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‘White Gold’ Guano Fertiliser drove Agricultural Intensification in the Atacama Desert from 1000 AD

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Summary (150 words max)

The archaeological record shows that large pre-Inca agricultural systems supported settlements for centuries around the ravines and oases of northern Chile's hyperarid Atacama Desert. This raises questions about how such productivity was achieved and sustained, and its social implications. Using isotopic data of well-preserved ancient plant remains from Atacama sites, we show a dramatic increase in crop nitrogen isotope values ($\delta^{15}N$) from ~AD 1000. Maize was most affected, with $\delta^{15}N$ values as high as +30‰, with human bone collagen following a similar trend; moreover, their carbon isotope values ($\delta^{13}C$) suggest a significant increase in the consumption of maize at the same time. We attribute the shift to extremely high $\delta^{15}N$ values – the highest in the world for archaeological plants – to the use of seabird guano to fertilise crops. Guano – "white gold" as it came to be called – thus sustained agricultural intensification, supporting a substantial population in an otherwise extreme environment.

Introduction

The pre-Hispanic archaeological record of northern Chile preserves large quantities of desiccated crop remains in both domestic and funerary contexts due to exceptional organic preservation in the hyperarid Atacama Desert. Their abundance and diversity suggest a level of agricultural success that is difficult to explain given the region's arid environment. The transition to agriculture began here around 1000 BC and eventually supported permanent villages and a sizable regional population[1]. How was this development possible, given the extreme environmental conditions? Although evidence for irrigation canals and terraces has been identified in the Atacama[2,3], water is not the only prerequisite for successful agriculture. In the hyperarid core of the Atacama, most soils must be conditioned for agriculture by the addition of organic matter and nutrients, with (possible) exceptions around oases and river terraces where organic content is higher. Recent studies of several hyperarid soils associated with certain archaeological sites where agricultural activity took place contain elevated concentrations of total organic C, N and PO_4. These sites, located between 1000-3200 masl, date to 2000, 1000 and 400 years ago respectively, suggesting an anthropic influence in those periods[4,5].

The question remains, however, as to how these fields and soils were enriched (probably using manure) for agricultural purposes.

We analysed the stable carbon and nitrogen isotope composition of archaeological plants (n=246) to investigate manuring practices in northern Chile, specifically the Tarapacá region (19º–21ºS), South Central Andes (Figure 1, Sup. Inf. 1). Based on archaeological context and direct radiocarbon dates on plants, our dataset spans the transition to agriculture from ca. 1000 BC to the expansion of the Inca State ca. AD 1450 and the following Spanish conquest in the Tarapacá region, comprising the Formative (1000 BC – AD 900), Late Intermediate (AD 900-1450), Late (Inca) (AD 1450-1531) and Colonial Periods (AD 1531-1800). We further compile human stable carbon and nitrogen isotope data from northern Chile in order to evaluate changes in diet associated with agricultural practices. The human data includes the Middle Period (AD 500-1000), an archaeological period that is not present in Tarapacá, but is found in the regions of Arica to the north and San Pedro de Atacama to the south.

Results

Published radiocarbon dates together with new direct radiocarbon dates on crops from the archaeological sites considered here are presented in Sup. Table 1. Isotopic results for the main C_4 plants, maize (*Zea mays*) and amaranth (*Amaranthus* sp.), and C_3 plants, *quinoa* (*Chenopodium quinoa*), chili pepper (*Capsicum* sp.), gourd (*Lagenaria* sp.), squash (*Cucurbita* sp.), common beans (*Phaseolus vulgaris*), lima beans (*P. lunatus*), cotton (*Gossypium* sp.) and the wild legumes *algarrobo* (*Prosopis* sp.) and *chañar* (*Geoffroea decorticans*) from inland Tarapacá sites are shown in Figure 2 and Sup. Table 2. Plants using C_3 or C_4 photosynthetic pathways are clearly distinguished by their $\delta^{13}C$ values. The $\delta^{15}N$ values are uniformly high compared to most other parts of the world, but by far the highest values occur in plants from the Late Intermediate Period onwards (Figure 2).

Formative Period crop $\delta^{15}N$ values show a mean and standard deviation of 6.3 ± 4.0‰ (n = 70). We exclude on statistical grounds three clear outliers with very high values of 18.3‰, 19.5‰ (both squash) and 23.0‰ (maize). They may have been misattributed to the period due to post-depositional disturbance (Sup. Inf. 1). A dramatic increase is observed with the Late Intermediate Period (20.2 ± 6.5‰, n = 83; $p < 0.001$, Kruskal-Wallis test, Sup. Table 3) (Figure 2), that is maintained in the Late and Colonial Periods, which cannot be distinguished statistically (Sup. Table 3). Wild fruits, *algarrobo* (*Prosopis* sp.) and *chañar* (*Geoffroea decorticans*), also show a marked increase in $\delta^{15}N$ values for the Late Intermediate and Late Periods (Figure 2c), compared to the preceding Formative Period (Sup. Table 3). One wild plant (*Prosopis* sp.) sample with exceptionally high $\delta^{15}N$ (31.1‰) in the Formative is a statistical outlier, and again may be intrusive due to post-depositional disturbance.

