Delayed demographic transition following the adoption of cultivated plants in the eastern La Plata Basin and Atlantic coast, South America

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1. Introduction

The transition from hunting and gathering to economies based on agriculture led to a major turn in human demography. In Eurasia, a dramatic growth in birth rates following the adoption of farming resulted in unprecedented population expansion, a phenomenon known as the Neolithic Demographic Transition (NDT) (Bocquet-Appel, 2011; Bocquet-Appel and Bar-Yosef, 2008). Originally, the NDT was inferred from bioanthropological data (Bocquet-Appel, 2002) and genetic clines in modern populations (Cavalli-Sforza et al., 1994), with population replacement during the spread of farming later confirmed by ancient DNA (Haak et al., 2010).

The mechanism that allowed farmers’ population growth is much debated, with explanations mostly revolving around changes to fertility or increase in carrying capacity (Smith, 2015). In the first case, it is argued that fertility was raised as a result of higher caloric intake and lower energy expenditure with mobility, which allowed for shorter birth intervals (Bocquet-Appel, 2011). In the latter case, carrying capacity is argued to increase with the density and growth rate of resources – both of which are higher among plants and, especially, domesticated plants (Bettinger, 2016). The chain of causation is inverted, with pressure on land leading to agriculture as a form of maximizing energy returns through higher labour input per unit of land (Bettinger, 2016; Boserup, 1965). Both explanations are not mutually exclusive: a positive feedback may be envisaged between intensification, raising of carrying capacity, and subsequent population growth – which demands further intensification.

More recently, statistical analyses of aggregated radiocarbon dates became a widely-employed method for assessing palaeodemography. The assumption behind such approaches is that relative population size will be reflected in the abundance of datable material and, consequently, on the number of radiocarbon determinations for a given period (Rick, 1987). Beyond the mere visual inspection of radiocarbon date frequencies, robust methods have recently been developed for explicit model testing. Most commonly, summed probability distributions (SPDs) of radiocarbon dates are compared to a null hypothesis, usually assuming uniform or exponential distributions, by means of Monte Carlo simulations (Timpson et al., 2014). This approach has the potential to identify significant peaks and troughs in the SPDs that are reflect...
calibration curve. When applied to the large number of radiocarbon determinations spanning the Mesolithic and Neolithic in Europe, the use of statistical analyses of SPDs as a proxy for population dynamics found a common pattern: in different parts of the continent, the onset of the Neolithic was followed by rapid growth and subsequent decline - the latter potentially explained by outmigration, disease or overshooting of carrying capacity (Shennan et al., 2013; Timpson et al., 2014).

The question remains open, however, whether the same trajectory was followed in other parts of the world. In the Americas, few assessments of the relationship between changes in subsistence systems and population growth have been made, hindering an evaluation of the NDT as a global phenomenon. In North America, it has been argued that the continent as a whole does conform to the pattern of the NDT (Bocquet-Appel and Naji, 2006). However, some regions that have been subject to more rigorous analysis appear to have experienced a different process. For example, in the US Southwest, bioarchaeological data do not support a change in birth rates until ca. two and a half millennia after the introduction of maize cultivation (Kohler et al., 2008; Kohler and Glaude, 2008; Kohler and Reese, 2014). Significant population growth, it is argued, was not driven by the adoption of cultivated plants per se, but by a series of later developments: the arrival of more productive varieties of maize, the broadening of the agricultural package, and the establishment of sedentary villages (Kohler et al., 2008).

In the tropics of South America, it was hypothesized that the process of transition to agriculture and the role of domesticated plants in local economies differed markedly from those observed in Eurasia (Fausto and Neves, 2018; Neves, 2013; Shepard et al., 2020). A form of “cultivation without domestication” has been suggested by some researchers to be prevalent in the Neotropics, thus explaining the long delay between initial plant domestication and the transition to economies more heavily dependent on agriculture (Fausto and Neves, 2018). Polyculture agroforestry – the combination of low intensity cultivation of a broad range of domesticated species, management of (semi)domesticated trees, and formation of anthrosols – has also been argued to be a widespread economic pattern in tropical forest environments (Clement et al., 2015; Levis et al., 2017; Maezumi et al., 2018; Neves, 2007, 2013; Piperno and Pearsall, 1998). Intensive land use, however, was practised in some regions – as documented by raised fields, drainage canals and other productive infrastructure (Blatix et al., 2018; Iriarte et al., 2012; Lombardo, 2010) – and there has been strong criticism of the view that pre-Columbian societies of the Neotropics were merely complementing their diets with a low intake of domesticated plants (Iriarte, 2009). Even in economies where agroforestry was dominant, the formation of anthrosols may be seen as a form of labour-intensive, long-term investment in the landscape, with the potential to support large populations in a sustainable manner (Iriarte et al., 2020).

Whatever the case, it is undeniable that agriculture in the Neotropics must be understood “on its own terms” and cannot be evaluated solely based on Eurasian standards (Denham et al., 2007). Although it would be incorrect to assume that Neotropical groups were mostly foragers who complemented their diets with a few crops (see criticism in Iriarte, 2009), it is also not necessarily the case that they were deriving most of their calories from domesticated plants or that they were practising field cultivation as Eurasian farmers.

