

ANTIQUITY

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CAMBRIDGE
UNIVERSITY PRESS

From the margins to the Mainstream: understanding the Polychrome Tradition Expansion in Central Amazon through spatial and chronological modelling

Journal:	<i>Antiquity</i>
Manuscript ID	AQY-2024-0170.R2
Manuscript Type:	Research Article
Keywords:	Amazonian Polychrome Expansion, Amazonian Archaeology, Computational Archaeology, Fast Marching methods, Summed Probability Distributions
Research Region:	South America
Abstract:	The authors apply computational methods to model and understand the ceramic Polychrome Expansion in Central and Western Amazonia c. AD 1000. This expansion is amongst the most widespread evidence of change in a period of broad social transformation in Amazonia. They critically examine the timing, routes and importance of trade and conflict for the process. The results suggest that the Polychrome Expansion should be reinterpreted as a long-lasting and gradual process that advanced from secondary Amazonian rivers and spread along main rivers, eventually impacting colonial history.

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5 **modelling**
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13 Polychrome Expansion in Central and Western Amazonia c. AD 1000. This expansion is
14 amongst the most widespread evidence of change in a period of broad social
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28 Computational Archaeology; Fast Marching methods; Summed Probability
29 Distributions.
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36 **Introduction**
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38 The archaeology of Amazonia, the world's largest tropical forest has experienced
39 a revolution during the last decades (Iriarte, 2024; Neves and Heckenberger, 2019). What
40 was considered a pristine forest is now understood as a biome deeply affected by
41 indigenous action for thousands of years before the European invasion (Clement et al.,
42 2015), one that offers a unique opportunity to discuss the relationship between cultural
43 and biological diversity (Fausto and Neves, 2018). A key period for these debates is
44 1000BP (calendar years Before Present). During this period, widespread socio-ecological
45 transformations in the Amazon took place, including the rise of large, nucleated
46 settlements in the Upper Xingu River, along the central branch of the Amazon, near the
47 modern city of Santarém, and in the Bolivian Llanos de Moxos, the drivers of which are
48 the subject of intense and ongoing study (Heckenberger et al., 2003; Schaan; Alves, 2015;
49 Prümers et al., 2022). Cultural dispersals and expansion processes in the Amazon have
50 been discussed as an archaeologically visible outcome of palaeodemographic dynamics
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3 among these highly diverse, stateless societies, highlighting that long distance population
4 movement can provide key insights into understanding the impacts that Indigenous
5 people have had on the biome (Almeida, Lopes and Stampanoni Bassi, 2021; Riris and
6 Silva, 2021; Shock, 2021; de Souza et al., 2019; Arroyo-Kalin and Riris, 2020).
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11 In the archaeological record, the most widespread of these dispersals is especially
12 associated with the dissemination of ceramics of the Amazonian Polychrome Tradition
13 (Figure 1), which covered an estimated area of 1,7 million square kilometres in the
14 Central and Western Amazon (Figure 2). This process, referred as Polychrome
15 Expansion, is distinctly identified in archaeological sites, forming singular Polychrome
16 occupation layers in the upper strata of mono componential and multi componential sites.
17 Earthworks, from middens (Pessoa et al. 2020) to artificial islands are associated with this
18 industry. Polychrome occupations are characterised especially by the presence of an
19 emblematic pottery style, which has as its main features red, brown and black painting
20 over white slip and grooving in anthropomorphic and snakelike motifs, as well as
21 distinctive morphologies including mid-rim vessels and anthropomorphic burial urns
22 (Almeida et al., 2018).
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33 The earliest dates for the Polychrome Expansion's chronology come from the
34 Middle Solimões region around 1500BP (Belletti, 2016), with assumed growth of
35 occupations from 1000BP onwards, and persistence during the colonial period (Figure 3).
36 Although studied systematically since the 1950s, recent studies have greatly advanced
37 data gathering on a regional scale, yet with very few systematic syntheses (Belletti, 2016;
38 Almeida et al., 2018). Amidst a continental region characterised by formidable cultural
39 diversity through time, the Polychrome Expansion would represent the second dispersal
40 of pan-Amazonian proportions, following the expansion of populations related to the
41 earlier Pocó-Açutuba Tradition, during the first millennium BCE, a phenomenon
42 discussed by Kater et al. (this volume). Reopened debates on the timing and routes of
43 dispersal of the Polychrome Expansion has also highlighted the potential importance of
44 conflict for the process.
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54 This paper approaches these debates through the application of exploratory
55 chronological and spatial modelling, providing novel findings with transformative
56 implications as how the Polychrome Expansion can be understood. First, classic and
57 current discussions on this expansion will be presented as well as known knowledge gaps.
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3 Then, dataset selection and main results will be explained. Methods are presented
4 separately in the **Supplementary Information**. Discussion will focus on contributions
5 for understanding this process and will highlight key data disparities that need to be
6 handled for creating more reliable models. Finally, concluding remarks are oriented to
7 present a new framework for the Polychrome Expansion and its meanings from an
8 Amazonian viewpoint.
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13 **The Polychrome Expansion**