Seabird guano during Pre-Hispanic times

The magnitude of the ^{15}N-enrichment in plants observed here cannot be explained by invoking standard influences, such as low rainfall, or conventional soil enrichment methods. Low rainfall (i.e., the "aridity effect") cannot account for these high $\delta^{15}N$ values. The highest observed plant $\delta^{15}N$ values in both modern and ancient natural Atacama ecosystems are well below 12‰ (ranging from -2‰ to 12‰; mean 5.9±3.2‰)[6,7], while soil $\delta^{15}N$ values decrease below the threshold at which most biological activity ceases[6]. Similarly, high $\delta^{15}N$ values cannot be the product of diagenesis as argued by DeNiro and Hastorf[8], who obtained high $\delta^{15}N$ values for desiccated plants from Peruvian coastal sites in contrast with charred highland specimens yielding low values more consistent with the usual range for plants. Recent studies, however, dispute the diagenesis explanation[9,10,11]. For instance, no systematic differences were found in $\delta^{15}N$ values between Late Moche charred and desiccated plants in northern Peru[10]. Finally, it is now widely recognised that manuring leads to ^{15}N-enrichment[12,13], and that this effect can be marked. Plant growth chamber experiments evaluating the impact of organic fertilisers on crops showed that seabird guano can increase plant $\delta^{15}N$ values up to 20-40‰[14]. Field experiments using modern maize in Peru showed that application of llama dung to crops increased maize $\delta^{15}N$ values by 1.8-4.2‰, whereas seabird guano increased them by 11.3-20‰[15].

Seabird guano deposits are abundant on the Pacific coast and their use as fertiliser was documented post-contact by early chroniclers[16, 17, 18, 19, 20]. The main species responsible for guano deposits on the Pacific coast are *Phalacrocorax bougainvillii* (*Guanay* or cormorants), *Sula variegata (Piquero* or Peruvian booby*)* and *Pelecanus thagus*

(Peruvian pelican)[21]. Seabird guano has conspicuously high δ^{15}N values reflecting the birds' consumption of ^{15}N-enriched fish, which is further strongly increased by aerobic decomposition and subsequent volatilization of ammonia[22]. This leads to extremely high δ^{15}N values for rookery deposits off Antarctica[22, 23] and northern Chile (23.0 ± 8.4‰)[24]. Based on this information, we argue that the high crop δ^{15}N values could only have been caused by the use of seabird guano as a fertiliser.

From their δ^{15}N values (8.1 ± 7.0‰, n = 45), some wild legumes, *algarrobo* (*Prosopis* sp.) and *chañar* (*Geoffroea decorticans*), may also have been irregularly and indirectly fertilised with seabird guano. Although both species grow wild in the Atacama along under- or above-ground water courses today, they were likely a human introduction ca. 3000 years ago[25]. While both are N_2-fixers (with expected δ^{15}N values close to atmospheric nitrogen), just nine samples out of 46 approached ~0‰ in our study. Experiments show that fertilisers do influence the nitrogen isotope composition of legumes[26]; thus, we argue that *algarrobo* and *chañar* values were also influenced by the uptake of enriched ^{15}N from fertilisers, including seabird guano.

It is likely that a range of organic fertilisers were used in northern Chile from the Formative, such as camelid dung and composted green manure; in addition, human night soil, fish heads (sardines) and/or decomposed leaves (poña) are specifically mentioned in the chronicles of the Colonial Period[18,27]. The use of naturally occurring nitrates can be ruled out, as these exhibit low δ^{15}N values[28], with those in the Atacama Desert specifically ranging from -5‰ to 5‰[29]. None of these fertilisers even approach the high δ^{15}N values seen with seabird guano, which can reach values as high as +35‰[22].

We therefore conclude that the high δ^{15}N plant values observed for the Late Intermediate Period onwards are due to application of seabird guano to crop fields, while lower crop values during the preceding Formative Period reflect a combination of manuring with compost, camelid dung, etc.[15] Thus, the use of seabird guano beginning with the Late Intermediate Period marks a shift in both agricultural intensification and large-scale regional interaction that continued into the Late and Colonial Periods. Systematic use of seabird guano required its acquisition and transport from the coast, likely in a similar manner to that observed historically[16, 27], with the transport of guano by llama caravans or people from the coast to oasis settlements over distances of more than 90 km, under very difficult travelling conditions through the desert.

Historical accounts of seabird guano use

The seabird guano trade was observed and documented by early European chroniclers post-contact. The earliest documented evidence for the use of guano is immediately post-contact, in 1548-1549[17]. Ethnohistorical records from the 16th to 19th centuries describe how local people travelled in small watercraft to obtain guano from rocky islets off the Pacific shore, from southern Peru to the Tarapacá coast in northern Chile, how seabird guano was extracted, transported inland and applied in small amounts to obtain successful harvests[16-20, 30]. Their complex rafts were made of two joined sea lion skin pontoons with a wooden deck, as described and drawn by Frezier[16] (Figure 4).