Thus, given the different expansion capacities of agricultural systems worldwide ( Harris, 2003), it is possible that the agroforestry economies of tropical South America resulted in a later onset of demographic expansion than those observed in other parts of the world. Or were the more intensive systems developed in the Neotropics capable of fostering rapid demographic growth? In this paper, we address that question with a regional case study, performing statistical analysis of aggregated radiocarbon determinations from the eastern La Plata Basin and adjacent Atlantic coast, one of the most intensely studied regions of lowland South America.

The application of formal model-testing to radiocarbon data with the aim of exploring prehistoric demography in South America is recent. Population growth rates have previously been estimated by fitting a two-phase model to the continental SPD curve, showing logistic growth until ~5500 cal BP followed by a phase of exponential growth (Goldberg et al., 2016). In contrast with the expectations of the NDT, the transition between the two demographic regimes did not immediately follow the introduction of plant domesticates, but coincided with a trend towards increased sedentism (Goldberg et al., 2016). A more recent and complete assessment of the South American radiocarbon record has brought further evidence for a significant decline at the beginning of the mid-Holocene during a period of marked precipitation variability and aridity, followed by population recovery after ~6000 cal BP (Riris and Arroyo-Kalin, 2019). Renewed growth occurred in tandem with a broadening of the role of managed and cultivated plants in the economy, which may have mitigated the effects of drought (Riris and Arroyo-Kalin, 2019). For the initial occupation of South America, Prates et al. (2020) show that a logistic model better explains the continental SPD for the period ~15000-8000 cal BP. Significant positive deviations, however, appear to coincide with the Antarctic Cold Reversal stadial at ~15500 cal BP, and with the emergence of specialised economies ~8400 cal BP (Prates et al., 2020).

SPDs for specific regions of South America have also been subject to explicit model-testing in order to assess population dynamics. For the Peruviano coasts and highlands, for example, Riris (2018) has argued that sustained population growth occurred throughout the Holocene, except for an event of decline ~5000 cal BP. In the South-Central Andes, Gayo et al. (2015) found a decline in population levels ~9500-6000 cal BP, followed by rapid recovery. The coastal Atacama Desert, however, conform to a different pattern, with stable (albeit low) population levels ~7800-6000 cal BP followed by a brief expansion and another event of decline ~5500-4550 cal BP (Gayo et al., 2015). For the Amazon Basin, Arroyo-Kalin and Riris (2020) have identified a phase of logistic growth starting ~1700 cal BP, an indication that Amazonian populations may have reached carrying capacity at the eve of the European encounter. The latter trend deserves special attention, as its onset follows by a few centuries the appearance of anthrosols (Amazonian Dark Earths or terra preta) throughout the basin (Iriarte et al., 2020), at least suggesting that intensive agroforestry systems may have enabled rapid population growth. However, given the spatial variability in demographic trajectories so far observed in South America, more regional case studies are necessary to evaluate local responses to changes in the subsistence system.

Here, we assess the radiocarbon record of the eastern La Plata Basin and Atlantic Coast (ELBAC), southeastern South America, as a proxy for population dynamics. By applying formal model-testing to SPDs, we compare the spatiotemporal distribution of radiocarbon determinations with the onset of key economic transitions. The region of study is here defined on the basis of climatic, geographical and cultural criteria (Iriarte et al., 2016). It encompasses the subtropical domains of the Paraguay, Paraná and Uruguay River Basins (which form the La Plata River) together with the adjacent Atlantic coast (Fig. 1). Most of the study area coincides with the La Plata Basin proper. However, because we considered cultural as well as geographical criteria in the delimitation of the study zone, areas that are not technically part of the basin are also included in the analysis. This is the case, for example, with the Uruguayan pampas, whose archaeology has deep connections to that of the subtropical areas of southern Brazil (Iriarte, 2006). Similarly, the southern Brazilian Atlantic coast was settled by cultures that were also present in the interior of the La Plata Basin (Sonomo et al., 2015; Noelli and Souza, 2017). In contrast, some areas that are technically part of the La Plata Basin are not addressed – such as the wetlands and savannas that form the basin’s headwaters – as they have cultural connections elsewhere (the Amazon, Central Brazil) or have insufficient radiocarbon data.

The study region is a privileged setting in lowland South America for evaluating the signal of the NDT in Neotropical contexts: unlike (most parts of) the Amazon, where the scarcity of dates reliably affiliated to
distinct archaeological cultures undermines the significance of conclusions based on aggregated radiocarbon data (Riris, 2019), the ELBAC has a considerable density and coverage of high-quality data (Iriarte et al., 2016). Crucially, the introduction of plant cultivation to the region coincides, in part, with cultural dispersals from other parts of South America – namely, the Guarani from the Amazon Basin and the Jê from central Brazil (De Souza et al., 2020; Iriarte et al., 2016). Both traditions relied on agroforestry and the formation of anthropogenic forests (Noelli, 1998; Robinson et al., 2018). At the same time, before the arrival of the Guarani and southern Jê, cultivated plants were already present and may have played an important role in the development of the mid-Holocene societies of Uruguay and the Brazilian coast, who engaged in the construction of earthen and shell mounds (Iriarte et al., 2004; Wesolowski et al., 2010). Thus, both endogenous and exogenous processes were at play at different times in the transition to agroforestry-based economies in the ELBAC.

