Cortegoso et al., 2012). We propose that the quantification and comparison of the set of archaeological ^{14}C ages can be used to evaluate the settlement preferences of human groups in disparate areas.

Neme and Gil (2008, 2009) previously discussed ^{14}C date distributions to understand the human response to the environmental changes that arose from the extreme aridity of the mid-Holocene. Their study in the eastern Andes and foothills and plains to the east between 32° and 38° S showed a marked decrease in dates between 7000 and 6000 BP; and although it was not expressed uniformly, it was more pronounced in the extra-Andean plains than in the intermountain valleys and high Andes (Neme and Gil, 2008,

2009). These antecedents allowed us to generate two preliminary hypotheses:

1. The hiatuses or decreases in the ^{14}C signature of certain areas will coincide with time periods of higher aridity detected through regional environmental records.
2. The hiatuses or decreases in the ^{14}C signature of certain regions will denote positive signatures in neighboring areas with different ecological characteristics, which would have worked as alternative zones for the hunter—gatherers during the same period.

To test these hypotheses, we expanded the spatial range to construct the ^{14}C-age database including all the Andean areas between 29° and 35° S and between the Pacific coast and 67° W. This area provides a comparable dataset from archaeological sites studied west and east of the Andes, Chile, and Argentina, respectively. In this paper, we explore the behavior of ^{14}C patterns, discuss potential biases, chiefly research decisions and reservoir effect, and suggest preliminary interpretations linking changes in climate to the spatial organization of hunter—gatherers as expressed through the archaeological record.

2. Regional setting

The study area includes a region between ~29 and 35° S and from the Pacific coast (72°—71°30′) to 67° W. Prevailing air masses,

Fig. 1. Distribution of archaeological sites with ^{14}C ages between 9000 and 3000 BP in the study area; sites in Chile (circles), sites in Argentina (squares).

the proximity to the sea, and altitude are the three main constraints on the climate and environmental characteristic from the region. The air masses depend on the actions of two anticyclones, one located to the west (Pacific Anticyclone), seasonally blocking the westerlies and allowing mostly winter rains, and the other located to the east (Atlantic Anticyclone) permitting summer rains (Garreaud et al., 2009). Between them, the Andean mountain raises with heights exceeding 6000 masl, thus producing a strong impact over the regional climate, vegetation, and faunal distributions.

In a broad sense, we subdivide this region in three major environments:

a) The Pacific coast and western valleys comprises an area characterized by dry summers and relatively humid winters, which is a product of the interaction between the Pacific anticyclone and the northern margin of the Westerlies Wind Belt (Garreaud et al., 2009). As such, this area represents a latitudinal gradient of precipitation increase (~80–740 mm per year) and the average annual temperature decrease (~16°–14 °C) (Romero, 1985; Luebert and Pliscoff, 2006). Climate variability at inter-annual and multi-decadal scales is controlled by El Niño Southern Oscillation (ENSO), with relatively wet years during El Niño events and the opposite trend during La Niña years (Rutllant and Fuenzalida, 1991; Garreaud et al., 2009). Differences in rainfall regimes generate Asteraceae-dominated shrubland in the north of the area, whereas the sclerophyll forests dominate the south (Luebert and Pliscoff, 2006). Faunal communities include mostly rodents and other small-sized mammals. However, the coastal band provides a year-round assemblage including fish, invertebrates, seabirds, and edible plant resources (Quintanilla, 1983).

b) The Andean ecosystem extends all along the area and is characterized by relatively wetter environment, though strongly conditioned by the altitude. Winter precipitation controlled by the Pacific anticyclone dominates, with ranges between 300 and 800 mm per year, the latter at the highest parts (Capitanelli, 1972, 2005; Abraham et al., 2009). The flora belongs mostly to the Altoandina ecosystem, especially up to 2500 masl, with xeric vegetation of the Patagonia ecosystem below this altitude and Puneña ecosystem in the north (Cabrera, 1976; Roig et al., 2000; Luebert and Pliscoff, 2006; Martínez Carretero, 2006; Abraham et al., 2009). Most of this environment is highly productive with regards to large mammals (dominated by *Lama guanicoe*); but less productive in seeds, roots, fruits, and other human edible plant resources; with productivity higher in the south than in the north.

c) Semi-desert foothills and plains mostly dominated by the Atlantic anticyclone extend to the east of the Andes. Precipitation ranges between 250 and 500 mm per year and allows the existence of the Patagonia ecosystem in the south and west and the Monte ecosystem in the north and east (Cabrera, 1976; Roig et al., 2000; Abraham et al., 2009). Plant productivity is higher with regards to human edible plants than in the Andes, but at the same time, faunal productivity decreases, especially in terms of big game.

Other minor traits have impacts on local scale environmental conditions, such as the coastal mountain range in central Chile, precordillera in northern eastern slope, the volcanic field of La Payunia in the southern eastern slope, and the general decrease in the altitude of the Andes from north to south. However, there is: (i) a west-east precipitation gradient, (ii) a north-south temperature gradient, and (iii) an altitude Andean gradient. Combined, these have a strong impact over the plant and faunal distributions, their productivity, seasonality, and complementarity.