Although guano was said in early historical accounts to be equitably distributed to each village[18, 31], the same sources state that access to guano was strictly regulated, warranting the death penalty for those who extracted more than authorised or entered their neighbour's guano territory, emphasising its high value. Similarly, it has been argued that strictly controlled Inca practices on access to guano had earlier antecedents[27], and that along the Peruvian coast guano access was more likely to be unequal than not with exclusive access to particular accumulations for some groups[32, 33]. This view is consistent with our findings.

Human diet changes and guano influence

To evaluate the impact of the consumption of fertilised crops on human diets through time, we compiled and analysed 846 published human stable isotope measurements from the Formative to the Late Periods across northern Chile with $\delta^{13}C$ measurements on bone collagen, apatite and tooth enamel, and $\delta^{15}N$ measurements on bone and dentine collagen (Figure 3, Sup. Table 4). Since we include data from the Arica-Occidental valleys (north of Tarapacá) and the Loa-San Pedro de Atacama (south of Tarapacá) areas, we include the Middle Period (AD 500-1000), reflecting the presence of Tiwanaku influence in these regions.

Humans in inland sites show a dramatic increase in $\delta^{15}N$ values (Kruskal-Wallis, $p < 0.001$, Sup. Table 5) after the Formative Period, following the same trend observed for crops (Figure 3). No significant differences are found between the Middle (AD 500-1000), Late Intermediate and Late Periods (Sup. Table 5). The $\delta^{15}N$ shift does not occur on the coast or in the precordillera. A clear increase in $\delta^{13}C$ values for human bone collagen and bioapatite is also observed for post-Formative inland Atacama sites. Even strongly marine diets are unlikely to show $\delta^{13}C$ values above ca. -10 to -12‰ for collagen and ca. -8 to -10‰ for bioapatite[34]; rather, higher values than this should reflect C_4 consumption[35]. Inland humans in the Formative are significantly lower in both collagen and bioapatite $\delta^{13}C$ compared to the subsequent Middle, Late Intermediate and Late Periods (Kruskal-Wallis, $p < 0.001$; Sup. Table 5), mirroring the trend seen in crop $\delta^{15}N$ values (Figure 2b).

The data indicate that the consumption of maize increased substantially to the status of a staple crop only after the Formative Period in inland sites, as seen in the step change in in human $\delta^{13}C$ values, and that this coincided with the application of seabird guano as a fertiliser, as seen in the high $\delta^{15}N$ values of both crops and humans. An increase in abundance of maize cobs and kernels is also observed in Late Intermediate and Late Period sites[36, 37], in contrast to the previous Formative in which less frequent maize finds suggests that they may have been used primarily in ritual contexts[38, 39]. Consumption of fertilised crops clearly had a marked impact on the isotope composition of domestic animals as well as humans. At the Pica 8 cemetery (AD 900-1400), $\delta^{15}N$ values for camelid fibres reached a maximum of ca. 19‰, which is extremely high for a terrestrial herbivore[40]. Hence, it seems that some camelids also had access to fertilised crops or crop waste. No comparable trends are observed for any period on the coast, where human $\delta^{13}C$ and $\delta^{15}N$ values remain similar over time, demonstrating the persistence of a distinct, strongly marine-focused diet[41, 42]. Further, coastal human $\delta^{13}C$ values are never as high as they are in inland sites, suggesting that maize, even though it was certainly consumed, never became a staple food, consistent with previous archaeological and archaeobotanical studies[1].

Furthermore, no consistent offsets were found at Pica 8 between paired radiocarbon dates of humans with high $\delta^{15}N$ values (above 20‰)—often assumed to represent high trophic level marine diets—and camelid fibres. If marine foods were consumed, the ^{14}C

offsets should reflect a marine reservoir effect of up to 800 years[40]; that they did not, indicates that high human values reflect consumption of ^{15}N-enriched crops rather than of marine foods. One implication is that the use of high δ^{15}N values as straightforward indicators of marine diets is problematic, at least in inland individuals from the Middle, Late Intermediate and Late Periods in northern Chile, and probably also in southern Peru. This provides further support for previously proposed cautions regarding the interpretation of high δ^{15}N values from inland sites as necessarily being indicators of marine diets[15, 40].

While high on average, the considerable variability of δ^{15}N values for plants, humans and camelids in inland sites suggests differential access to seabird guano during the Late Intermediate and Late Periods, (Figures 2a and 3). Some individuals, it seems, lacked regular access to guano, and likely continued to rely on other means of maintaining soil fertility[27]. Thus, exchange links with the coast, whether kin-based or otherwise, were not equally distributed and were possibly a source of influence and power. The use of maize in feasting contexts to build or consolidate socio-political support is a well-known “pathway to power” in the Andes[43, 44], which in this context may have incentivised its initial intensification, facilitated by the use of guano. An additional factor potentially relevant for the timing of extensive use of seabird guano in the Late Intermediate Period is the increasingly unpredictable climate from ca. AD 1100, with the resulting social stresses recorded in a shift in settlements from the valley bottoms to defensive hilltop locations[45]. This situation may have encouraged new means of enhancing crop security and productivity.