In this paper, we aim to address the following questions: does the demographic trajectory in the ELBAC repeat the “boom and bust” patterns that have been argued to follow the adoption of agriculture elsewhere (Timpson et al., 2014)? Or did the region experience lower growth rates, due to a lower expansion capacity of polyculture agroforestry and to the lag between first adoption of domesticates and full reliance on plant cultivation in the tropics (Fausto and Neves, 2018)? Are there regional variations within the ELBAC?

In what follows, we briefly review the evidence for the adoption of cultivated plants in the major cultural traditions of the ELBAC, before moving to the analysis of the radiocarbon record. For a thorough review of the archaeology of the region, we refer the reader to Iriarte et al. (2016).

1.1. Evidence of plant cultivation in the ELBAC

The currently available archaeobotanical data suggest that the transition to plant cultivation in the ELBAC, similar to other cases in lowland South America, was multifocal, responding to endogenous and exogenous processes. In southeastern Uruguay, the earliest evidence of domesticated plants is provided by phytoliths of maize (Zea mays) and squash (Cucurbita sp.) from preceramic contexts of mound villages (Cerritos) ~4700 cal BP (Iriarte et al., 2004). The presence of maize and other cultigens, including beans (Phaseolus sp.), has been confirmed...
from phytolith and starch grain evidence from Cerritos sites dated at least ~3900-2900 cal BP (Iriarte, 2003). In other sites that have been analysed, however, phytoliths of cultivars (maize and beans) appear only after ~2000 cal BP, suggesting some temporal heterogeneity in the adoption of plant cultivation or perhaps a late intensification of that strategy (del Puerto et al., 2016). The adoption of cultivars in the region coincides with transformations in site architecture and settlement patterns by Cerritos societies, with the appearance of more permanent sites and formal architectural layouts, including circular arrangements of mounds around central plazas (Iriarte et al., 2004).

In the southern Brazilian coast, starch grains recovered from dental calculi of individuals buried in shell mounds (Sambaquis) attest the consumption of sweet potato (Ipomoea batatas) and yam (Dioscorea sp.), among other cultivars, since ~4800 cal BP, thus showing the adoption of plant cultivation at approximately the same time as in the Uruguayan Cerritos (Wesolowski et al., 2010). The importance of tubers has been confirmed by stable isotope analysis and oral health markers, which attest the consumption of carbohydrate-rich plants among Sambaqui populations (Boyadjian et al., 2016; Scheel-Ybert and Boyadjian, 2020). Microbotanical evidence from dental calculi also attest the presence of maize after ~1300 cal BP, associated with the arrival of the southern Jé tradition to the coast (see below) (Wesolowski et al., 2010). The Brazilian Sambaquis represent an intensification of coastal adaptations during the mid-Holocene, long thought to reflect larger and more sedentary populations whose economy was based on marine resources, with the monumental shell mounds currently interpreted as ceremonial sites for collective burials around key points of the coastal landscape (De Blasis et al., 2007).

A second wave of transition comes with the arrival of cultural traditions from outside the ELBAC: the Guarani and the southern Jé. The Guarani represent the southermost branch of the Tupi-Guarani family, which spread from either southwestern or (most likely) eastern Amazon to the Paraná basin, Atlantic coast, and most forested areas of eastern South America (Bonomo et al., 2015; Brochado, 1984; Iriarte et al., 2017; Noelli, 1998). Archaeologically, the northermost parts of the ELBAC were also occupied by the Tupinambá, so that we use the more inclusive label “Tupí-Guaraní” in Table S1. Guarani sites are distributed around major navigable rivers and forested areas of the ELBAC, recognized by distinct anthrosols, corrugated and polychrome ceramics and urn burials (Bonomo et al., 2015; Milheira and DeBlasis, 2014; Noelli, 1998). There is ample ethnohistorical evidence for the role of forest management and polyculture agroforestry among the Guarani and other Tupí-Guarani populations, who brought a rich package with many varieties of cultivated plants (maize, manioc, beans, sweet potato, among others) to the regions they settled (Noelli, 1993). In fact, pollen evidence of maize ~2000 cal BP in southern Brazil coincides with the approximate date of arrival of the Guarani to the region (Behling et al., 2005). Currently, direct evidence for the consumption of maize and beans by the Guarani is provided by starch grains recovered from ceramic sherds ~500 cal BP (Schneider et al., 2016).