3. Mid-Holocene paleoclimate

Holocene paleoclimatic records for the study area are mainly located on the western Andean slope (Fig. 2). The Pleistocene–Holocene transition in this area is characterized by changes in hydrology and precipitation regimes which lead to drier conditions (Lamy et al., 1999; Valero-Garcés et al., 2005) through a step-wise transition mode (Kim et al., 2002; Maldonado et al., 2010). Although resolutions vary, several marine and land records (especially those pollen from sedimentary cores) indicate arid conditions between 9000 and 5500 cal BP (e.g., Heusser, 1990; Veit, 1996; Villa-Martínez and Villagrán, 1997; Lamy et al., 1999; Jenny et al., 2002; Kim et al., 2002; Valero-Garcés et al., 2005; Maldonado and Villagrán, 2006). This dry phase was interpreted as the result of the southern migration of the Westerlies Wind Belt area of influence, which was expressed as the appearance and/or increase of the xerophytic vegetation south of its original area of occurrence (Heusser, 1990; Villagrán and Varela, 1990; Maldonado and Villagrán, 2006). In addition, a drier pulse during the arid phase was recorded between 7800 and 5700 cal BP in the coastal Palo Colorado swamp forest gully located at 32° S (Maldonado and Villagrán, 2006). This observation coincides with the inferences based on the ^{18}O alkenone record of marine sediments at 32°45' S showing the occurrence of maximum sea surface temperatures between 7500 and 6000 cal BP and a subsequent decrease toward modern conditions since that time (Kim et al., 2002). Furthermore, this period is broadly coincidental to the minimum activity of ENSO as expressed by offshore sediment records at 13°30' S (Rein et al., 2005).

In the eastern Andes, records framed within the period of interest are scarce, and they include pollen profiles and geomorphological analyses of glacial advances (Zárate, 2002). These records suggest glacier re-advances between 6000 and 6500 cal BP due to increased winter precipitation at high altitudes. The only extra-Andean record is that of the pollen profile of the Gruta del Indio site. This record indicates an increase in annual plants, as would be expected with a decrease in summer precipitation or an increase in summer temperature (Markgraf, 1983). However, the existence of discordant stratigraphic data and a temporal hiatus in this profile weakens the validity of this inference for the entire period between 8850 and 4380 cal BP.

The coastal swamp forests at ~32° S are sensitive to regional winter precipitation (Maldonado et al., 2010; Maldonado and Moreiras, 2013). These records indicate a gradual increase of humidity starting at 5700 cal BP, with a significant rise between 4200 and 3800 cal BP (Maldonado and Villagrán, 2002, 2006). Other fossil pollen records suggest similar precipitation conditions in the study area (Jenny et al., 2002), which are further in agreement with sedimentary changes observed in marine cores near at 32°45' S since 4000 cal BP (Lamy et al., 1999). This information is consistent with the supposition of glacial advances in the east Andes and the pollen records of locations at ~35° S (Navarro et al., 2012), which suggest that the current climate patterns were established between 4500 and 4000 cal BP, in agreement with strong ENSO activity (Rein et al., 2005).

4. Material and methods

All of the available ^{14}C ages for the study area between 9000 and 3000 BP (~10000–3100 cal BP) were included in the database. Uncalibrated radiocarbon dates were considered as minimum analytical units based on the archaeological site of origin. These were paired with geographical and ecological information, laboratory codes, standard errors, δ^{13}C, dated material, dating methods, primary references, and a basic type of site definition. The current
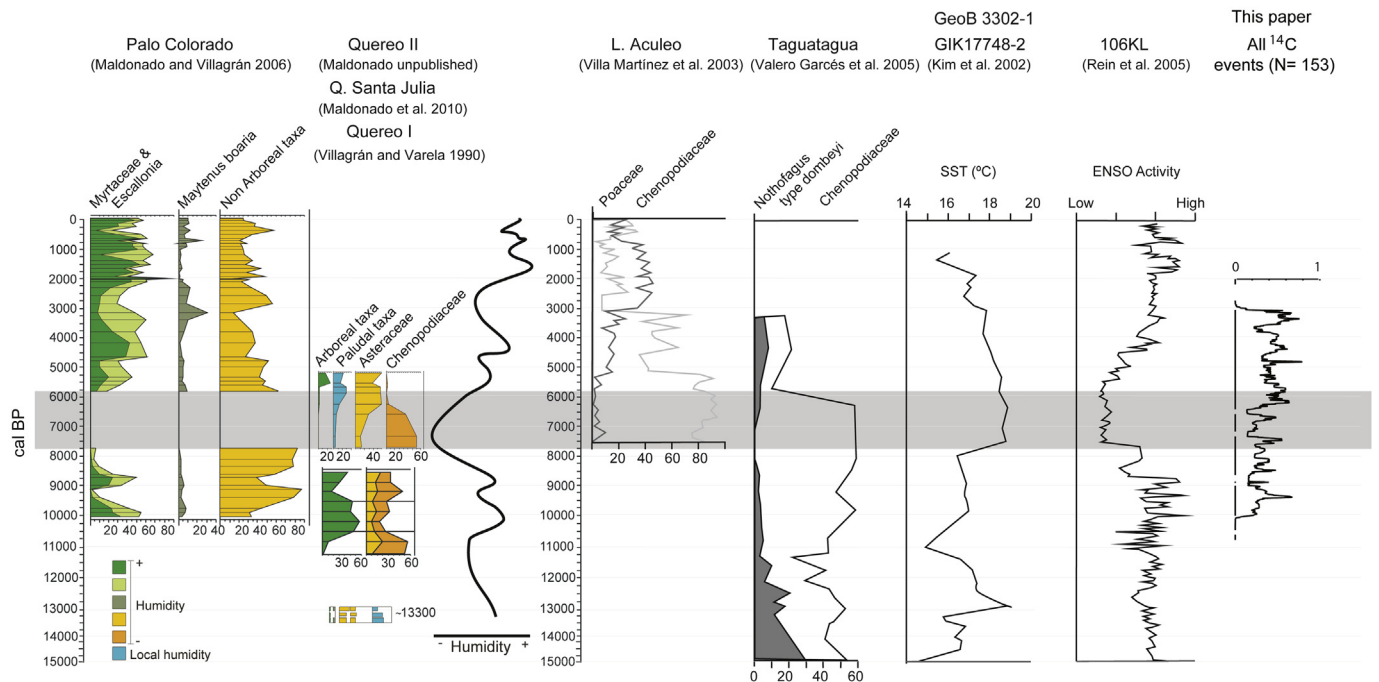
Fig. 2. Summary of major paleoclimatic records for the Subtropical Andes and adjacent areas, including a summed probability plot for all occupational events discussed in this study. The major dry pulse (7800—5700 cal BP) is highlighted.