Recently published crop δ^{15}N values[46] mainly from the Formative and Middle Periods from south of Tarapacá, associated with the Loa-San Pedro cultural region, also show no strong ^{15}N-enrichment prior to the Late Intermediate Period (Sup. Inf. 3). However, the practice of using seabird guano for fertiliser may be earlier elsewhere, if we accept that the high δ^{15}N values reported for some desiccated plants from the coastal valleys of central Peru[8] are not diagenetic but authentic[10]. While no direct radiocarbon dates for those plant remains from Central Peru are available, some of these sites could be considerably older. The implications are different for the two regions, however, since the Atacama case involved transport of guano over 90 km from the coast to inland oases, and at considerable cost.

Conclusions

We conclude that the most parsimonious explanation for high $\delta^{15}N$ values observed for crops and humans in northern Chile is the use of strongly ^{15}N-enriched manure, which can only refer to seabird guano. Based on the plant data, the systematic use of guano is attested from the Late Intermediate Period onwards (ca. AD 1000). Its application to crops is mirrored by trends in human collagen $\delta^{15}N$ values for many, but not all, individuals, implying unequal access. The marked effects on human $\delta^{15}N$ values argue against their use as straightforward indicators of marine diets under such circumstances. Given the chemical composition of seabird guano with its high phosphate concentrations[22, 23], a complementary test for guano application to agricultural soils would be the existence of spatially demarcated areas of high PO_4 concentrations in sites.

Concomitant shifts in human bone collagen and apatite $\delta^{13}C$ indicate an increasing reliance on maize, denoting that the importation and use of seabird guano and intensive cultivation of maize are tightly linked. Notwithstanding the general shift at the onset of the Late Intermediate Period, however, the variability in the human isotopic data implies differential access to guano, which likely constituted a source of status and power within local communities. Seabird guano was transported from the coast to the interior in large quantities for at least 400 years prior to the Inca. Enormous effort was expended on this process, an investment which clearly brought rewards in the form of higher crop yields for oasis and valley communities, particularly for the staple maize. It is for this reason that seabird guano became widely known in the 19th century as "white gold"[47].

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Figure 1. Map of northern Chile. Archaeological site locations are indicated by numbers.

Figure 2. (a) Bivariate plot showing variation in $\delta^{13}C$ and $\delta^{15}N$ values for archaeological crops and wild fruits. Plant species are indicated by symbol and cultural periods are indicated by colour. C_3 plants fall on the left of the plot with lower $\delta^{13}C$ values, whereas C_4 plants fall to the right with higher $\delta^{13}C$ values. (b) Boxplots showing $\delta^{15}N$ values for (upper) crops and (lower) 'wild' plants through time for inland sites.

Figure 3. Boxplots showing variation in $\delta^{13}C$ values for bone and enamel apatite, and bone collagen $\delta^{13}C$ and $\delta^{15}N$ values from archaeological human samples from coastal, inland and Precordillera sites dating to the Formative, Middle, Late Intermediate and Late Periods.

Figure 4. (a) Modern seabird guano accumulations in Patache, Tarapacá region, northern Chile (picture of Exequiel Sagredo-Wildner); (b) Man on sea-lion skin raft described by Frézier (1717); these rafts were used for collecting guano on the Pacific coast of northern Chile (Cieza de León, 1984); (c) Maize cob with grains and popcorn collected from the Formative site, Tarapacá 40 analysed in this work.

Methods

A total of 246 desiccated plant samples was analysed, including crops and ‘wild’ fruit species. Details regarding the sites are provided in Sup. Inf. 1. The cultural sequence is: Formative Period (1000 BC – AD 900), Late Intermediate Period (AD 900-1450), Late Period (AD 1450-1531) and Colonial Period (AD 1531-1800).

New archaeological excavations were carried out at the Tiliviche 1B site to obtain maize samples for this study. The excavation was authorised by the National Council of Monuments of Chile (Permit number 3575). All other macrobotanical remains were sampled with permission from museum and university collections: the Departamento de Antropología of the Universidad de Chile, Instituto de Investigación Antropológica of the Universidad de Antofagasta, Centro Experimental Canchones of the Universidad Arturo Prat, Instituto de Investigaciones Arqueológicas y Museo of the Universidad Católica del Norte and the Museo Regional de Iquique.

All plant samples were well preserved. They were cleaned manually to remove dust and sand particles before homogenization in a cryogenically-cooled Spex mill at the University of Oxford, while a set (n=200) were ground using a pestle and mortar and mechanical grinder at the Universidad de Antofagasta. All samples were rinsed in MilliQ and distilled water after being ground, centrifuged three times, and freeze-dried[48]. Samples were analysed separately for carbon and nitrogen isotopes, since larger sample sizes are generally required for nitrogen, given the much smaller amounts of this element usually present in plants. Measurements were made on a SERCON 20/22 continuous flow mass spectrometer coupled with an elemental analyser. Results were checked for precision and calibrated using IAEA CH-6 and caffeine standards for the carbon isotope runs, and IAEA USGS-40 and USGS-41 for the nitrogen isotope runs[49]. Analytical precision was 0.1‰ and 0.3‰ for carbon and nitrogen, respectively, based on repeat measurements of the standards. Results for %C and %N are presented in Sup. Table. 1.