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16 The initial debate about the Polychrome Tradition and its expansion started in the
17 1950s, permeated by the viewpoint of the Amazon as a pristine forest with ecological
18 restrictions that inhibited cultural development (Meggers, 1971). For Betty Meggers and
19 Clifford Evans, the spread of Polychrome ceramics was considered evidence of a
20 migratory wave of farmers that descended the Andes down the headwaters of the Amazon
21 and along the river until its estuary at Marajó Island, the only spot where occupations
22 would not quickly collapse upon encountering poor soils for agriculture (Meggers and
23 Evans, 1957, 1961; Evans and Meggers, 1968). The eastward march was hypothesised
24 from sites in the Napo, the Solimões and the Amazon estuary with an inconsistent use of
25 radiocarbon dates (Roosevelt, 1991).
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35 Donald Lathrap and his colleagues challenged this model from the 1960s onward,
36 relying on a premise of the distinction between river bluffs (*terra firme*) and floodplains
37 (*várzeas*). In their view, while the former zone would fit into the previous model of
38 inadequate terrain for agriculture, the latter, especially in main Amazonian rivers,
39 represented highly fertile ground that would facilitate agriculture and, consequently,
40 stimulated population growth (Lathrap, 1970a, 1970b; Neves, 1998). That growth from
41 the *várzeas* would thus generate periodic demographic pressures that would give birth to
42 large expansion processes associated with widespread indigenous linguistic families and
43 cultural traditions. Lathrap interpreted data gathered from excavations in Polychrome
44 sites done by Peter Hilbert (1968) in Central Amazon to pinpoint the region around the
45 Negro-Solimões and Amazon-Madeira meetings (henceforth referred as NSAM area), as
46 the heart of these processes, from where demographic pulses would spread through the
47 main tributaries (“arteries”) of the Amazon. This was the *cardiac model* (Neves, 1998).
48 The Polychrome Expansion would be one of these processes, where Tupi-Guarani
49 speakers, such as the Upper Amazon Omágua, would be associated with the rapid spread
50 of polychromic pottery within and from Amazonia (Brochado, 1989). These population
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3 movements included the Guarani expansion through the Paraná Basin and the Tupinambá
4 expansion down the Brazilian coast (Bonomo et al. 2015 and this volume), along the
5 present-day Brazilian borders.
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9 One of the starting points of the aforementioned general review of Amazonian
10 archaeology was the testing of Lathrap's cardiac model in the NSAM area (Neves and
11 Petersen, 2006). Although home to large-scale and long-lasting occupations, the region
12 did not present corresponding dates to validate the model. The expansion of data coverage
13 across the Amazon also helped challenge the basis for both Meggers and Lathrap's
14 models (Heckenberger and Neves, 2009). The concept of environmental limitations
15 inhibiting cultural development in the Amazon was rejected even for *terra firme* areas as
16 more and more large-scale occupations and earthworks are still being discovered away
17 from *varzeas* and main rivers (Shepard et al., 2020).
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26 New data and outlooks have rekindled debates on the dynamics of the Polychrome
27 Expansion. Despite a few resemblances, most recent literature now agrees with the
28 separation of the Polychrome Expansion as a Central and Western Amazon phenomenon,
29 apart from Eastern Amazonian historical developments such as that of Marajoara, Tupi-
30 Guarani and late occupations in the Guianas. Another agreement is the plastic nature of
31 Polychrome occupations, with high diversity in ceramic production and occupation
32 dynamics, that indicate adoption of Polychrome Tradition ceramics by different, pre-
33 existing riverine populations and not just population movement (Belletti, 2016; Almeida
34 et al., 2018; Oliveira, 2022). This more fluid view regarding the meaning of this tradition
35 led to a few loose ends of Lathrap and Brochado's model being addressed, such as the
36 extensive presence of Polychrome ceramics along the Rio Negro, where there is no
37 historical accounts of the presence of Tupi-Guarani peoples. Finally, recent linguistic
38 studies (e.g. Michael, 2014) re-classified the Omágua - formerly the historical example
39 which enabled Lathrap to set the Tupi-Guarani/Polychrome relation - as peoples who
40 were assimilated by Tupi groups probably during pre-colonial times (Almeida, Lopes &
41 Stampanoni Bassi, 2021). Hence, the nature of the Polychrome expansion has steadily
42 gained complex outlines, with recent historical linguistics research setting the Omagua
43 language as closer to the Tupinambá (Ferraz Gerardi, 2023).
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58 Furthermore, in reference to the timing of the Polychrome Expansion, some
59 authors agree with a fast dispersal process from 1000BP onwards (Neves, 2022), while
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3 others have defended a more drawn-out process commencing some centuries earlier
4 (Tamanaha, 2018; Belletti, 2016). Regarding the routes of expansion, some have
5 advocated for a multi-route dispersal from Southwest Amazonia, particularly the Upper
6 Madeira (Almeida and Moraes, 2016) and others have postulated also a multi-route
7 spread, but from the Middle Solimões (Lopes, 2018; Tamanaha, 2018). Lopes (2018) and
8 Tamanaha (2018) have argued for a two-phase spread, one that proceeded through
9 secondary rivers up until around 900BP when bluffs overlooking main rivers would
10 become favoured spots for occupations. The warlike nature of the expansion was first
11 emphasised (Moraes and Neves, 2012) based on data for defence structures in the NSAM
12 area, such as circular ditches and palisades around dark earth sites, contemporaneous with
13 substitution of Incised Rim/Barrancoid sites by Polychrome occupations. This view was
14 later balanced by evidence of trade and hybridism between Polychrome producers and
15 other, contemporaneous ceramic-producing groups (Belletti, 2016; Lopes, 2018).
16 Emerging topics include the relations between Polychrome occupations and European
17 colonisation (Lopes, 2021) and the association of land-use patterns and climate change
18 with the rise of Polychrome occupations (Azevedo et al., 2019; De Souza et al., 2019).
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36 **Methods**