analysis excluded incomplete ^{14}C data, archaeological sites with unreliable contextual information, and dates with sigma ≥200 (Pettitt et al., 2003). Although the database included thermoluminescence dates (obtained from rocks exposed to fire), these data were excluded because this method has low reliability for ages >3000 BP (Dincauze, 2000). Although the database considered the ages on mollusk shells, analyses isolated these measurements because there is no available correction for reservoir effect in this region.

To critically evaluate our research question, we minimized the data biases that may arise from considering large amount of dates from rich-dated archaeological sites, condition that might artificially enhance the ^{14}C signature of one or more specific chronological episodes and thereby introduce an over-represented human signature. To control for this sample size effect, we defined "occupational events" at the minimum spatial unit of the archaeological site (based on the literature). These events were calculated by averaging the dates at sites with multiple ^{14}C measurements. Specifically, dates were sorted in ascending order and two or more dates were averaged when their differences were not significant ($\alpha = 0.05$) according to a *T*-test (Ward and Wilson, 1978). The number of occupational events that resulted from these operations must be considered a "minimum number of events" (Méndez, 2013). We decided not to average the dates on mollusk shells with those on other types of material due to the potential biases introduced by a reservoir effect.

The analysis consisted of plotting frequency curves as well as quantifying the number of dates and occupational events in 500 calibrated-year intervals. In addition, the summed probability distributions were obtained using the grouped and ungrouped data according to the different ecological bands. The use of summed probability distributions is an accepted method for the analysis of ^{14}C data series obtained at the regional level (Williams, 2012). All calibrations were performed with Calib 7.0.0 program (Stuiver et al., 2013) with the ShCal13 curve (Hogg et al., 2013).

5. Assessment of potential biases

Several potential biases may greatly affect the temporal trends (e.g. Williams, 2012), thus caution is required while analyzing them. One of the most significant biases in the study area is the "aging" of the ^{14}C signatures due to the use of samples that led to potential reservoir effect (i.e. shell samples). Their exclusion improves the precision of the analyses but countered the information provided by data gathered at various archaeological sites, which might significantly contribute to the understanding of the temporal trends. Only when we are able to properly measure this error will it be possible to arrive at more substantial conclusions.

Taphonomic bias is among the main factors influencing the results of ^{14}C time series analysis because the strength of a later archaeological signature, less affected by destructive processes, may mimic population growth (Surovell and Brantingham, 2007). However, as suggested by Williams (2012), taphonomic correction should not be routinely applied without first considering if time-dependent taphonomic loss is a valid assumption. In this article, we include a region sufficiently diverse enough to include several contrasting landforms which are not expected to be constrained by same time-dependent taphonomic losses and therefore minimizing the possibility of unique trends affecting the disappearance of datable material and/or sites containing such. Additionally, we explicitly do not address population growth as a research question, but rather we focus on the presence/paucity of the radiocarbon signal in order to assess trends in the temporal distribution of the archaeological record.

The most significant research bias was the difference between the greater frequencies of Chilean sites included in the database, versus the greater number of dates per site obtained in Argentina (Table 1, Appendices A, B, C). This is chiefly related to a greater proportion of researchers involved in the production of radiocarbon dates in the former region, most probably due to the proximity of home institutions to the study area. On the other hand, archaeological data from western Argentina comes from more

intensely studied sites. However, comparing data from the two countries, although the number of dates is different, the quantity of averaged events is slightly more similar. This result leads us to suppose that the chronological behavior of both slopes is more comparable; and that dates, especially when averaged into occupational events, are defendable indirect demographic measurements.

Table 1
Regional distribution of ^{14}C dates in the Mid-Holocene database (includes only accepted ^{14}C dates).

Slopes	Administrative regions	^{14}C age frequency	
East of the Andes (Argentina)	San Juan	26	14.13%
	Mendoza	56	30.43%
	Subtotal	82	44.57%
West of the Andes (Chile)	Coquimbo	56	30.43%
	Valparaíso	13	7.07%
	Metropolitana	21	11.41%
	O'Higgins	12	6.56%
	Subtotal	102	55.74%
Total		184	100.00%

Another research bias is the uneven spatial coverage of the archaeological sample. This remains a limitation based on the history of investigation and it is well illustrated by data on the Pacific coast. Here, the chronological signature is biased in favor of the Los Vilos area which includes 62.3% (N = 36 ages) of the coastal dates. In other words, a linear 32-km strip representing 4.77% of the 670 km between 29° and 35° S comprises more than half of the coastal sample. This minimal proportion can hardly represent the archaeological ^{14}C trends of the entire environmental band. This situation may be considered analogous to that in the Argentinean segment of the study area where four rich-dated sites (El Desecho, Arq 18, Arroyo Malo 3, and Gruta del Indio) account for 57.32% of the dates. These sites are located on the north and south extremes of the study area and do not represent a random geographical distribution.

In light of these problems, the behavior of the ^{14}C signatures must be understood as preliminary and in need of further testing with additional lines of evidence. The analysis of the ^{14}C data series should be viewed as a way to represent datasets and compare them, but not as a conclusive test. However, once the potential biases of the overrepresentation of the ^{14}C signatures and the taphonomic constraints for most dated sites have been addressed, it is possible to suggest general trends regarding the chronological behavior of the studied area.