Statistical analyses were performed in R[50]. As the data were not normally distributed, as determined by Shapiro-Wilk tests, Kruskal-Wallis tests coupled with post-hoc Dunn tests were carried out to compare the different crops and periods. A significance level of

$\alpha = 0.05$ was used for all analyses. Outliers were identified using Median Absolute Deviation (MAD)[51].

A recent experimental study[10] pointed to a potential problem with $\delta^{15}N$ measurements in plants with very high C/N, thus we tested this relationship for the Atacama Desert macrobotanical remains reported here. They show no correlation between $\delta^{15}N$ and C/N atomic ratios ($r^2 = 0.001$, $p = 0.567$; Sup. Inf. 4). Just 3 out of 246 samples had C/N ratios above 100 and they show low $\delta^{15}N$ values (see Sup. Inf. 4 for plot and discussion of the questions related to high [C], low [N] questions).

Nine radiocarbon dates were carried out at the Oxford Radiocarbon Accelerator Unit. Pre-treatment was carried out following the ABA protocol for plants[52]. Dates were calibrated using the SHCal13 calibration curve[53] using the Oxcal Programme version 4.3[54].

Archaeological plant carbon and nitrogen isotope values were compared with data obtained by Díaz et al.[6] and Santana-Sagredo[55] for modern plants, as presented in Sup. Inf. 2.

A total of 846 published human stable isotope values obtained from bone and dentine collagen, bone apatite, enamel apatite data for northern Chile were analysed using the same statistics. The human values come from studies in the Tarapacá region but also from the Arica/Occidental Valleys and San Pedro de Atacama/Loa areas. Only results with C/N ratios falling in the expected range for good collagen preservation (2.9-3.5) were used, and results lacking published C/N ratios were excluded. We included only adolescent and adult individuals, in order to avoid possible nitrogen isotope variability influenced by breastfeeding or childhood growth[56]. Human data were divided into Formative, Middle, Late Intermediate and Late Periods, and by geographical location to coastal (0-10 km from the coast), inland (10-150 km from the coast) or precordillera (>150 km inland).

Stable carbon isotopic values on bioapatite were considered in order to address the isotopic overlap between marine resources and C_4 plants that are both enriched in ^{13}C.

This leads to two possible sources when only bone collagen values are used because collagen, a polypeptide, is strongly influenced by the isotopic composition of dietary protein, whereas bioapatite $\delta^{13}C$ instead reflects the integrated isotopic composition of the entire diet including the input from carbohydrates[57], and thus provides a more holistic indication of C_4 plant consumption.

Methods References

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Data Availability Statement

The authors declare that all data generated or analysed during this study are included in this published article (and its supplementary information files).

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Author Contributions

F.S.-S., R.J.S. and J.L.-T. original idea and research design. F.S.-S., P.M.-Q., A.V.-E., M.U., R.L. and A.M.-F. conducted and participated in the fieldwork. F.S.-S., A.V.-E. and A.M.-F. carried out sampling in universities and museum collections. A.V.-E., V.B.M., V.M., F.P.D. undertook taxonomic analysis of crops and wild fruits. F.S.-S. and A.M.-F. conducted samples processing and laboratory work. F.S.-S and P.M.-Q collected information and worked on the human isotope and radiocarbon dates databases. F.S.-S., R.J.S. and C.H. undertook the statistical analysis. R.L. designed the map. F.S.-S., J.L.-T., R.J.S. and C.H. interpreted the results. C.L. and C.M.S. contributed interpreting the data based on the local ecology and archaeology. F.S.-S. wrote the paper with the help of R.J.S. and J.L.-T.; all the authors commented on the manuscript.

Competing interests

The authors declare no competing interests.

Additional Information

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Supplementary Information

Supplementary Information 1. A brief description of the archaeological sites from which archaeobotanical remains were collected is given here.

Supplementary Information 2. Bivariate plot of $\delta^{13}C$ and $\delta^{15}N$ values for modern plants[13,14], archaeological crops (analysed here) and archaeological wild plants from the Atacama Desert (between latitudes 20º25'S and 23º50'S) Modern plants $\delta^{13}C$ values were corrected by +1.5‰ for the Suess effect[15].

Supplementary Information 3. Bivariate plot of $\delta^{13}C$ and $\delta^{15}N$ for (a) archaeological plants analysed in this study compared to (b) archaeological plants published for the Loa-San Pedro cultural area[16]. Plant species are indicated by symbols, while periods are indicated by colours.

