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Did pre-Columbian populations of the Amazonian biome reach carrying capacity during the Late Holocene?

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Abstract

The increasingly better-known archaeological record of the Amazon basin, the Orinoco basin, and the Guianas both questions the long-standing premise of a pristine tropical rainforest environment and also provides evidence for major biome-scale cultural and technological transitions prior to European colonisation. Associated changes in pre-Columbian human population size and density, however, are poorly known and often estimated on the basis of unreliable assumptions and guesswork. Drawing on recent developments in the aggregate analysis of large radiocarbon databases, here we present and examine different proxies for relative population change between 1050 BC and AD 1500 within this broad region. By using a robust model-testing approach, our analyses document that the growth of pre-Columbian human population over the 1,700 years prior to European colonisation adheres to a logistic model of demographic growth. This suggests that, at an aggregate level, these pre-Columbian populations had likely reached carrying capacity (however high) before the onset of European colonisation. Our analyses also demonstrate that this aggregate scenario shows considerable variability when projected geographically, which bears on our overall understanding of the resilience of past human food procurement strategies. Lastly, our results provide important insights into pre-Columbian demographic trends and offer novel perspectives on demic expansions, language diversification, and subsistence intensification in the Amazonian biome during the late Holocene.

Keywords: Amazonian biome, Amazonian archaeology, Palaeodemography, Summed Calibrated Probability Distributions, late Holocene

In the broad lowland region of the Amazon basin, the Orinoco, and the Guianas, the late Holocene is widely regarded as a crucial timeframe for the amplification of anthropic landscape transformations [1–3]; the emergence of long-lived and widespread archaeological traditions [4]; and the diversification of important indigenous language families [5–7]. These and other processes, including increased social integration [8] and agricultural intensification [9–13], cannot be explained through appeal to mechanistic cause and effect nor detached from historical contingency. Indeed, archaeological research shows that the relationship between language families and specific archaeological material culture traditions is complex and multidirectional, likely overlapping only partially over space and time [5]. It also documents multiple forms of niche construction that, in aggregate, cannot be attributed to a single cultural determinant, however defined. All such processes, however, are *per force* demographically-sensitive phenomena: simply put, the size of human populations bears on how novel human niches are formed, how traditions of material culture evolve, why people intensify food production, and how new languages diversify within a language family. Hence, aside from relying on archaeological, environmental, or linguistic evidence to ascertain or infer an onset for these processes (which often limits us to "as early as" narratives), we argue that an appreciation of underlying demographic trends is essential to assess how they likely unfolded in pre-Columbian history.

Although the rise, expansion, and demise of South American native populations from the time of European colonisation has played a pivotal role in scholarly discussions over several decades [14–19], our understanding of pre-Columbian demographic fluctuation for the Amazonian biome is at best limited. A recent approach to infer prehistoric demographic change is the use of time-series based on the summed probability distribution (SPD) of calibrated radiocarbon dates associated with archaeological evidence. SPD-based studies assume that the frequency of calibrated radiocarbon dates over time can be examined as a proxy of relative change in population size. SPD-based studies, therefore, quantify the overall probability of distinctive occupation events that took place in a defined geography as a proxy for relative population fluctuation. In the Amazon basin, a number of studies have explored putative links between SPDs and the formation of anthropic landscapes, relationships between palaeoecology and broad spatio-temporal patterns of human occupation, and the resilience of pre-Columbian livelihoods [12,20,21]. These studies, however, have either relied on very small datasets or eschewed explicit model-testing to assess whether fluctuations in the constructed SPD time series constitute demographic shifts worthy of attention [22]. While this is partly an outcome of a lower intensity of archaeological research in the region, resulting in fewer and heterogeneously distributed radiocarbon dates compared to other world regions, the importance of employing large datasets and a model-testing approach [23–26] is underscored by a more recent study [27] that identifies links between multiple phases of middle Holocene demographic downturn and high climatic variability in South America. This study demonstrates that following a middle Holocene demographic nadir, sharp population growth in South America started around the 4th millennium BP, a finding that is consonant with suggestions that between 5.5 and 2.0 ka BP South America witnessed exponential human population growth [28].

Did the pre-Columbian human population of the humid tropical lowlands of northern South America continue to grow (exponentially) until the onset of European colonisation in the 16th century AD? This is an important implicit assumption of the recent wave of Amazonian research that has sought to reject a determining role for so-called environmental limitations to population growth [1,29]. However, by and large it remains an empirically underexamined assumption with significant implications for reconstructions of pre-Columbian cultural history. Here we approach this question through the analysis and discussion of an SPD-based demographic proxy of relative population change during the late pre-Columbian period, 3000-500 BP (i.e. 1050 BC to AD 1500; we use calibrated BC/AD instead of BP). Model testing and derived measures, based on nearly 1,400 radiocarbon dates associated with archaeological remains, reveal demographic patterns during the Late Holocene that are highly distinctive and have important implications for evaluating competing accounts of pre-Columbian cultural history. The trends we document permit discussing whether exponential population growth prevailed into the millennia immediately prior to European colonisation and also expand our understanding of the demographic dimension of multiple pre-Columbian phenomena, including linguistic diversification, human-induced environmental impact, and the resilience of pre-Columbian lifeways.