6. Results

6.1. Sample structure

The sample was obtained from 74 archaeological sites, 52 of which are located in Chile (70.27%) and 22 in Argentina (29.72%). The database considered 193 numerical dates, but only 184 ^{14}C ages were included in the current analysis based on the aforementioned exclusion criteria (Appendix A). Based on the regional distribution of the sample, we infer that although the majority of the sampling units were located west of the Andes, the frequency of accepted dates for the studied interval did not significantly differ between slopes (west: 55.74%; east 44.57%). Furthermore, because the number of dates per site is an appropriate measure to evaluate the reliability of the chronologic data (Faught, 2008), we sought to characterize their "repeatability" (Steele and Politis, 2009) within the sample. This analysis revealed that the larger portion of the

sample (42.93%) was obtained from sites yielding two to five ^{14}C dates, although the percentage of sites with one single ^{14}C age remains high (17.93%). In addition, this result emphasizes the fact that the majority of sites with more ^{14}C ages within the interval under study are located in Argentina.

The use of charred organic material (primarily charcoal; 65%) dominated (Table 2), thereby providing reliability to the dataset. Mollusk shells (15.76%) are a frequent choice in sites near the Pacific because they are predominantly found as byproducts derived from shellfish processing. In turn, charcoal in these locations is infrequent due to strong winds. The current inexistence of reservoir effect determinations in this area limits the possibility of defining the offsets on radiocarbon dated shells and caution against their use for regional comparisons. Other organic materials, such as bones, are predominantly related to the dates on bioarchaeological remains and are mostly represented in the sample obtained west of the Andes (11.41%).

Table 2
Dated materials in the Mid-Holocene database (includes only accepted ^{14}C dates).

Slopes	Dated material	Frequencies	
East of the Andes	Bone	5	2.72%
	Charred organic material	74	40.22%
	Dung	1	0.54%
	Human tendon	1	0.54%
	Wood	1	0.54%
	Subtotal	82	44.57%
West of the Andes	Bone	21	11.41%
	Charred organic material	46	25.00%
	Human tooth	4	2.17%
	Pigment (organic material)	1	0.54%
	Sediments	1	0.54%
	Shell	29	15.76%
	Subtotal	102	55.43%
Total		184	100.00%

A review of dating methodologies suggests that conventional ^{14}C has been given priority (49.74%, Table 3). Accelerator mass spectrometry (AMS) ^{14}C dating is mainly restricted to recent studies, and as such, it has a weaker representation throughout the dataset (31.6%). However, the frequencies of the use of different methods are similar on both slopes of the Andes. Thermoluminescence dates are restricted to Chile and correspond to experimental analyses on rocks exposed to high temperatures (Román and Jackson, 1998). They were excluded based on their high sigma values.

Table 3
Dating techniques in the Mid-Holocene database (includes all dates).

Slopes	Dating techniques	Frequencies	
East of the Andes	^{14}C AMS	30	15.54%
	^{14}C conventional	47	24.35%
	No available data	5	2.59%
	Subtotal	81	42.49%
West of the Andes	^{14}C AMS	31	16.06%
	^{14}C conventional	49	25.39%
	Thermoluminescence	6	3.11%
	No available data	25	12.95%
	Subtotal	111	57.51%
Total		193	100.00%

Finally, a broad discrimination of type of site from which the dates were obtained showed that although open-air localities dominate the western side of the Andes, cave/rockshelter sites are

the primary source of chronological information in the eastern slope (Table 4). A chi-square test indicates that the samples in the eastern and western slopes are statistically different across the type of site ($p < 0.0001$).

Table 4
Date frequencies partitioned according to general type of site in the studied sample (includes only accepted ^{14}C dates).

Slopes	Type of site	Date frequencies	
East of the Andes	Open-air	16	8.70%
	Cave/rockshelter	66	35.87%
	Subtotal	82	42.57%
West of the Andes	Open-air	85	41.30%
	Cave/rockshelter	26	14.13%
	Subtotal	111	55.43%
Total		184	100.00%

6.2. Spatial trends in the ^{14}C signatures of the mid-Holocene

Dates are unevenly distributed across the environments comprised in the study area (Fig. 3). Two major environmental bands dominate the frequencies of dates and events: the Pacific coast and the eastern part of the Andes Mountains. The coast and valleys western slope represent a geographical unit because major barriers restricting movement do not exist. The distribution of the sites along the coastal axis is uneven and strongly biased in favor of Los Vilos area (31°50′ S; e.g., Jackson et al., 2004; Méndez and Jackson, 2004, 2006). In this area, the Punta Chungo sites (LV. 046a and LV. 046b) stand out, with eight ^{14}C dates that equally represent eight human occupational events (Jackson and Méndez, 2005), as well as the Los Rieles site (Fig. 4) with seven ^{14}C dates that represent six occupational events (Jackson et al., 2012). Although the larger portion of the sites during this interval is located along the coast, valleys yield important ^{14}C datasets, such as the Cuchipuy site, with six ^{14}C dates which represent four occupational events (Kaltwasser et al., 1983).