Supplementary Information 4. Bivariate plot of C/N atomic ratios and $\delta^{15}N$ values for archaeological plants analysed in this study including crops (maize, chili peppers, squash, pumpkin, quinoa, beans, potatoes) and wild plant legumes (*algarrobo* and *chañar*).

Supplementary Tables

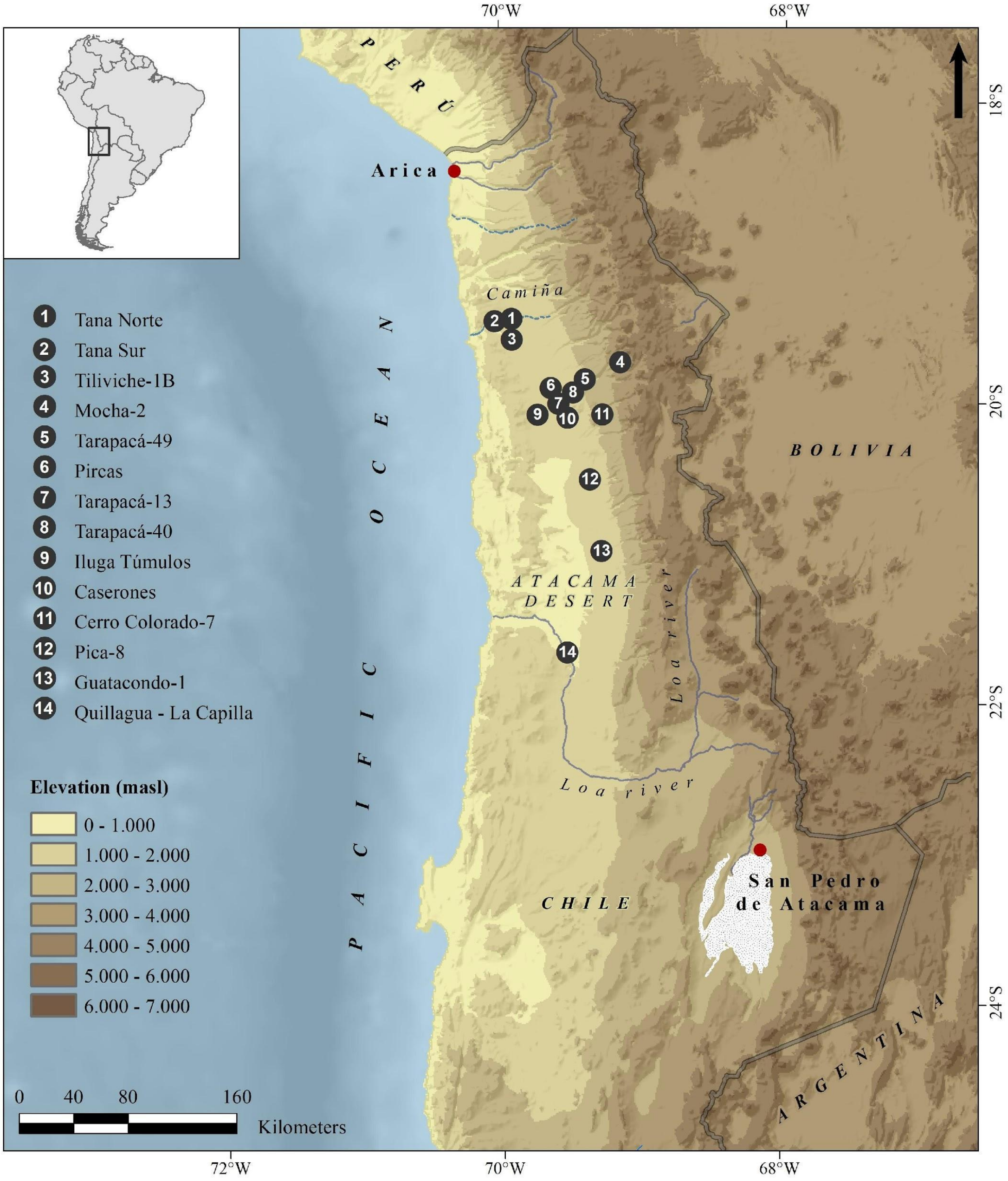
Supplementary Table 1. Radiocarbon dates for nine plants analysed in this study, and published radiocarbon dates for the relevant sites. All dates were calibrated using the SHCal13 curve.

Supplementary Table 2. $\delta^{13}C$ and $\delta^{15}N$ results for archaeological plant remains obtained in this study, together with %C, %N and atomic C/N ratios, geographical location and time period.

Supplementary Table 3. Results of statistical analyses (Kruskal-Wallis) for crops and wild plants by period.

Supplementary Table 4. Human $\delta^{13}C$ collagen, $\delta^{13}C$ apatite (enamel and bone) and $\delta^{15}N$ from sites of northern Chile dating to the Formative, Middle, Late Intermediate and Late Periods.

Supplementary Table 5. Results of statistical analyses (Kruskal-Wallis) for human isotope data from northern Chile by period and geographical area.