Materials and Methods

We compiled a database of georeferenced radiocarbon dates (hereafter RAmazon, see ***Supplementary Material.3***) from an exhaustive and ongoing survey of the extant grey and academic literature in the Amazonian biome. This survey was initiated by the lead author over 15 years ago and has been supported by the UCL Institute of Archaeology since 2011. While unlikely to represent all archaeological radiocarbon dates obtained since the availability of radiometric dating, we are confident that RAmazon represents the vast majority of them. As is becoming a standard hygiene protocol in the aggregate analysis of radiocarbon data [23,24], we withheld from our analyses radiocarbon dates whose errors exceed ±200 years, as well as dates whose calibrated age range extend into the present at 2σ. Almost 2,000 usable radiocarbon determinations, spanning from approximately 14 ka ^{14}C BP to the present, resulted from these efforts. Here, we focus on the dates that fall within the final three millennia (younger than 1050 BC) in a broad region (***Figure 1a***) defined by the major western tributaries of the Amazon basin, the Orinoco basin, and the Guianas. This extensive region is regarded as the geographical setting for the diversification of Arawakan (Maipurean) languages, as indexed by the spatial distribution of distinctive modelled-incised archaeological pottery and extant speakers of these languages [6]. Two other similarly extensive archaeological ceramic traditions -the Amazonian Polychrome tradition and Incised-Punctate tradition/Arauquinoid series- are considered indexical of the expansion of Tupi-Guarani and Carib languages starting in the late first to early second millennium AD [15]. For our period of interest (1000 BC – AD 1500), the RAmazon database includes 1,393 usable radiocarbon determinations from 375 separate archaeological sites. Of these, 46 sites (185 dates, concentrated in modern French Guiana) cannot be accurately georeferenced based on published data: below we exclude these sites from our spatial tests but include the dates in other graphic summaries.

Calibration, aggregation, and analysis of this dataset were carried out in R using the package '*rcarbon*' version 1.3.1 [30]. The code for reproducing our analyses accompanies this manuscript (see ***SM.2)***. For calibration we followed recommendations for tropical settings laid out by Marsh et al. [31] and employed a 50/50 mix of IntCal13 [32] and SHCal13 [33], with combined uncertainties calculated in quadrature. In order to avoid skewing the probability of specific calendar date ranges and creating abrupt spikes in the summed probability distributions at points where the calibration curve is steep [24,34] we have not normalised the post-calibration probability densities. To facilitate a broad understanding of the structure of this dataset, we visualise the calibrated dates employing two complementary techniques: Summed Calibrated Probability Distributions (SPDs) and Composite Kernel Density Estimates (CKDEs). In the case of the former (***Figure 1b, Figure 2a***), and in order to examine expectations derived from prior research [20,27,28], we attempted to fit our SPD time-series to exponential (reflecting population growth with unlimited resources) and logistic (reflecting a decreasing rate of population growth as resources become scarce) models. To this end, we simulated and back-calibrated *n* random dates, where *n* is the number of bins, before summing their calibrated probability distributions. This procedure was repeated 999 times to generate a theoretical confidence envelope for the null model from the distribution of simulated SPDs, permitting both comparison with the empirical SPD [25,30] and identification of demographic shifts that, by exceeding the confidence envelope, indicate population upturns and downturns beyond the expectations of the model [23,24]. We also deployed CKDEs, a more recent alternative to SPDs [35,36], that advantageously minimise calibration "noise" and provides complementary estimates of sampling- and calibration-derived uncertainty over time. We also derived geometric growth rate estimates from the CKDEs (***Figure 1c*** and ***1d***). The SPD, CDKE, and estimated growth rates were all produced with a running mean, kernel bandwidth, or backsight of 50 years. These summary measures of the dataset structure are shown in ***Figure 1a-d*** and ***Figure 2a***.

Model fitting of SPDs and CKDEs provide only aggregate measures of dataset structure that do not take into consideration variation in the spatial density of ^{14}C dates. Given the highly uneven geographical distribution of our dataset (***Figure 1a***), there is a high likelihood that certain subsets of the data will depart more markedly from other spatially proximate and chronologically contemporary subsets. Grouping radiocarbon data into marked subsets for use in *non-parametric permutation testing* of the marks with Monte Carlo methods [27,37] is a frequently-used solution to test for the effects of uneven geographic structure. A major point of contention with this approach, however, is the representativity and true meaning of these subsets of radiocarbon dates in archaeological terms and, hence, their validity as *a priori* units of analysis [22,24]. For instance, subsets of dates established on the basis of specific archaeological parameters (e.g. subsistence type, a given archaeological ceramic style) create spatial groupings that are relevant to specific time slices but potentially entirely irrelevant to prior or later time slices and, hence, to overall palaeodemographic processes at regional scale. To circumvent the need to manually partition RAmazon, we employed *spatial permutation testing* (***Figure 2b, Figure SM.1***) under a null assumption of homogeneous growth [38,39]. We proceeded by shuffling date locations in the place of bins. We permuted 10,000 times to ensure robust results. In addition to the calibration and binning procedure, we relied on an additional free parameter whose final value we arrived at through multiple sensitivity analyses: the bandwidth size for deriving local growth models. We tested seven ranges from 50-600 km, increasing in 100 km intervals for each above 100 km. The shortest ranges represent extremely small areas in the context of the study region as a whole, while the largest verges on half the median inter-site distance in the RAmazon dataset. We found that a mid-range spatial bandwidth of 250 km represents an acceptable balance between the distribution of the data and the goal of studying broad-scale patterns in a study region of this size. This procedure enabled us to investigate differences in growth patterns between adjoining 100-year blocks, which we label A to Y (i.e. 200-year time slices, see Weninger et al. [34]), for a total of twenty-four comparisons. Following Crema et al. [38], we report q-values alongside p-values to detect *hot* (*cold*) spots*, i.e.* locations where the observed local growth rate is *higher* (*lower*) than the randomised set, while guarding against incorrectly rejecting or failing the null hypothesis of growth (see ***SM.1***).