The Andes corresponds to the major orographic unit in the study area. Mountain settlements pose particular challenges that make the humans who inhabited them seem more represented at cave/rockshelter sites. In these naturally confined areas, site redundancy prevails; thus there are more prone to yield datable events. High dating frequency increases the probability of defining averaged occupational events (see Fig. 3, eastern Andes). Although the number of dates is greater in Argentina ($N = 57$) than in Chile ($N = 33$), the difference between the minimum number of occupational events at both slopes of the Andes is less marked (39 and 30 events, respectively); thus, they are fairly comparable with regard to their chronological signatures. The larger portion of the ^{14}C ages and events from the western slope originate from the sites in the Cajón del Maipo (e.g., Cornejo et al., 1998; Cornejo and Sanhueza, 2003, 2011). The archaeological sites are more infrequent on the eastern slope, but the chronological precision level is higher. The ARQ18 site in San Juan stands out (Fig. 4), with thirteen ^{14}C ages, representing nine human occupational events (Cortegoso et al., 2012; Cortegoso, 2013), as does the Arroyo Malo 3 and El Desecho sites in Mendoza, the former yielding eleven ^{14}C ages and seven occupational events (Dieguez and Neme, 2003) and the latter with fifteen ^{14}C ages and seven occupational events (Gil et al., 2008).

Eastern foothills and plains comprise the third geographical unit and yield the lowest ^{14}C age frequencies in the studied sample, thus representing only a minor proportion of the occupational events.

6.3. Chronological frequencies during the mid-Holocene

The occupational events, defined by averaged ^{14}C dates, allow us to describe the temporal trends across the three defined geographical units (Fig. 5 and Table 5). In order to discuss temporal trends with more precision, dates on shells were treated independently. Although this only affects the area west of the Andes, its effect is worth noting because the dates in mollusk shells comprise 41% of the average human occupational events for this area.

Table 5
Frequency of occupational events at each geographical unit considering dated materials.

Intervals in cal BP	Coast and western valleys		Andes mountains	Foothills and eastern plains	Total
	Various materials	Shell	Various materials	Various materials	
3000—3500	6	2	5	1	14
3501—4000	4	1	5	1	11
4001—4500	3	2	6	3	14
4501—5000	3	0	8	1	12
5001—5500	4	1	5	2	12
5501—6000	5	3	5	1	14
6001—6500	2	5	8		15
6501—7000	3	1	3	1	8
7001—7500	0	1	3	1	5
7501—8000	1	3	7		11
8001—8500	1	0	2	3	6
8501—9000	3	2	1	1	7
9001—9500	1	3	5	3	12
9501—10000	1	2	6	2	11
>10000	0	0	0	1	1
Total	37	26	69	21	153

First, ^{14}C data preceding 10,000 cal BP for all three geographical units is available. The information corresponding to the first ^{14}C signature in these areas has been previously systematized (Neme and Gil, 2008, 2009; Méndez, 2013). We chose this maximum date limit to frame the beginning of the maximum Holocene aridity episode in order to generate an artificial starting point for our frequencies. Likewise, the minimum limit (~3100 cal BP) of the sample also introduced an artificial term and broadly corresponds to the last presence of hunter—gatherer adaptations throughout the study area.

For the interval between ~10,000 and 9000 cal BP, seven occupational events were observed in the coast and western valleys, eleven in the Andes, and six in the eastern foothills and plains. If we exclude the dates on shells, then the number of events in the first environmental band is reduced to two. The recorded values in each unit define the different trends for the interval between 9000 and 8000 cal BP. While the numbers of occupational events at the western and eastern slopes are relatively maintained, a marked decrease in frequencies is observed for the Andes Mountains because only three occupational events were defined.

The millennium between 8000 and 7000 cal BP comprises the beginning of the arid regional episode (7800—5700 cal BP). The coast and valleys west of the Andes show a marked lack of ^{14}C signature because only one event was recorded when the shell dates (which defined four events) are excluded. This decrease is also visible at the eastern foothills and plains because only one occupational event was counted. On the other hand, the Andes Mountains yield ten occupational events, thereby experiencing a notable rise during this same period. During the following millennium (7000—6000 cal BP) when arid conditions prevailed, the mountain environments continue to exhibit high ^{14}C signatures (eleven occupational events). In the areas to the east of the Andes only one occupation event was recorded, while to the coast and western valleys five events (excluding shell dates) suggest an increase.

Between 6000 and 5000 cal BP, occupational events show relative increases across two of the three geographical units and are relatively maintained in the Andes Mountains. Nine events were recorded at the coast and valleys (after excluding shell dates), ten events at the Andes, and three events at the eastern foothills and plains. This millennium shows a gradual return towards more humid environmental conditions. The events in the Andes and the eastern units continued to increase (fourteen and four events, respectively) between 5000 and 4000 cal BP, whereas the coast showed a slight decrease with six non-shell averaged events.

The millennium between 4000 and 3000 cal BP revealed the marked beginning of humid conditions and precipitation regimes similar those in the present. Occupational events increased in the western slope units ($N = 10$, excluding shell dated events), and decreased in the Andes ($N = 10$) and to the eastern units ($N = 2$). The values of this last interval must be considered with caution because the cutoff of our sample at ~3100 cal BP reduced this last interval to 900 calibrated years.

6.4. Chronological trends based on summed probability distribution models

Summed probability distributions, both aggregated and divided by the geographical units, allow us to discuss methodological issues and the temporal behavior across the period under study. The complete dataset results in an averaged curve which conceals the differential behavior of the archaeological record (peaks and troughs) observed when the sample is divided into geographical units (Fig. 6). Equally, the averaged curve for the Andes Mountains disguises the variability acquired when partitioning the sample between both sides. Although the shell-based dates affected the ^{14}C age frequencies and events on the coast when using 500 and 1000-year intervals, the results are different when employing summed probability distributions. Significant differences between the curve morphologies that included the shell samples and those that excluded them were not observed, except for the interval between ~7600 and 6300 cal BP. Except for one marked peak at ~7500 cal BP,

this interval shows peaks and troughs enhanced in the larger dataset. Thus, we opted to exclude the dates using shells due to their potential inaccuracy.