The southern Jé, archaeologically identified as the Taquara/Itararé tradition, represent the southernmost branch of the Jé family that spread throughout the central Brazilian savannah (cerrado) and reached the southern Brazilian highlands and adjacent coast (Noelli, 2005; Noelli and Souza, 2017). Archaeological sites in the highlands of Paraná represent earthen architecture with pit houses, ceremonial enclosures and burial mounds (Corteletti and Iriarte, 2018; Noelli and Souza, 2017). After ~1000 cal BP, the highest density of sites is attained, coupled with evidence for emerging socio-political hierarchies in the settlement and funerary records (De Souza et al., 2016a, 2016b). The demographic trajectory of the southern Jé seems to have been sustained by an agroforestry base, combining plant cultivation and forest management, potentially influencing the spread and maintenance of Araucaria angustifolia (Robinson et al., 2018). As in the Guarani case, the first appearance of maize pollen in southern Jé territory (in the highlands of Misiones, Argentina) is dated to ~1800 cal BP, broadly coinciding with the southern Jé arrival to the ELBAC (Gessert et al., 2011). Archaeobotanical data available so far indicate the presence of maize, squash, beans and manioc in domestic contexts ~600 cal BP (Corteletti et al., 2015). In ceremonial contexts, ceramics from a large mound and enclosure complex yielded phytoliths of maize in a context related to ceremonial feasting dated ~700 cal BP (Iriarte et al., 2008). Preserved maize cobs were recovered from a funerary rock shelter of similar age (Lazzarotto et al., 1971). As mentioned above, on the coast, southern Jé burials dated ~1300 cal BP, postdating the Sambaquis, contained starch grains of sweet potato and maize in their dental calculi (Wesolowski et al., 2010).

Finally, in the lower Paraná, the local Goya-Malabrigo tradition has also been considered a dispersal from Amazonian environments, potentially related to Arawak speakers based on ceramic decoration, settlement patterns and social organization as described in historical accounts (Politis and Bonomo, 2012). That association, however, has been questioned by proponents of a local origin for the ceramic complex (Loponte and Acosta, 2016). Whatever the case, the Goya-Malabrigo occupied settlements with moulded architecture along the floodplains of the lower Paraná and its delta beginning around 2000 cal BP (Bonomo et al., 2011b). Evidence for plant cultivation in the region spans almost the entire duration of the Goya-Malabrigo tradition. Maize starch is attested since ~1650 cal BP (Bonomo et al., 2017), whereas phytoliths and starch grains of beans, maize and manioc were recovered from ceramic sherds and stone artefacts in contexts dated ~1100-500 cal BP (Bonomo et al., 2011a, 2017).

In summary, currently available archaeobotanical data suggest two periods of incorporation of cultivated plants into local economies. The first, ~4800 cal BP, attested in the Cerritos and in the Sambaquis, appears to have resulted from an endogenous process that also involved increased sedentism and emergence of earthen and shell monumental architecture. The second, ~2000 cal BP, was promoted by the arrival of the Guarani and southern Jé to the ELBAC, bringing with them a package of domesticated plants and agroforestry practices from lower latitudes (Bonomo et al., 2015; Corteletti and Iriarte, 2018). The arrival of the Goya-Malabrigo tradition to, or potentially its local emergence in the ELBAC, was part of the same transition. Even though domesticated plants were already present among the Cerritos and Sambaquis, the second wave brought plant cultivation to areas where it was previously unattested, as in the case of the southern Brazilian highlands.

Based on the broad picture defined above, we proceed to analyse aggregated radiocarbon determinations in order to assess population dynamics in relation to the identified economic transitions in the ELBAC. Specifically, we aim to test the following hypotheses:

1. If ELBAC societies experienced demographic processes similar to those of Eurasia, it is expected that statistically significant peaks in the SPDs will follow the appearance of plant cultivation;
2. Alternatively, if polyculture agroforestry as practised in the tropics provided a lower expansion capacity than Eurasian agriculture (Harris, 2002), no significant peaks should be observed.

The multifocal, diffuse nature of the adoption of cultivated plants in the ELBAC, as in other parts of South America (Piperno, 2011), offers a further challenge. Different responses may have been triggered by the two proposed transitions (~4800 and ~2000 cal BP): 3. It is possible that a double boom-and-burst pattern will be observed following each of the transitions; 4. Alternatively, a slow transition could be followed by a dramatic increase in the second moment, if the latter incorporated other elements (beyond plant cultivation) that fostered population growth (Kohler and Reese, 2014). This scenario is expected under the
hypothesis of a long delay, in the Neotropics, between first adoption of crops and a heavier dependence on cultivation (Fausto and Neves, 2018).

2. Materials and methods

2.1. Compilation of radiocarbon dates

We compiled a total of 1139 radiocarbon dates from 504 archaeological sites in the ELBAC. Dates and site coordinates were compiled from a variety of sources, including published literature, unpublished reports and existing databases (Bonomo et al., 2015; De Blasis et al., 2007; Noelli, 1999; Noelli and Souza, 2017; Politis and Bonomo, 2012), which were cross-checked with the original sources (Table S1). Although we are principally interested in mid- and late Holocene economic transitions, we compiled dates available for all periods since the late Pleistocene. The analysis was limited to the period 6000-500 cal BP, which encompasses the duration of the archaeological cultures of interest and allows us to observe the trends that precede the first occurrence of plant domesticates ~4800 cal BP. Extending the time window to ca. a millennium before the economic transition of interest is a procedure previously adopted in the analysis of SPDs as a paleodemography proxy (Shennan et al., 2013). As per standard practise, however, models are fitted including dates within 500 years of the time window so as to avoid edge effects. The selected time window also dovetails with the transition in South American palaeodemographic dynamics suggested by (Goldberg et al., 2016). Our period of interest ends at the approximate date of the Columbian encounter, since later demographic processes cannot be dissociated from the impact of that event.