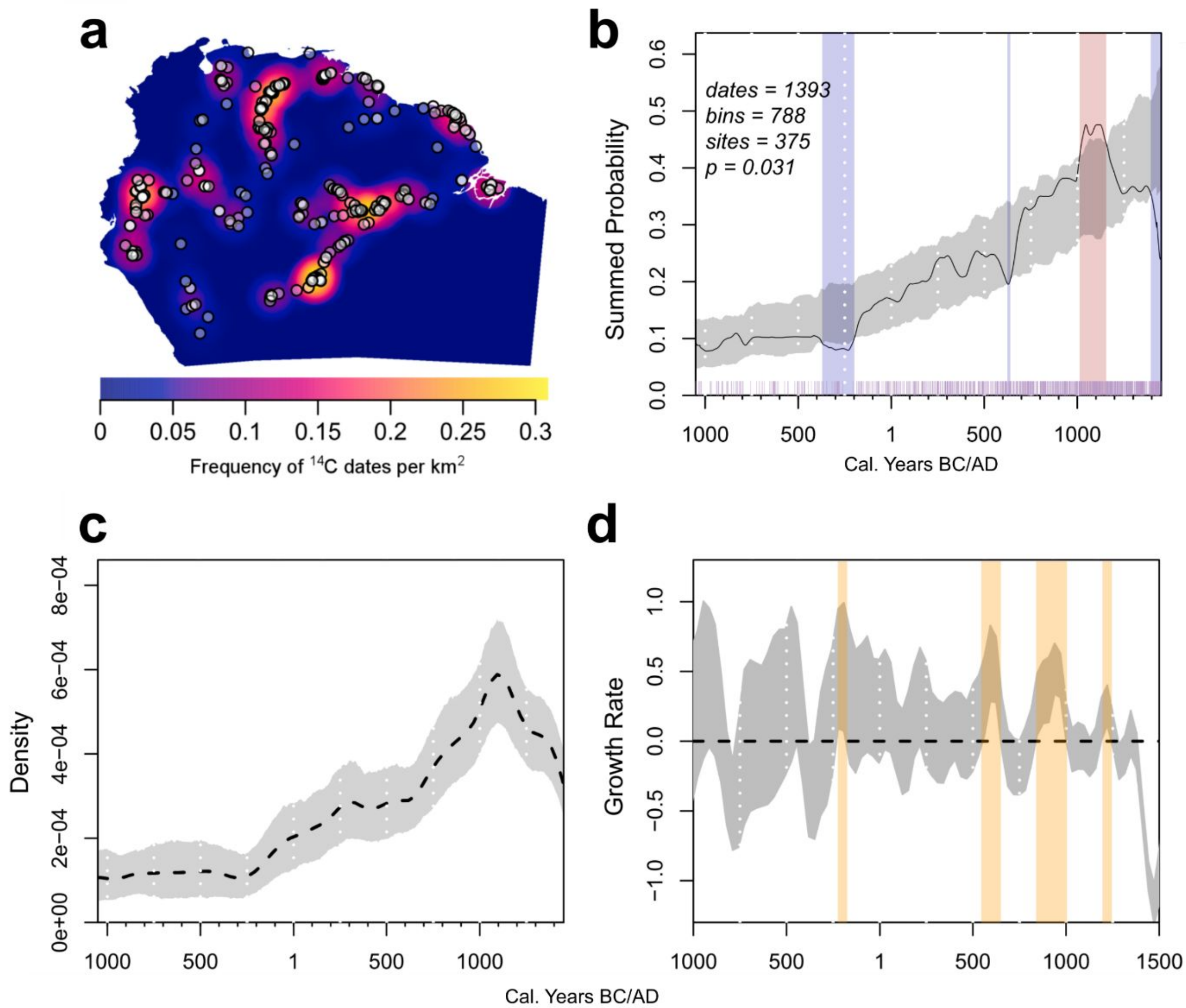

***Figure* 1: Summary of ^{14}C record for the study region**. a) Geographical distribution of all radiometric dates employed in this study. b) The late pre-Columbian 14C record fitted to a global exponential model, with a significance envelope derived from 1,000 Monte Carlo simulations. Note globally statistically-significant departures (p=0.0031) from the null hypothesis of exponential population growth produced by locally significant departures around 400-300 BC and AD 1000-1200. The downturn around 1400 AD is an edge effect. c) Bootstrapped composite kernel density estimate and, d) first derivative (rate of change) with confidence intervals of the bootstrapped composite kernel density estimate, identifying four uneven phases of rapid pre-Columbian population growth starting around 300 BC.