Fig. 7 shows a comprehensive selection of the most reliable occupational events through summed probability plots divided by geographical units underscoring their potential complementarity. The curve for the Pacific coast and western valleys depicts a variable ^{14}C signature prior to 5900 cal BP, with periods of lowest ^{14}C signatures or troughs between ~7850—7300 and 6650-6300 cal BP. Although still variable after 5900 cal BP, the signature was relatively continuous.

By separating the samples of both slopes of the Andes, differences stand out. These can be better observed when considering the troughs in ^{14}C signature. For the western Andes, periods with lowest chronological signature were located at ~9100—8200, 7550—7200, and 6600—6200 cal BP, the first one being the most pronounced and continuous in the whole data set. On the other hand, the eastern Andes show an intermittent, yet continued ^{14}C signature, yielding only one significant trough at ~7000—6500 cal BP. Periods with strong ^{14}C signature and even peaks in one slope fully coincide with segments with low or no ^{14}C signature. This alternation may be the reason for the resulting averaged morphology of the curve that incorporates all chronological data obtained in Andean sites, with only one relative decrease in the ^{14}C signature between ~9100 and 8200 cal BP.

The foothills and plains to the east showed a curve with more intermittence, depicting two pronounced peaks (at ~8400—8100 and 4500—4100 cal BP) and five periods of troughs. The first three ^{14}C signature decreases occurred before 8400 cal BP and are small. However, the more pronounced troughs occurred between ~7700—7300 and 6550—6000 cal BP. This variability is due to the scarce ^{14}C data that comprise the curve.

7. Discussion

Considering the potential biases outlined earlier, results show that the inclusion/exclusion of shell dates does not change
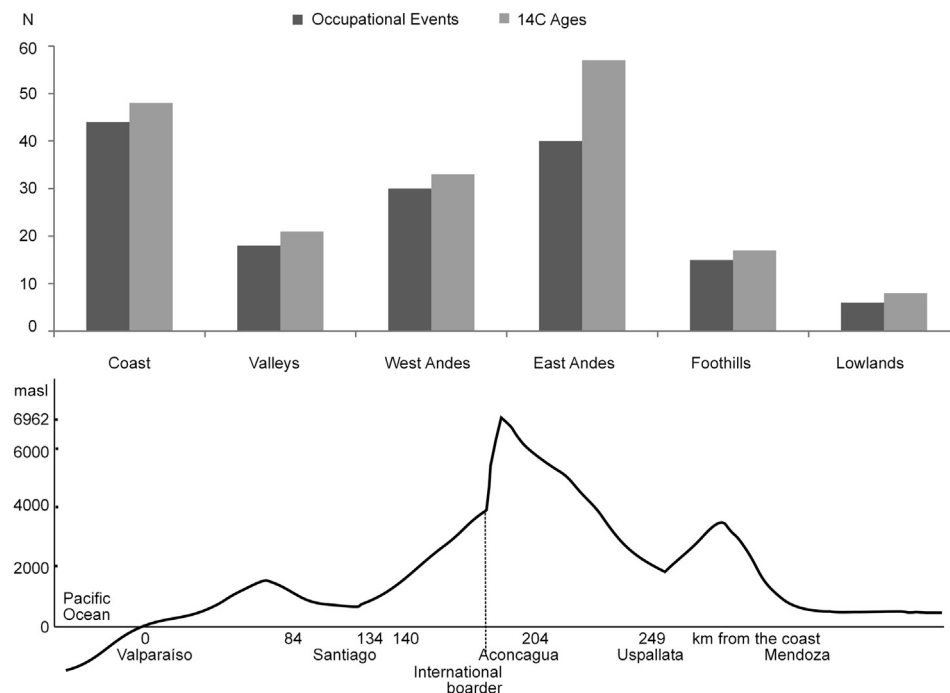

Fig. 3. Distribution of mid Holocene ^{14}C ages and occupational events at each environmental band.

Fig. 4. Selected sites and environments, A. ARQ-18 (eastern Andes), B. Los Rieles (Pacific coast), C. Agua de la Cueva (eastern Andean foothills), D. Techo Negro (western Andes).

significantly chronological patterns as expressed in the summed probability plots in this case study. Although a slight raise in the chronological signal may be observed in the later segment of this dataset, it does not represent an exponential growth either by
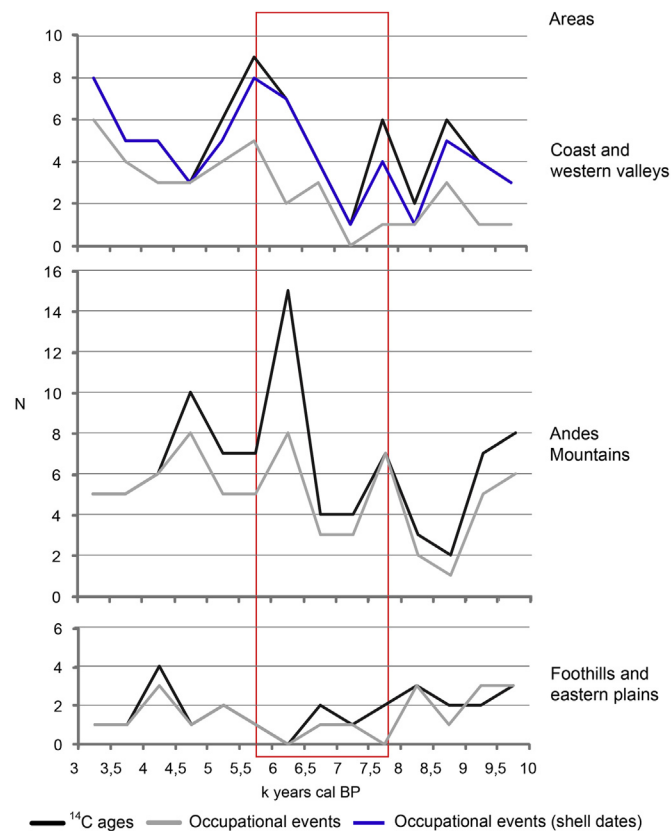