37 For our modelling of the Polychrome Expansion, we evaluated, selected and
38 enhanced data from AmazonArch, an already existing archaeological database, that
39 encompasses data from over 12,000 Amazonian archaeological sites (Tamanaha, 2018).
40 A complementary task of data preparation was to circumscribe Polychrome Tradition
41 regional ceramic styles and occupations (Table 1). The concepts of Phases and Traditions
42 still hold an important place in Amazonian archaeology. Although initially applied as
43 narrow categories, recent studies have reevaluated them as useful tools to organize the
44 archaeological record. In this paper we consider archaeological traditions as durable and
45 cohesive material productions which are reproduced dynamically generation to
46 generation and can help access long term cultural structures (Almeida et al., 2021). This
47 data preparation was based on Almeida and colleagues' (2021) arguments to differentiate
48 between the Polychrome Tradition and other Amazonian polychromic ceramics. Our
49 approach in selecting regional pottery styles and occupations is grounded in a thorough
50 comparison of spatial distribution, chronology, and specific aspects of pottery technology
51 and design. As we have seen, these recent researches rule out, for example, Marajoara
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3 and other Eastern Amazon styles, which although share traits, have, according to these
4 authors, distinct styles and historical trajectories. Nevertheless, we do acknowledge the
5 existence of similarities which we understand might be related to both the similar
6 historical origins in Pocó-Açutuba pottery as well as to pan-Amazonian spheres of
7 influence associated with the AD 1000 period. Complete discussion of this selection as
8 well as the methods and dataset selection process are fully described in the accompanying
9 **Supplementary Information** with code and data outlined here.