Results and Discussion

Our results offer novel insights and comparative information on pre-Columbian human population growth rates in the Amazonian biome during the late Holocene. At first glance, the SPD between 1050 BC – AD 1500 (**Figure 1b**) fits into the overall pattern of Late Holocene exponential demographic growth suggested by prior research [27,28]. However, model testing also reveals a statistically-significant (p = 0.031) departure from the fitted exponential model. Our CKDE (**Figure 1*d***), in turn, identifies up to four potential periods of relatively rapid population growth starting around 300 BC in the aggregate dataset, an observation that is consistent with a previously-documented “stepped” pattern of late Holocene population growth [20]. We hypothesised that the most persistent significant departure (at 95% confidence) from the exponential model marks a potential demographic regime shift, and, on the basis of the CKDE curve, we tested a composite exponential-logistic model with a breakpoint at 2200 cal BP (or its BC/AD equivalent). The evident fit (***Figure 2*a**), which controls for the majority of late Holocene variation in our demographic proxy, suggests population growth in the Amazonian biome was not fully exponential during the last 1700 years before European colonisation. Rather, our population proxy adheres much more closely to a logistic curve characterised by a) overall rapid population growth until c. 1200 AD, and b) overshoot and stabilisation at carrying capacity during the final centuries before European colonisation.

Given that, in aggregate, the logistic model is largely adhered to, all things being equal we might expect few statistically significant deviations in local growth rates. ***Figure 2b***, however, highlights spatially heterogenous demographic growth patterns in a total of twenty-four comparisons. We refer to these comparisons as time slices using letters from A to Y. Each of these refers to a comparison of growth rates between adjacent centennial-scale blocks rather than a period of a century. For example, time slice F-G compares change in growth rates between 550-450 BC (block F) and 450-350 BC (block G). For ease of writing, we employ the median dates of each set of blocks when reporting change over time, i.e. we refer to time slice F-G simply as 500-400 BC.

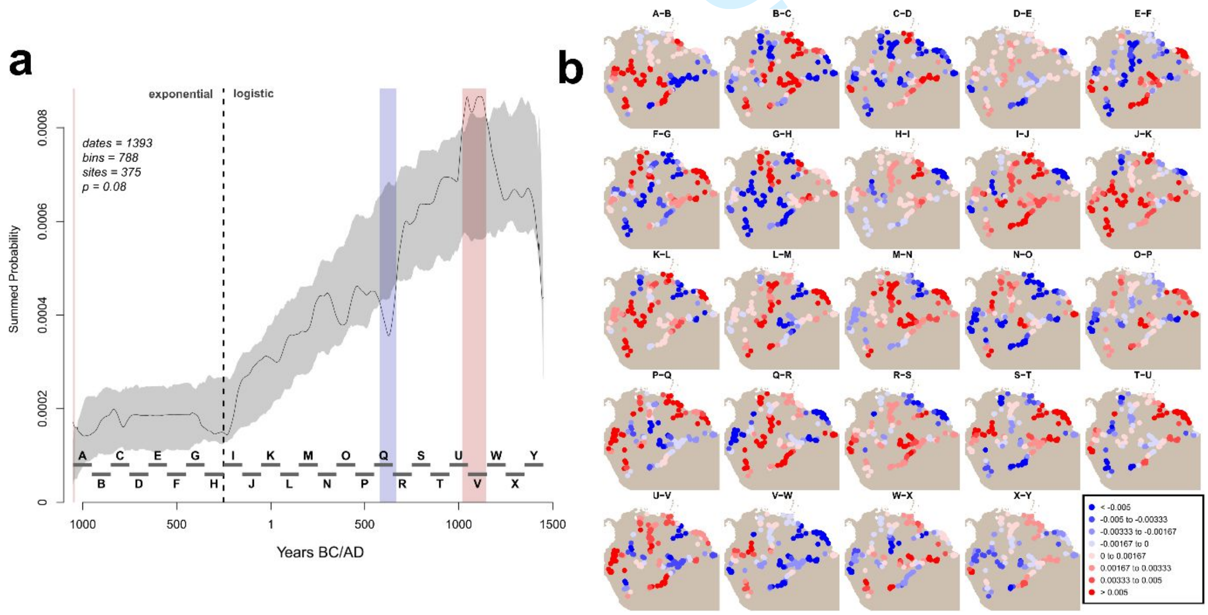

Figure 2. a) The late pre-Columbian ^{14}C record fitted to exponential (1000 BC-300 BC) and logistic models (300 BC- AD 1500), with a significance envelope derived from 1,000 Monte Carlo simulations. Note statistically-significant departures from the null hypothesis of logistic population growth around AD 600 and AD 1000-

1200. b) Raw growth rates (dimensionless) based on 10,000 spatial permutations, comparing local growth rates between adjoining 100-year (letters A-Y). General adherence to a logistic model in the global test can be explained with recourse to spatially-variable growth rates counterbalancing each other over time.