Fig. 5. Descriptive graphs showing ^{14}C age and occupational event frequencies at each environmental band. The major dry pulse (7800–5700 cal BP) is highlighted.

population growth or taphonomic bias (Surovell and Brantingham, 2007). The main sources of bias derive from research decisions and are related to the intensity of dating sites and the geographical coverage at the different environmental bands. In the future, more intense dating programs on a site by site basis must be performed in the western slope. Dating sites with a wider distribution should be of chief importance in the eastern slope and in the Pacific coast. Quantification of ^{14}C ages using 500 and 1000-year intervals restricted the identification of periods without chronological signatures. This initial analysis revealed variations in the date frequencies and differential behaviors at each geographical unit during the millennia of maximum aridity (8000–6000 cal BP). We observed a marked decrease of the ^{14}C signatures in the coast and western valleys and in the eastern foothills and plains when considering occupational events, whereas a notable and continuous increase during this period occurred in the Andes Mountains. The areas to the west and east of the Andes differed in the frequency, magnitude, and timing of these changes. This quantification allowed us to identify the first trends to be contrasted with the analysis of the summed probability distributions.

We pose a preliminary interpretation considering the analysis of different geographical units using the chronological distribution analysis and emphasizing temporal trends. From these curves, we observed the intervals with troughs in ^{14}C signatures and compared them with the regional environmental trends. We assume that these troughs indicate the absence of dated deposits and therefore indirectly indicate a lack of anthropogenic information in time and space. In the coast and western valleys, the period with the most significant troughs was between ~7850 and 6300 cal BP. Other previous decreases were isolated and non-continuous. The Andes show a more sustained ^{14}C signature with less pronounced intermittences, and a trough between ~9100 and 8200 cal BP. However, the most significant difference results when dividing the ^{14}C information across both slopes within the mountain range. Although ^{14}C signature absences were observed on one slope, the other showed a concentration of dated occupational events, thereby underscoring their complementarity. Finally, the most sustained trough in the eastern foothills and plains occurred
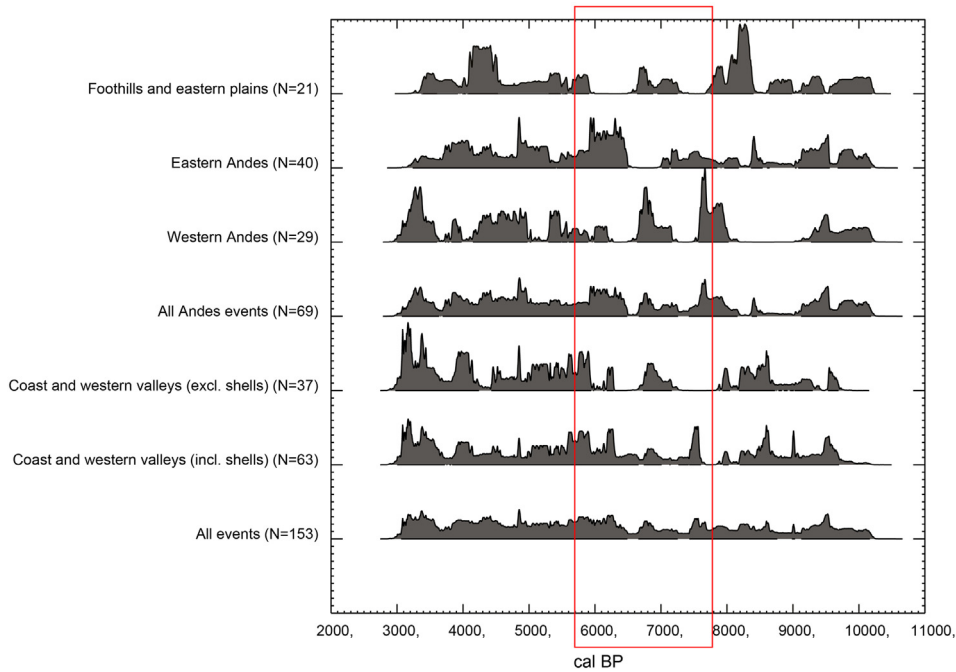
Fig. 6. Summed probability plots of occupational events for each environmental band and subunits. The major dry pulse (7800–5700 cal BP) is highlighted.

between ~7700 and 6000 cal BP, despite other minor earlier decreases in the chronological signature.

Two scenario interpretations are possible:

(1) The chronological signatures of the Pacific coast and western valleys and the eastern foothills and plains showed troughs that were in relative synchronicity and with the major dry climate phase. The decrease in the occupational events in the Andes as a whole occurred before the signature decrease in the other two extra-Andean areas and predates the major dry pulse.