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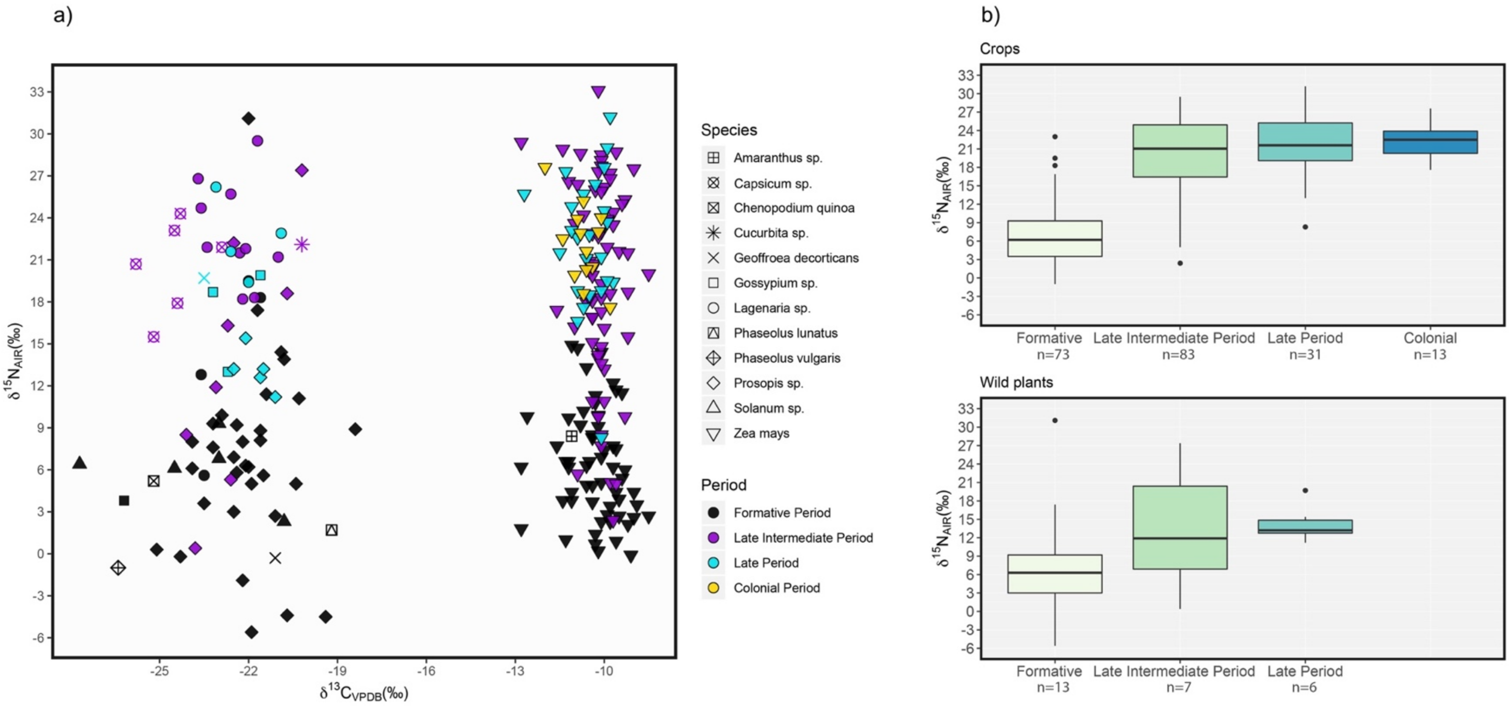