Comparison of ***Figures 1b, 2a*** and ***2b*** reveals that significant biome-wide population decline observed around ~400-200 BC in the SPD masks subregions within the biome that witnessed significant population growth (slice G-H. Significant to $p < 0.05$, see ***Figure*** **SM.1**). If we follow these through the spatially-represented time series, it would appear that they "consolidate" into a global pattern of growth in the final two centuries of the first millennium BC (slice I-J), a pattern sufficiently robust to extend into western Amazonia by AD 1 (slice J-K). This pattern provides further support for our claim that a demographic regime shift ensues and, importantly, identifies raw population growth earlier in the middle Orinoco and the northern Guianas (slice H-I). For this time range, archaeological artefactual evidence from the Orinoco basin, the southwestern, middle, central, and lower Amazon, as well as the upper Ucayali basin, record the debut of occupations characterised by pottery variously described as Barrancoid-Saladoid (outside of Amazonia), or associated with the Incised-rim tradition (within the Amazon basin). This widespread tradition is generally associated with the diversification of Arawakan languages [6,8,40]. Contrary to received accounts [15], the earlier growth northeast of the Amazon basin (***Figure 2b***, slices I-J and J-K) suggests that this demographic pattern may originate in the middle Orinoco and Guianas region and expand south and west along major waterways into the Amazon basin. Irrespective of whether a long or a short chronology for the ceramic Barrancoid series is adopted [41], and not discounting some early archaeological sites that can be associated stylistically [42], the demographic signal is consistent with an *expansion* of Arawak speaking fisher/root cropping societies [6] into the Amazon basin during the early centuries of the first millennium AD. P-significant plots starting at slice G-H (400-300 BC) can be argued to signal the beginning of an Arawakan expansion, while p-significant areas in J-K and K-L may be further florescence of this phenomenon (***Figure SM.1***). The fact that, in aggregate, our demographic signal never overshoots the expectations of the logistic model can be interpreted as empirical evidence that populations never exceeded carrying capacity. We argue that this better supports a "pull" model of population expansion [43], one characterised by "budding off" of splinter groups, than a "push" model of Arawakan expansion, the latter instigated by population pressure under scarce landed resources [15]. We also argue that it contradicts a "strong" version of the "trade and exchange" hypothesis [8], which we understand would presuppose the presence of significantly large pre-existing populations.

Our logistic model test (***Figure 2a***) shows a clear and steep population upturn from AD 100-300 (***Figure 2b***, slices K-L to M-N) to AD 500-600, when a statistically-significant downturn (assessed against the logistic model) is observed (***Figure 2b***, slices P-Q to Q-R). Note that this downturn is similarly recorded as significant in our exponential model test (**Figure 1b**). For this time range, archaeological artefactual evidence suggests the continuing evolution and inter-regional cross fertilisation of groups using modelled-incised pottery in eastern Amazonia (consonant with a “weak” version of the “trade and exchange” hypothesis [8]), alongside increasingly more frequent formation of small expanses of Amazonian dark earths. Geographically (***Figure 2b***), this period is marked by regionally heterogenous growth rates, with a significant hot spot in the coastal Guianas. While populations are undoubtedly growing over the course of the early half of the first millennium AD, the empirical SPD never exceeds the confidence envelope, which again argues against suggestions of population reaching carrying capacity. The downturn in our SPD towards AD 500-600 appears to be a function on an overall reduction in the rate of demographic growth in the central and lower Amazon, as well as along the far western part of our domain (slices P-Q & Q-R). This slowdown, however, appears reversed in the Guianas, Madeira basin and, possibly, the Orinoco basin. This contrast not only emphasises how non-spatial aggregate measures on a biome-wide scale can be misleading, but also offers a demographic perspective on the initial period of formation of Amazonian dark earths in eastern Amazonia: these seem to form over a period of demographically expanding populations that is punctuated by a marked but short-lived deceleration in regional growth rates.

Our logistic model test (***Figure 2*a**) highlights continued and sharp population growth starting from ~600 AD and reaching up to AD 1200. Importantly (slice Q-R), both the middle Orinoco and the upper Madeira show high grow rates before the central and lower Amazon, which records a lagged significant growth thereafter (slice R-S). For the first time in the time series, and in contrast to the first half of the first millennium AD, our SPD briefly exceeds the confidence envelope at the beginning of the second millennium AD before stabilising (slices V-W to W-X) at a lower ceiling (***Figures 1b, 2a***). At an aggregate level, we argue this can be interpreted as the reversal of a brisk pre-Columbian demographic expansion that stabilised at carrying capacity at least three centuries prior to European colonisation. Examined from the point of view of the archaeological record, it is relevant to highlight that the largest expanses of Amazonian dark earths often contain higher frequencies of artefacts associated with human occupations of this period [5]. This suggests, then, that the overall peak of human activity leading to the formation of large expanses of Amazonian dark earths takes place in the centuries around 1000 AD [44,45]. It is also worthy of note that this period epitomises the expansion of both Arauquinoid/Incised-punctuate ceramic complexes (which are often associated with Carib languages) and pottery of the Amazonian Polychrome tradition (which in western Amazonia can be associated with Tupi-Guarani languages): both reach their apogee early during the second millennium