(2) The chronological signatures of the Pacific coast and western valleys, the west Andes, and the eastern foothills and plains showed ^{14}C signature troughs that are in relative
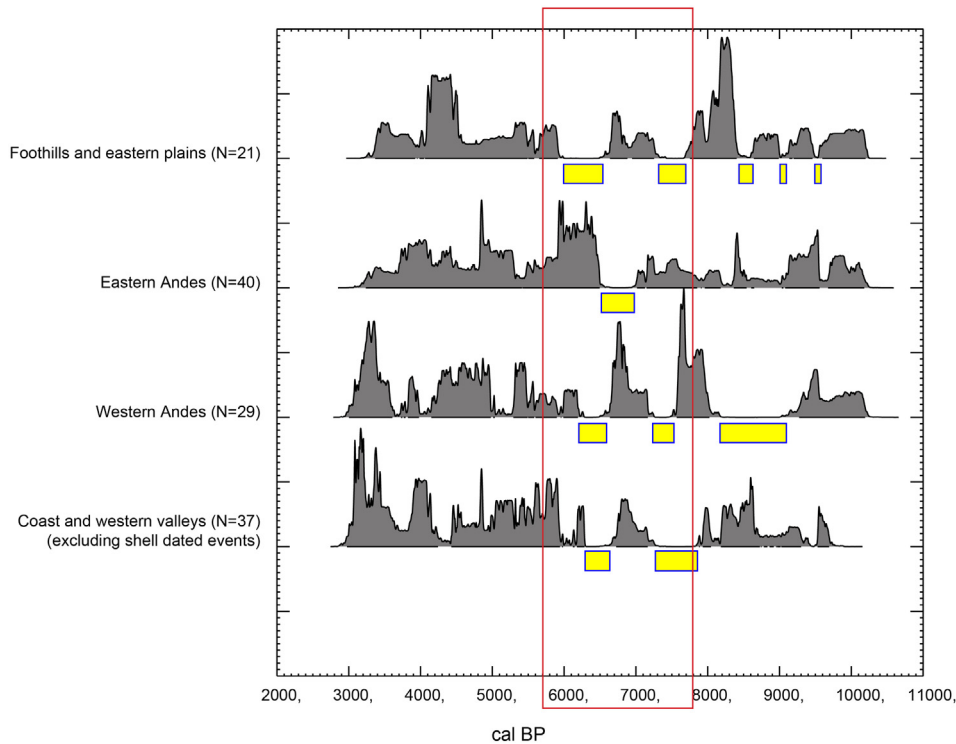

Fig. 7. Summed probability plots of occupational events for each environmental band. The major dry pulse (7800–5700 cal BP) is highlighted. Solid blocks represent periods with null ^{14}C signature.

synchronicity (~7800–7300 and 6600–6400/6000 cal BP) and with the major dry climate pulse. However, a previous and sustained trough was observed in the west Andes. The chronology of the occupational events across the three described geographical units differed from that observed at the eastern Andes, which showed chronological increases and decreases across during different episodes compared with the signatures of the other units, both in terms of peaks and troughs. The only period with a marked decrease in ^{14}C signature in the eastern Andes fully coincides with peaks in all other units.

In summary, the beginning and end of the phase with troughs in the ^{14}C signature of the geographical units located to the west and east of the Andes are noteworthy for their synchronicity. In addition, the synchronicity between the decrease in human activity and the phase of maximum aridity during the mid-Holocene (7800–5700 cal BP) emerges as a suggestive result. Finally, the chronological signature of the coast and western valleys and foothills and eastern plains, being asynchronous with regard to dated human activity in the Andes, is also significant. Specifically, a significant trough was localized in the western Andes between ~9100 and 8200 cal BP, and the two millennia between 8000 and 6000 cal BP showed intermittent and alternating chronological patterns between both slopes.

8. Conclusions

Analysis of radiocarbon date series is a powerful quantitative tool that can establish human presence at a regional level and indicate the magnitude of its spatiotemporal signature. As such, it is an important (though not infallible) method of establishing indirect demographic parameters once research and taphonomic biases are addressed. Because hunter–gatherers populations were highly mobile societies, spatial reorganization is considered an alternative to the negative environmental fluctuations that affect the availability of resources (i.e., Fagan, 1999). Spatial reorganization has been previously observed with regard to Holocene environmental fluctuations in South America (Núñez et al., 2002; Barrientos and Pérez, 2005; Araujo et al., 2005-6; Méndez and Jackson, 2006; Grosjean et al., 2007; Neme and Gil, 2009). In these cases, the effects of the changes were interpreted as restrictions in the availability of resources and limitations with regard to inhabiting certain regions. However, it is true that the spatial organization of human groups depends on the degree of knowledge of environmental conditions. The onset of the Mid-Holocene (~9000 cal BP) postdates by some four thousand years the initial occupations recorded in the region and ever since a chronological signal has been recorded (Neme and Gil, 2008, 2009; Méndez, 2013). As such, it is fair to consider that most of the study area was already inhabited by the start of the driest phase.

Positive relationships between adverse climate pulses and decreases in ^{14}C signatures should be evaluated as potential indicators of reconfigurations in mobility patterns and use of space. However, collation between trends derived from different datasets should not be necessarily understood as causation (Sandweiss and Quilter, 2012). Casual hypotheses should be evaluated and judged with regard to their magnitude, either by increasing archaeological sampling, ^{14}C dating, including complimentary datasets, and/or expanding the spatial scale of analysis. For instance, the coastal environments have been signaled as potential buffer zones in times of resource shortages because they yield predictable resources and are occasionally high in productivity (Waselkov, 1987; Erlandson and Fitzpatrick, 2006). However, our results show that when excluding shell dates, at least during some phases, these areas were devoid of radiocarbon signals. A program devoted to determining the reservoir effect is crucial in assessing if by including corrected shell-dated material from a significant amount of dated sites, chronological trends will vary or remain. This work preliminarily concludes that an effect existed in the reconfiguration of the spaces occupied by humans during the mid-Holocene in the Andean region between 29° and 35° S. The drought conditions recognized along the coast and valleys of the western slope between 7800 and 5700 cal BP may have had an effect on preferential use of spaces as shown by ^{14}C signature patterns. The Andes Mountains also may have offered alternative and more stable resources, and thus they were effectively occupied in a relatively inverse pattern with regards to the other environmental bands. However, the different ^{14}C signatures between the western and eastern Andes may be equally interpreted to represent differing human presence on both slopes during the evaluated period.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quaint.2014.06.059.

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