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16 In short, our approach entails the calibration, binning, and aggregation of
17 radiocarbon dates associated with Polychrome occupations. We used summed probability
18 distributions (SPD) as the basis for our palaeodemographic modelling (Crema and Bevan
19 2021), focusing on two outstanding issues: 1) variation in time of dated Polychrome
20 occupations in the context of other, broadly contemporaneous lowland South American
21 traditions, and 2) the rate of rise and decline of the Polychrome Expansion as reflected in
22 the radiocarbon data, as well as the timing of the shift between the two idealised states.

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29 Comparison with contemporaneous historical processes is crucial to understand
30 what, if any, chronological variability is particular to the Polychrome Expansion in its
31 broader Amazonian context. Additionally, insights into the internal dynamics of the
32 expansion may be important for understanding the palaeodemographic processes that
33 underpinned it, as well as generate hypotheses for testing with future archaeological work.
34 For these purposes, data on Incised Rim/Barrancoid and Arauquinoid sites were also
35 gathered (Figure 2). Arauquinoid dates were used to compare the Polychrome Expansion
36 with a contemporaneous, but apparently unrelated process in Amazonia, which could
37 point to general influences in patterns such as climate change and systematic underdating.
38 Barrancoid, on the other hand, was chosen for its direct relationship with Polychrome
39 occupations, which replace it in several contexts (Moraes; Neves, 2012). Comparisons
40 could point to the timing of this substitution, which relates, for example, to ideas of a
41 rapid conquest. We address these questions through mark permutation testing (Crema et
42 al. 2016) and the application of a Bayesian inferential framework developed for
43 radiocarbon data (Crema and Shoda 2021). The workflow for both approaches is
44 described in the **Supplementary Information** and in an accompanying repository
45 (<https://github.com/philriris/m2m-bayesian>).

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3 For assessing the timing and probable routes of dispersal we explicitly modelled
4 different dispersal scenarios using a Fast Marching algorithm that computes the arrival
5 time of an expanding wavefront at each cell of discrete lattice or raster (Silva; Steele,
6 2012, 2014). Predicted arrival times are then compared to the empirical dates in the
7 database, and the model parameters are optimised in order to provide the best-fit to the
8 chronometric data. Finally, the different models are compared using Akaike's
9 Information Criteria (AIC) thereby allowing one to identify the scenario that best
10 describes the available archaeological data.
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18 For the Polychrome Expansion, ten models for the source and ease-of-movement
19 in the Amazonian landscape were developed. With respect to the dynamics of the
20 dispersal itself, the following hypotheses were modelled:
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- 23 • Model 0: the dispersal speed is the same throughout the entire region;
- 24 • Model 1: dispersal is faster along rivers, with no differentiation between main and
25 secondary rivers;
- 26 • Model 2: dispersal is faster along rivers, but main and secondary rivers can have
27 different speeds;
- 28 • Model 1+D: same as Model 1, while allowing for a defended region around
29 NSAM which would have slowed down dispersal;
- 30 • Model 2+D: same as Model 2, while allowing for a defended region around
31 NSAM which would have slowed down dispersal.
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44 Finally, two possible source locations were considered – Conjunto Vilas in the
45 Middle Solimões, and Teotônio in the Upper Madeira – and all the above models were
46 rerun for each of these source locations so we could explicitly and quantitatively compare
47 the model predictions with the empirical data.
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55 **Results**