AD. That population growth in the Madeira region accelerates earlier than the middle Amazon can lend support to suggestions of a southwestern origin for Amazonian Polychrome tradition groups [46], although testing this hypothesis exceeds the scope of this paper. For the same overall period (slices Q-R to U-V), a sharp upwards shift in population growth rates is observed in the westernmost portion of the Amazon basin, which is consistent with an East to West expansion of Amazonian Polychrome tradition people [47,48]. Similarly, the earlier increase in growth rates in the Guianas and Orinoco is consistent with Arauquinoid/Incised-Punctuate occupations, associated with Carib speaking communities, originating in the Middle Orinoco. This suggest fairly late and parallel processes of linguistic diversification for separate language communities (Tupi-Guarani stock; Carib). In broad terms, the subsequent period (AD 1200-1500) is characterised by a slowdown in biome-wide population growth occupying the last two to three centuries before AD 1500, which in aggregate suggests a stable population at carrying capacity leading up to the times of early European exploration (but note some regions witnessed significant population growth, see ***Figure*** **SM.1**). The sharp final drop in our SPD proxy is likely to be an outcome of archaeological sampling biases [22], compounded by demographic decline and dispersal as Europeans enter the region.

Conclusion

Our large sample size and use of Monte Carlo simulation methods makes us confident that the results presented above represent a first-order approximation to indigenous population dynamics of the Amazonian biome over the final 2,500 years of pre-Columbian history. Our approach offers a rigorous alternative to watershed- or floodplain-focused discussions of indigenous population history, and also side-steps the potentially problematic issue of only employing dates from cherry-picked cultural phases. By choosing to examine the aggregate patterns derived from our SPD-based time series against their geographical distribution, we are able to identify robust patterns that suggest a potential ceiling to population growth was reached at around AD ~1200 AD. Inasmuch as changing regional growth rates provide a reasonable proxy for productive capacity (i.e. centennial-scale variation in the answer to the question of 'how many mouths can we feed'), our spatial analyses also provide a sharper and more nuanced control of regional demographic fluctuations that are related to specific pre-Columbian livelihoods in the Amazonian biome. Indeed, despite overall adherence to logistic growth (***Figure 2*****a**), no single cluster of data points (***Figure 2b***) shows sustained population growth throughout the entire 2,500 years of our analysis, highlighting that specific food producing strategies may not have been resilient at the scale of multiple centuries [12]. Lastly, our time-series analysis offers significant spatial and temporal refinements to the demographic dimension of broad ceramic traditions and potential association with language communities [5]. Specifically, our analyses strongly scaffold suggestions that major events of diversification of three of the most significant language families of the Amazonian biome took place as recently as the first millennium AD. Evidently, the trends we identify are robust only against the present state of the aggregate radiocarbon dataset for our study region. Future research will undoubtedly expand this dataset and potentially challenge the general outlook we provide. More than offering answers, however, the results of our analysis posit questions that we hope will encourage future research.

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References

1. Arroyo-Kalin M. 2016 Landscaping, Landscape Legacies, and Landesque Capital in Pre-Columbian Amazonia. In *The Oxford Handbook of Historical Ecology and Applied Archaeology* (eds Christian Isendahl, Daryl Stump), pp. 1–24. Oxford: Oxford University Press. (doi: 10.1093/oxfordhb/9780199672691.013.16)

2. Clement CR, Denevan WM, Heckenberger MJ, Junqueira AB, Neves EG, Teixeira WG, Woods WI. 2015 The domestication of Amazonia before European conquest. *Proceedings of the Royal Society B* **282**, 20150813. (doi:10.1098/rspb.2015.0813)

3. Watling J, Mayle FE, Schaan D. 2018 Historical ecology, human niche construction and landscape in pre-Columbian Amazonia: A case study of the geoglyph builders of Acre, Brazil. *Journal of Anthropological Archaeology* **50**, 128–139. (doi:10.1016/j.jaa.2018.05.001)

4. Barreto C, Lima HP, Jaimes-Betancourt, C. 2016 *Cerámicas arqueolôgicas da Amazônia: Rumo a uma nova síntese*. Belém: MPEG/IPHAN.

5. Neves EG. 2011 Archaeological Cultures and Past identities in the pre-Colonial Central Amazon. In *Ethnicity in Ancient Amazonia* (eds Alf Hornborg, JD Hill), pp. 31–56. Boulder: University Press of Colorado.

6. Heckenberger MJ. 2002 Rethinking the Arawakan diaspora: hierarchy, regionality and the Amazonian Formative. In *Comparative Arawakan Histories: Rethinking Language Family and Culture Area in Amazonia* (eds Jonathan David Hill, F Santos-Granero), pp. 99–122. Chicago: University of Illinois Press.