2.2. SPDs

Analysis was performed with the rcarbon 1.3.3 package for R (R Core Team, 2018).

For the SPDs, dates were calibrated using the SHCal12 curve (Hogg et al., 2020), except for those obtained on marine shell, in which cases we used the Marine20 curve (Heaton et al., 2020) and average ΔR offsets and errors based on the 10 nearest published values (http://calib.org/marine/). To account for oversampling of some sites, we aggregated dates from the same site into 200-year bins. SPDs are not normalised in order to minimize artefacts of the calibration curve on their shapes (Bevan et al., 2017).

2.3. Model testing

When comparing SPDs against a null hypothesis, an exponential model is commonly chosen, as it is assumed to reflect population growth in combination with taphonomic processes (Timpson et al., 2014). In addition to testing the observed SPD against a simple exponential model, we follow the established procedure of fitting multi-phase models with the aim of identifying changes in the demographic regime itself (Goldberg et al., 2016; Riris and Arroyo-Kalin, 2019). We accomplish this by fitting a suite of nine additional models (Models A to I) to the summed calibrated probability distributions for the ELBAC, representing different potential demographic models and points of transition between them. Our range of models is based on qualitative inspection of the shape of the SPD. We formally compare the fits with Akaike’s Information Criterion (AIC) (Table 1) to penalize model complexity while optimizing information gain, following precedent in the literature (Fernandez-Lopez de Pablo et al., 2019; Riris and Arroyo-Kalin, 2019). To do so, we extracted model likelihoods for each fitted model, calculated AICs, and summed them to derive overall model weights and ΔAIC values. As likelihoods are additive, so is the AIC (Burnham and Anderson, 2002, 2004).

To assess the goodness-of-fit of these models, simulated SPDs are produced by generating a number of random dates (equivalent to the number of bins in the empirical dataset) based on the assumed distribution (e.g. exponential), for a number of Monte Carlo runs (n = 999). A 95% confidence interval is then calculated from the simulated SPDs, and significant deviations from the null model are highlighted by comparing the empirical SPD to that envelope.

2.4. Permutation tests

To assess regional departures from the global demographic trajectory in the ELBAC, we employed a random mark permutation test (Crema et al., 2016). In this procedure, the marks (in this case, regional affiliations) associated with each bin are randomly shuffled, and simulated SPDs are computed for a number of Monte Carlo runs (n = 999). The simulated SPDs are then used to calculate a 95% confidence interval that represents the null of no spatial structure in the subsets of the empirical data. Significant regional departures from the global SPD are defined as the periods where the empirical SPDs are above or below that envelope. For the marks, we subdivided our dataset into four regions of cultural and geographical pertinence:

Region 1: the Atlantic coast, whose sites are mostly related to the Sambaqui societies.
Region 2: the pampas or plains of Uruguay and adjacent southern Brazil, broadly coinciding with the extent of the Cerritos;
Region 3: the southern Brazilian highlands, primarily occupied by the southern Je;
Region 4: the forested lowlands of the middle Paraná, Uruguay, Jacuí Rivers and neighboring areas settled by the Guarani;
Region 5: the lower Paraná and its delta, mainly occupied by the Goya-Malabrigo tradition.

Although each region has the predominance of a particular archaeological tradition, the analysis has been carried out considering all sites independently of cultural affiliation. Besides the fact that cultural affiliations are not always agreed upon, subdividing the data could mask the broad demographic patterns in a region for a given time period. Including all dates is justified by previous studies concerning regional population changes relative to economic transitions (Shennan et al., 2013).

In addition to comparing each local SPD to the pan-regional trend, we performed pairwise comparisons of the permutation test of all regions (Fig. S2). All of the procedures described in this section are

Table 1
Comparison of statistical fits to the empirical SPD for the ELBAC study region.

| Model | Type | Breakpoint (cal BP) | Parameters | Total AIC | ΔAIC | w |
|-------|------|---------------------|------------|-----------|------|---|
| I     | Exponential, Linear, Exponential | 4000, 2000 | 3, 3, 3 | -104665 | 0 | 1 |
| H     | Exponential, Linear, Exponential | 4000, 1500 | 3, 3, 3 | -104635 | 30.9 | 1.89E-07 |
| G     | Logistic, Linear, Exponential | 4000, 2000 | 5, 3, 3 | -104105 | 560.8 | 1.61E-122 |
| F     | Linear, Linear, Linear | 4000, 1500 | 3, 3, 3 | -104072 | 593.5 | 1.29E-129 |
| C     | Logistic & Exponential | 2000 | 5, 3 | -100837 | 3828.9 | 0 |
| E     | Logistic & Exponential | 3000 | 5, 3 | -99391 | 5274.5 | 0 |
| D     | Logistic & Logistic | 4000 | 5, 5 | -95134 | 9531.8 | 0 |
| A     | Exponential | N/A | 3 | -88605 | 16600.7 | 0 |
| B     | Logistic | N/A | 5 | -87874 | 16791.6 | 0 |
available as R code in the supplementary information (Appendix S3).