56 Summed probability distributions (Figure 4) showed a more gradual increase in
57 dates of Polychrome occupations culminating in the 14th century, rather than just a rapid
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3 growth in 1000BP. Nonetheless, discrete pulses seem to happen at key periods, most
4 overtly around 700BP. More surprising were results for subsequent periods, with a
5 decrease around 550BP, before the expected decrease with the arrival of the first
6 Europeans and earlier than the Portuguese conquest of Central Amazonia in the 17th
7 century. This decrease is followed by a second one around 300BP. From the resulting
8 map, the initial range (orange) indicates a process that starts locally and gradually expands
9 to a few other regions. The subsequent period (yellow) registers a larger general
10 expansion in Central and Western Amazonia. Finally, the last phase of this process
11 (purple) suggests maintenance of Polychrome production in most dispersal areas.
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20 Mark permutation test results of Polychrome and Arauquinoid (Figure 5)
21 occupations showed distinctions, such as a more pronounced rise in dates around 1000BP
22 and an earlier decaying of dates, but, overall, there are no significant variations, including
23 decrease of dates before the 16th century. These data pointed to similar moments of
24 inflection for both Polychrome and Arauquinoid occupations around 600BP.
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29 Mark permutation tests with Barrancoid dates (Figure 5) reinforce the perspective
30 of a substitution process of Barrancoid occupations by Polychrome occupations, seen in
31 Central Amazonian sites (de Souza *et al.*, 2019; Neves, 2022). Observed deviations in the
32 permutation test indicate that the general process of transition occurs also around 800BP.
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37 Turning to the dispersal of Polychrome sites, table 2 shows Δ AIC values for all
38 Fast Marching models tested. The lowest Δ AIC identifies the model that best fits the
39 empirical data, whereas all models with a Δ AIC greater than 4 are outside of the
40 equivalent of a 2-sigma confidence envelope and, therefore, statistically they are
41 significantly poorer explanatory models. As is clear from the table, Conjunto Vilas in the
42 Solimões is preferred as the source of the dispersal when compared with Teotônio, in the
43 Upper Madeira, for all tested models.
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50 In addition, Model 2+D – with different speeds of dispersal for Main and
51 Secondary rivers and the addition of a defended area around NSAM – is a much better fit
52 to the chronometric data than the other dispersal models. The dispersal parameters for
53 this model are as follows:
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58 · Speed boost in main rivers: 0.05x;
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- Speed boost in secondary rivers: 13.92x;
- Speed boost in defended area: 0.06x.

It is important to remember that a value lower than 1x indicates a speed decrease, whereas a value above 1x indicates a speed increase. Our spatially heterogeneous dispersal modelling, therefore, indicates that, along the main rivers, Polychrome dispersed at a considerably slowed down speed that corresponded to only 5% of its inland speed. The same applies to the defended areas around NSAM, where the speed was 6% that of its inland spread. On the other hand, on secondary rivers the dispersal of Polychrome was accelerated almost 14 times. Figure 6 shows the predicted latest arrival time for best-fitting model 2+D.

Discussion

The data gathered, prepared, analysed, modelled, and visualised with computational methods presents a complex new picture of the Polychrome Expansion. It also points to critical data gaps that need to be dealt with in order to build more robust models. Firstly, computational data underpinned spatial gaps of dated Polychrome sites mainly in Western and South-Central Amazon, which need systematic archaeological research and dating.