7. Muysken P *et al.* 2014 The languages of South America: deep families, areal relationships, and language contact. In *The Native Languages of South America: Origins, Development, Typology* (eds L O'Connor, P Muysken), pp. 299–322. Cambridge: Cambridge University Press.

8. Hornborg A. 2005 Ethnogenesis, regional integration, and ecology in prehistoric Amazonia: toward a system perspective. *Current Anthropology* **46**, 589–620. (doi: 10.1086/431530)

9. Arroyo-Kalin M. 2010 The Amazonian Formative: crop domestication and anthropogenic soils. *Diversity* **2**, 473–504. (doi: 10.3390/d2040473)

10. Fausto C, Neves EG. 2018 Was there ever a Neolithic in the Neotropics? Plant familiarisation and biodiversity in the Amazon. *Antiquity* **92**, 1604–1618. (doi:10.15184/aqy.2018.157)

11. Iriarte J, Dickau R. 2012 As culturas do milho? Arqueobotânica de las sociedades hidráulicas das terras baixas sul-americanas. *Amazônica* **4**, 30–58. (doi: 10.18542/amazonica.v4i1.879)

12. de Souza JG *et al.* 2019 Climate change and cultural resilience in late pre-Columbian Amazonia. *Nature Ecology & Evolution* **3**, 1007–1017. (doi:10.1038/s41559-019-0924-0)

13. Maezumi SY *et al.* 2018 The legacy of 4,500 years of polyculture agroforestry in the eastern Amazon. *Nature Plants* **4**, 540–547. (doi:10.1038/s41477-018-0205-y)

14. Denevan WM. 2014 Estimating Amazonian Indian Numbers in 1492. *Journal of Latin American Geography* **13**, 207–221. (doi: 10.1353/lag.2014.0036)

15. Lathrap DW. 1970 *The Upper Amazon*. Southampton: Thames & Hudson.

16. Meggers BJ. 1971 *Amazonia: Man and Culture in a Counterfeit Paradise*. Washington: Smithsonian Institution Press.

17. Heckenberger MJ, Neves EG. 2009 Amazonian Archaeology. *Annual Review of Anthropology* **38**, 251–266. (doi: 10.1146/annurev-anthro-091908-164310)

18. Dull RA, Nevle RJ, Woods WI, Bird DK, Avnery S, Denevan WM. 2010 The Columbian Encounter and the Little Ice Age: Abrupt Land Use Change, Fire, and Greenhouse Forcing. *Annals of the Association of American Geographers* **100**, 755–771. (doi: 10.1080/00045608.2010.502432)

19. Koch A, Brierley C, Maslin MM, Lewis SL. 2019 Earth system impacts of the European arrival and Great Dying in the Americas after 1492. *Quaternary Science Reviews* **207**, 13–36. (doi: 10.1016/j.quascirev.2018.12.004)

20. Arroyo-Kalin M. 2017 Human Niche Construction and Population Growth in Pre-Columbian Amazonia. *Archaeology International* **20**, 122–136. (doi: 10.5334/ai.367)

21. McMichael, Crystal N.H, Bush, Mark B. 2019 Spatiotemporal patterns of pre-Columbian people in Amazonia. *Quaternary Research* **152**, 1–17. (doi: 10.1017/qua.2018.152)

22. Riris P. 2019 Sparse Radiocarbon Data Confound Culture-Climate Links in Late Pre-Columbian Amazonia. *Quaternary* **2**, 33. (doi: 10.3390/quat2040033)

23. Shennan S, Downey SS, Timpson A, Edinborough K, Colledge S, Kerig T, Manning K, Thomas MG. 2013 Regional population collapse followed initial agriculture booms in mid-Holocene Europe. *Nature Communications* **4**, 2486. (doi: 10.1038/ncomms3486)

24. Bevan A, Colledge S, Fuller D, Fyfe R, Shennan S, Stevens C. 2017 Holocene fluctuations in human population demonstrate repeated links to food production and climate. *Proceedings of the National Academy of Sciences of the United States of America* **114**, E10524. (doi: 10.1073/pnas.1709190114)

25. Timpson A, Colledge S, Crema E, Edinborough K, Kerig T, Manning K, Thomas MG, Shennan S. 2014 Reconstructing regional population fluctuations in the European Neolithic using radiocarbon dates: a new case-study using an improved method. *Journal of Archaeological Science* **52**, 549–557. (doi: 10.1016/j.jas.2014.08.011)

26. Edinborough K, Porčić M, Martindale A, Brown TJ, Supernant K, Ames KM. 2017 Radiocarbon test for demographic events in written and oral history. *Proceedings of the National Academy of Sciences of the United States of America* **114**, 12436. (doi: 10.1073/pnas.1713012114)

27. Riris P, Arroyo-Kalin M. 2019 Widespread population decline in South America correlates with mid-Holocene climate change. *Scientific Reports* **9**, 6850. (doi: 10.1038/s41598-019-43086-w)

28. Goldberg A, Mychajliw AM, Hadly EA. 2016 Post-invasion demography of prehistoric humans in South America. *Nature* **532**, 232–235. (doi: 10.1038/nature17176)