3. Results and discussion

3.1. Model-fitting

The observed SPD for all sites in the ELBAC significantly departs from a null exponential model for the period of interest (Fig. 2a). Two positive deviations are observed at ~5400–3900 and ~800–500 cal BP, intercalated with a period of negative deviation ~2800–1300. Having confirmed the inadequacy of an exponential model to explain the ELBAC data we found that the best-fit model (Model I) adequately describes the observed SPD by combining a phase of exponential growth ~6000–4000 cal BP, followed by a gently linear decrease ~4000–2000 cal BP and, finally, a renewed phase of exponential growth ~2000–500 cal BP (Fig. 2B, Fig. S4, Table 1). The first part of the overall trend is in agreement with previous models published for the entire South American continent, which show exponential growth following ~6000–5500 cal BP (Goldberg et al., 2016; Riris and Arroyo-Kalin, 2019). The putative early Late Holocene phase of population contraction, as opposed to stabilisation at theoretical carrying capacity (Goldberg et al., 2016), is, to the best of our knowledge, unique to the ELBAC.

3.2. Permutation test

Demographic trends were not homogeneous throughout the research area. The results of the permutation test show that all regional SPDs exhibited significant departures from the pan-regional trend (Fig. 3). Overall, trajectories are asynchronous and in antiphase between two broad regions: (1) the coast and the pampas, and (2) the southern Brazilian highlands, Paraná lowlands and delta. Whereas the former regions show positive deviations until ~2000 cal BP, followed by decline, the latter show negative deviations until ~2000 cal BP, followed by growth. The pairwise permutation test reinforces this result, with the SPDs for the coast and pampas showing no statistically significant deviations from each other, but exhibiting significant deviations from the other three regions (Fig. S2). It is important to notice that the latter also show some regional variation, since only the permutation of the lower Paraná and the southern Brazilian highlands exhibited non-significant results (Fig. S2).

Comparing the regional curves with the best-fit model for the entire ELBAC, we may conclude that the three-phase model can be attributed to higher activity (albeit under different demographic regimes) in the coast, in the first instance (exponential growth ~6000–4000 cal BP), and in the highlands and Paraná delta, in a second moment (exponential growth ~2000–500 cal BP).

The pattern evidenced in the permutation test mimics the spatio-temporal heterogeneity in the adoption of plant cultivation, which is earlier in the coast and pampas, but a causal relationship is not obvious. In the coast, a significant positive deviation from the pan-regional trend spans the entire period ~6000–2000 cal BP (Fig. 3a), a peak of activity which coincides with the flourishing of the Sambaquis and the first adoption of plant domesticates. The earliest available evidence for consumption of cultivated plants, however, postdates the onset of significant growth in the region (Wesolowski et al., 2010). Thus, rather than promoting unprecedented demographic growth, plant cultivation may have been incorporated in the economy of populations that were already relatively large, settled and densely distributed thanks to the exploitation of marine resources. Indeed, the distinctiveness of social trajectories in coastal environments, whose abundant and predictable resources are capable of sustaining high population densities and sedentism, has long been recognized (Fitzpatrick, 2020). For example, it was recently shown that, contrary to many other regions of Europe, population growth in Scandinavia precedes the Neolithic, which has been attributed to the high productivity of marine environments during the Mesolithic (Lewis et al., 2020). In South America, the most obvious example is the emergence of sedentism and social complexity along the Pacific Coast of Chile and Peru ~7000–4000 cal BP during a phase of increased freshwater availability and high marine productivity (Beresford-Jones et al., 2018; Marquet et al., 2012).

The positive deviation prior to the adoption of cultivars deserves some attention in light of optimal foraging models that propose population packing as a driver of domestication (Kennett and Winterhalder, 2006). For example, in the Mediterranean rim, pressure over high-ranked game and declines in hunting intensity throughout the Epipalaeolithic have been demonstrated through shifts in prey composition, suggesting that population pressure played a role in Late Holocene developments such as the transition to agropastoralism (Munro et al., 2018; Stiner et al., 1999). In Eastern North America, kernel density estimates (KDE) of taphonomically-corrected aggregated

![](image-url) Fig. 2. a) Test of SPD against exponential null model. b) Best-fit demographic model (exponential-linear-exponential, with breakpoints at ~4000 and 2000 cal BP). The confidence interval from the simulated dataset is shaded in grey, and areas of significant positive and negative deviations are highlighted in red and blue, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
radiocarbon data also point to large Mid Holocene populations prior to the adoption of domesticates (Weitzel and Codding, 2020). In the ELBAC, however, the same pattern cannot be inferred solely from the radiocarbon record of other regions except for the coast.