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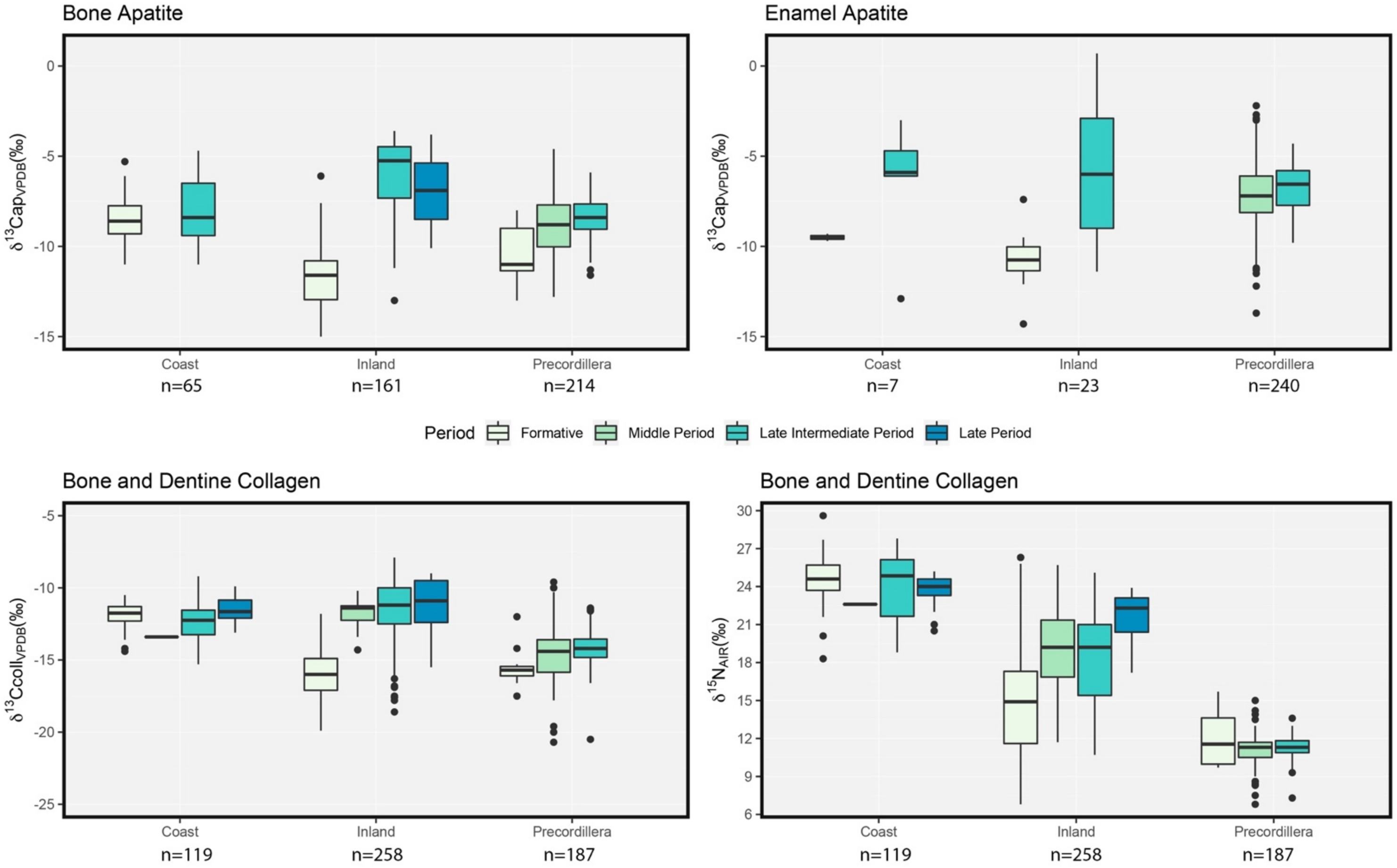

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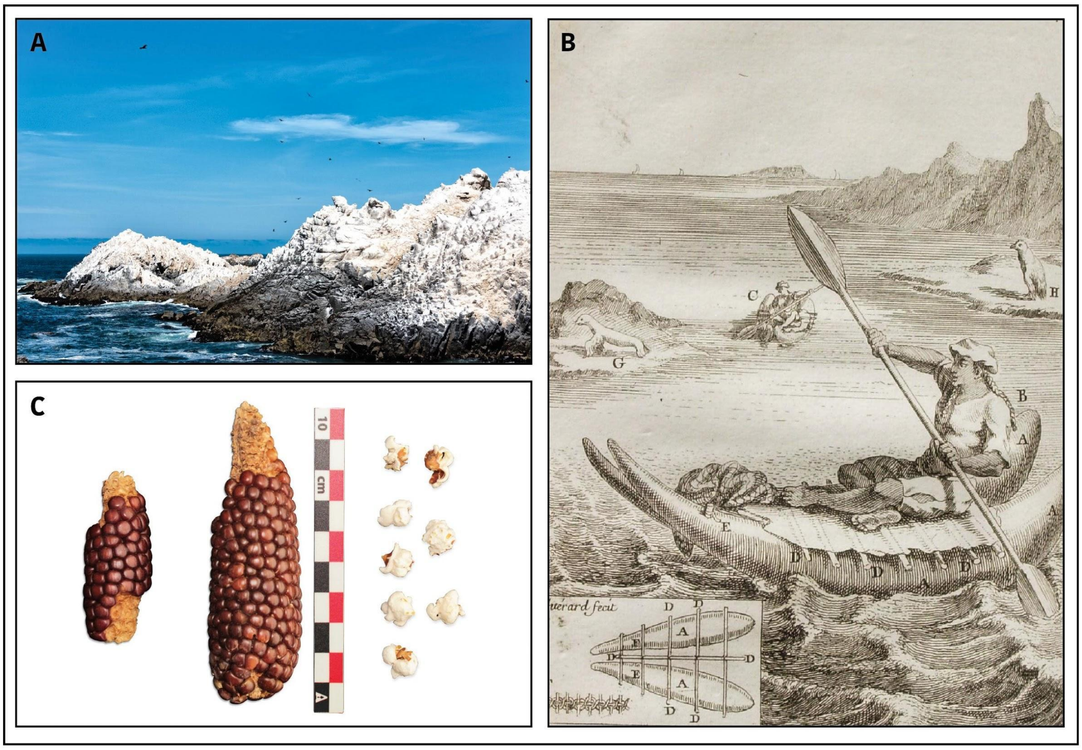

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