29. Balée W, Erickson CL. 2006 *Time and Complexity in Historical Ecology*. New York: Columbia University Press.

30. Bevan AW, Enrico Crema. 2020 rcarbon v1.3.1 : Methods for calibrating and analysing radiocarbon dates. (https://github.com/ahb108/rcarbon)

31. Marsh EJ, Bruno MC, Fritz SC, Baker P, Capriles JM, Hastorf CA. 2018 IntCal, SHCal, or a Mixed Curve? Choosing a 14C Calibration Curve for Archaeological and Paleoenvironmental Records from Tropical South America. *Radiocarbon* **60**, 925–940. (doi:10.1017/RDC.2018.16)

32. Reimer PJ *et al.* 2013 IntCal13 and Marine13 Radiocarbon Age Calibration Curves 0–50,000 Years cal BP. *Radiocarbon* **55**, 1869–1887. (doi:10.2458/azu_js_rc.55.16947)

33. Hogg AG *et al.* 2013 SHCal13 Southern Hemisphere Calibration, 0–50,000 Years cal BP. *Radiocarbon* **55**, 1889–1903. (doi:10.2458/azu_js_rc.55.16783)

34. Weninger B, Clare L, Jöris O, Jung R, Edinborough K. 2015 Quantum theory of radiocarbon calibration. *World Archaeology* **47**, 543–566. (doi:10.1080/00438243.2015.1064022)

35. Brown WA. 2017 The past and future of growth rate estimation in demographic temporal frequency analysis: Biodemographic interpretability and the ascendance of dynamic growth models. *Journal of Archaeological Science* **80**, 96–108. (doi:10.1016/j.jas.2017.02.003)

36. McLaughlin TR. 2019 On Applications of Space–Time Modelling with Open-Source 14C Age Calibration. *Journal of Archaeological Method and Theory* **26**, 479–501. (doi:10.1007/s10816-018-9381-3)

37. Crema ER, Habu J, Kobayashi K, Madella M. 2016 Summed Probability Distribution of 14C Dates Suggests Regional Divergences in the Population Dynamics of the Jomon Period in Eastern Japan. *PLOS ONE* **11**, e0154809. (doi:10.1371/journal.pone.0154809)

38. Crema ER, Bevan A, Shennan S. 2017 Spatio-temporal approaches to archaeological radiocarbon dates. *Journal of Archaeological Science* **87**, 1–9. (doi:10.1016/j.jas.2017.09.007)

39. Brown AA, Crema ER. 2019 Māori Population Growth in Pre-contact New Zealand: Regional Population Dynamics Inferred From Summed Probability Distributions of Radiocarbon Dates. *Journal of Island and Coastal Archaeology* (doi:10.1080/15564894.2019.1605429)

40. Eriksen L, Danielsen S. 2014 The Arawakan matrix. In *The Native Languages of South America: Origins, Development, Typology* (eds L O'Connor, P Muysken), pp. 152–176. Cambridge: Cambridge University Press.

41. Oliver JR. 2014 Nuevos aportes a la arqueología del sitio El Saladero, bajo Orinoco, Venezuela. In *Before Orellana. Proceedings of the 3rd International Meeting on Amazonian Archaeology* (ed Stéphen Rostain), Quito: IFEA/FLACSO/US Embassy.

42. Neves EG, Guapindaia VLC, Lima HP, Costa BLS & Gomes, J. 2014 A tradição Pocó-Açutuba e os primeros sinais visíveis de modificações de paisagens na calha do Amazonas", In *Before Orellana. Proceedings of the 3rd International Meeting on Amazonian Archaeology* (ed Stéphen Rostain), Quito: IFEA/FLACSO/US Embassy

43. Zucchi A. 2002 A new model of the northern Arawakan expansion. In *Comparative Arawakan Histories: Rethinking Language Family and Culture Area in Amazonia* (eds Jonathan David Hill, F Santos-Granero), pp. 199–225. Chicago: University of Illinois Press.

44. Moraes CP, Neves EG. 2012 O ano 1000: Adensamento populacional, interação e conflito na Amazônia Central. *Amazônica* **4**, 122–148. (doi: 10.18542/amazonica.v4i1.884)

45. Herrera LF, Cavelier I, Rodríguez C, Mora S. 1992 The technical transformation of an agricultural system in the Colombian Amazon. *World Archaeology* **24**, 98–113. (doi: 10.1080/00438243.1992.9980196)

46. Almeida FO. 2013 A Tradição Polícroma no Alto Rio Madeira. Unpublished PhD Thesis, University of São Paulo. Universidade de São Paulo, São Paulo.

47. Belletti J. 2016 A tradição polícroma da Amazônia. In *Cerámicas arqueológicas da Amazônia: Rumo a uma nova síntese* (eds C Barreto, Helena Pinto Lima, Carla Jaimes), pp. 348–363. Belém: MPEG/IPHAN.

48. Arroyo-Kalin M, Rivas-Panduro S. 2019 La arqueología del río Napo: noticias recientes y desafíos futuros. *Revista del Museo de La Plata* **4**, 331–352. (doi: 10.24215/25456377e080)