In summary, the early activity among the Sambaquis appears to drive the first phase of demographic regime in the ELBAC (exponential growth ~6000-4000 cal BP), a period when other regions (the southern highlands, Paraná lowlands and delta) exhibit long negative deviations from the pan-regional trend (Fig. 3). Although the first adoption of cultivated plants in the ELBAC occurred during this period, a causal relationship with population growth in the coast cannot be established, and a negative deviation from the pan-regional trend is evident in the coast after ~1300 cal BP, even though plant cultivation had been part of local economies for millennia (Fig. 3a). We caution against over-interpreting sustained negative deviations in the permutation test over the early exponential growth phase, as low archaeological visibility and low
The situation of the pampas is not as clear, with peaks of positive deviation from the negative, linear pan-regional trend ~4000-1500 cal BP (Fig. 3b). Local growth, however, may be unrelated to changes in the subsistence system. The first significant deviation follows, by several centuries, the earliest evidence of domesticated plants among the Cerritos (Iriarte et al., 2004). The bulk of the positive local deviations seen in the pampas after ~3300 cal BP (Fig. 3b) coincides with the transformation of Cerritos societies through the arrival of ceramics, diversification of mound architecture and greater formalization of village plans (Iriarte, 2003). Thus, we suggest that socio-political factors may have been more decisive in shaping the demographic trajectory of the region than the adoption of cultivated plants by itself. Alternatively, it is possible that the observed peaks are related to a later adoption (or intensification) of plant cultivation among most Cerritos societies, as in the case of the sites analysed by del Puerto et al. (2016), where crops only appear after ~2000 cal BP. Similar to the coast, sustained growth is apparently never achieved, with a noticeable decline in the final part of the sequence (Fig. 3b).

In the southern Highland, the arrival of the southern Je, coinciding with the first evidence of maize (Gessert et al., 2011), is followed by a positive deviation from the pan-regional trend after ~1300 cal BP, in antiphase with the coast (Fig. 3c). Although the arrival of the southern Je coincides with the onset of the second phase of exponential growth in the best-fit model for the whole ELBAC (~2000 cal BP), the deviation seen in the permutation test shows a delay of several centuries from the earliest date of that archaeological tradition. The period of local positive deviation coincides with two later phenomena: the expansion of Araucaria forests, potentially due to anthropogenic influence (Bitencourt and Krauspenhar, 2006; Iriarte and Behling, 2007; Robinson et al., 2018), and the development of novel forms of ceremonial and domestic architecture reflecting the formalization of leadership and growing inequality in the highlands (De Souza, 2018; De Souza et al., 2016a; Iriarte et al., 2008).

At the same time, the forested lowlands settled by the Guarani after ~2000 cal BP do not show a significant deviation from the pan-regional demographic trend, which is exponential at this point (Fig. 3d). Before that time period, the region shows the same long negative deviation as the highlands and Paraná delta, in contrast with the trend observed in the coast and pampas. A rapid demographic expansion – or “swarming” – has long been accepted as the main process of Guarani spread (Bonomo et al., 2015; Brochado, 1984; Noelli, 1998). This would lead us to expect a significant positive deviation from the pan-regional trend in the areas occupied by that archaeological culture after ~2000 cal BP. The absence of such trend is intriguing and adds to the results of recent simulation-based approaches that failed to replicate the Guarani expansion as a purely demographic dispersal – but the presence of questionable dates, lack of spatial structure in their distribution and overall incompleteness of the radiocarbon record must also be taken into account (De Souza et al., 2020).

We suggest that the principal driver of exponential population growth in the period following ~2000 cal BP in the ELBAC was triggered by the arrival of cultural traditions that originated outside the region: namely the southern Je and Guarani, who introduced a diverse package of cultivated plants and active forest management in the region (Bonomo et al., 2015; Robinson et al., 2018), but also the Goya-Malabrigo. Even though current archaeobotanical evidence suggests plant domesticates were present much earlier, it was only with this second wave that a demographic signal comparable to the NDT is evident in the ELBAC.

The observed trend is in agreement with dietary reconstructions based on stable isotopes from human bone collagen. For the Sambuquis, data spanning from ~6700 to 1700 cal BP show a predominantly marine diet, except for inland populations with higher intake of C3 terrestrial animals (Colone et al., 2014). There is, however, evidence for a higher intake of C3 plants among some coastal groups ~4800-4100 cal BP and in later southern Je sites, which also relied more heavily on terrestrial mammals (Pezo-Lanfranco et al., 2020). As for the Cerritos, although maize is present in the archaeobotanical record from early on, bone collagen δ13C values are very depleted, with a single exception, even in samples dated later than ~2500 cal BP (Bracco et al., 2005; del Puerto et al., 2014). The same is true of Goya-Malabrigo human remains, which exhibit average δ13C values lower than ~19‰ from ~1600 cal BP to the contact and no significant changes over time, with only two samples suggesting a higher C4 intake (Bonomo et al., 2017; Ottalagano and Loponte, 2017). Among the archaeological traditions of the ELBAC, the southern Je and Guarani exhibit the most enriched bone collagen δ13C values, with some individuals reaching almost ~10‰, but also much internal variation (Bonomo et al., 2017; De Masi, 2009; Loponte et al., 2016). Overall, the Guarani show values around ~16 to ~15‰, with the southern Je yielding more depleted values, especially in the case of samples from the highlands. The absence of a strong C4 signal before the Guarani and southern Je, even though maize is present in the archaeobotanical record, suggests maize may have been consumed in low quantities so as to be undetected isotopically for a long period of time until becoming a staple (Bonomo et al., 2017). Similarly, it is possible that C3 crops were more important than maize, as appears to be the case among some Sambuquis (Pezo-Lanfranco et al., 2020).

The palaeodemographic trajectory observed in our study area is different from that reconstructed for the South/Central Andes, Northwest Patagonia and South Patagonia by Perez et al. (2017) using mtDNA and frequencies of calibrated radiocarbon dates. In the South/Central Andes and Northwest Patagonia, abrupt population increases were noticed following the appearance of domesticated plants and animals. Furthermore, the region with the earliest time of adoption and diversity of cultivars (South/Central Andes, ~8500 cal BP) was shown to have attained the largest population. Although transition to marine diets was apparently also a driver of population growth, Perez et al. (2017) found that it was not sufficient to explain the difference between Northwest and South Patagonia: by ~2000 cal BP, the former had attained a population nearly twice the size of the latter, where domesticated resources were never adopted. In the ELBAC, in contrast, neither marine adaptations nor the age of adoption of cultivars were determinants of a region’s sustained growth – as can be seen in the case of the coast and pampas, which never exhibited the steep increase seen in the highlands or Paraná delta (Fig. 3).

The delay attested in the ELBAC between first appearance of cultivars, population growth and isotopic evidence of agricultural diets should come as no surprise. A delay of over two millennia between the adoption of cultivated plants and significant population growth has been described elsewhere in the Americas (Kohler et al., 2008; Smith, 2015). A similar situation has been hypothesized for the areas closer to the centre of domestication in Eurasia. In the Levant, a lag of over one millennium has been documented between the first evidence of agriculture and considerable population growth, which is related to the emergence of large sedentary villages (Kuijt, 2008). Unlike Europe, where the spread of agriculture was a process driven, in large part, by migration, the areas where plant domestication was actually carried out may have experienced slower transitions. The same phenomenon has been postulated for North America (Bocquet-Appel and Naji, 2006).

Although it is tempting to see the demographic consequences of plant cultivation as dependent on where domestication was carried out locally (slow transition) or brought by waves of migrant farmers (fast growth), the parallel with the ELBAC is imperfect. Cultivated plants like maize and sweet potato, which are present in the region by ~4800-4700 cal BP, were certainly not domesticated locally. Perhaps the fact that even the earliest crops introduced to the ELBAC were domesticated elsewhere is one of the causes of the lag between the first adoption of domesticates and significant population growth, as a pause might have been necessary before the adaptation of predominantly tropical plants to...
4. Conclusion

The nature of food-producing economies in the Neotropics continues to be debated. At the same time that some parts of lowland South America show evidence of large-scale landscape transformations, it is argued that a pattern of plant cultivation without full reliance on agriculture was predominant in most of the region, and that a Neolithic-like economic transition was never truly achieved (Fausto and Neves, 2018). If that is indeed the case for most of the tropics of South America, it is expected that the demographic trajectories of the continent should also differ from the well-known patterns of ‘boom and bust’ following adoption of agriculture as seen, for example, in Europe (Shennan et al., 2013). For a deeper understanding of the question, we believe as many lines of evidence as possible should be examined. In addition, considering the diverse environments and human land use practices attested across lowland South America, more regional studies are necessary.

In this paper, we aimed to contribute to the debate by incorporating a further line of evidence – statistical analysis of aggregated radiocarbon measurements – in the eastern La Plata Basin and Atlantic Coast (ELBAC). We compared the patterns observed in the spatio-temporal distribution of radiocarbon dates with archaeobotanical evidence for the first appearance of domesticated plants. Our results confirm that, as in other parts of the American continent, a delayed transition is observed between the initial adoption of crops and sustained population growth. We further demonstrate that, in the ELBAC, demographic trends are asynchronous and often antiphased between different subregions. For example, whereas the Atlantic coast experiences a significant positive deviation ~6000-2000 cal BP, the same period is marked by a negative deviation in the southern Brazilian highlands, where significant growth occurs only after ~1300 cal BP. When considering the ELBAC as a whole, the spatially heterogeneous demographic trajectories are reflected in two phases of exponential growth (~6000-4000 and ~2000-500 cal BP) intercalated by a period of contraction. Current archaeobotanical evidence confirms that plant domesticates are introduced in the ELBAC ~4800-4700 cal BP, when the first trend of exponential growth in the SPDs is already established. Therefore, the adoption of plant cultivation appears to follow rather than cause population growth during that first period. It is only after ~2000 cal BP, with the arrival of new archaeological traditions – and their respective packages of crops, agroforestry practices and potential adaptations to subtemporal environments – to the ELBAC that a causal relationship may be established between a higher reliance on domesticated plants and significant population growth. In summary, our results confirm to the expectations of a hypothetical long delay between adoption of crops and the consequences of heavier economic reliance on food production (including the purported demographic transition) in the Neotropics. At the same time, however, we suggest that a signal compatible with the Neolithic demographic transition may be observed in lowland South America under certain conditions, as seen in the later part of our sequence. The precise conditions responsible for this relatively late regime shift is in need of further study.

As more radiocarbon data are obtained for other parts of lowland South America, and as archaeobotanical evidence comes into sharper focus, we expect that similar regional studies will shed further light on the complex relationships between shifts in subsistence and demographic regimes across the continent.

Declaration of competing interest

The authors declare no competing interests.

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Appendix A. Supplementary data

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