Besides the spatial coverage of data, the results show possible chronological biases, especially in the beginning and end of the chronology of the Polychrome Expansion. At the start of the time sequence there is a gap between earlier dates around 1500BP and later dates around 1200BP. At the other end of the sequence, a drop in Polychrome dates was observed before the 16th century. Although it might represent an actual pattern in data, it might also represent systematic “underdating” of later Polychrome occupations. These usually correspond to the upper layers of archaeological deposits in Western and Central Amazon, and invariably next to site surfaces that are commonly related to previous and contemporary (re)occupations and activities. It is relatively common that significant amounts of Amazonian archaeological sites are located beneath modern occupations. To avoid dating modern materials, selection might preferentially have been done with deeper and more ancient samples. The recurrence of this pattern in the Arauquinoid sequence could signal a broader scale for this issue. We

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3 suggest that a way to counteract this possible discrepancy would be to privilege the dating
4 of ceramics: pottery shards with large inclusions of tree bark ash temper, or with lipid
5 remains.
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9 While these gaps in data may present some bias, the results provide a platform for
10 significantly rearranging existing hypotheses on the source points and expansion routes
11 for the Polychrome Expansion, while also offering clear pathways to bridge these gaps
12 and form more robust expansion models. To this end, we provide several contributions to
13 previously presented debates. With regards to the timing of the Polychrome Expansion,
14 the model indicates a time-extended process with key moments of spatial dispersal around
15 900BP and of an increase in dates around 700BP when expansion hits its maximum
16 spatial distribution. Between 900 and 700BP is also when the inversion between growth
17 rates of Polychrome and Barrancoid occupations occurs along all Central Amazonia, after
18 centuries of co-occurrence. This data reinforces the idea of a change in the modes of
19 dispersal after 1000BP in relation to slower and more localised spread of Polychrome
20 occupations in the previous period. Therefore, the data emphasises that the period around
21 1000BP can plausibly be seen as a turning point for Polychrome occupations, in
22 agreement with previous work (Neves, 2022).
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34 In reference to expansion routes, the model underlines Tamanaha's (2018)
35 proposition of a secondary river dispersal around a defended NSAM area. Fast Marching
36 strongly reinforces a Middle Solimões (or surrounding areas) point of origin, as
37 opposed to the Upper Madeira. The inferred speed for secondary rivers is vastly superior
38 to all other proposed alternatives, which differs from previous models. Instead of cardiac
39 pulses spreading from NSAM or the Upper Madeira through main rivers and then
40 descending secondary rivers, Fast Marching model indicates a "venous" pattern of
41 combined interfluvial and secondary river dispersal that surrounds main rivers, occupying
42 NSAM in a later moment. Although not centred in main rivers, this model does reinforce
43 Lathrap's ideas of a Central Amazon origin (outside of the NSAM region) for the
44 Polychrome Expansion that spreads on riverine pathways in all directions (Lathrap,
45 1970).
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56 Before 1000BP routes of dispersal would privilege southern and northern
57 tributaries of the Middle Solimões. Paths to the Middle Negro might have favoured the
58 Jaú and Unini rivers, popular indigenous trade routes recognized by the first European
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3 chroniclers (Lopes, 2021), while early Nofurei dates could indicate influences from the
4 Middle Solimões up the Caquetá-Japurá. As for the Southern routes, ethnohistorical data
5 also indicate long-distance interfluvial roads in the region that could reach the Upper
6 Madeira and Southwest Amazon (Lopes, 2021). Afterwards it would greatly expand to
7 Western and Eastern tributaries. This pattern of secondary river dispersal resembles
8 another one that occurred in the Central Amazon during the 18th century: the Mura
9 expansion (Amoroso, 1992). Highly mobile Mura groups would advance through
10 surrounding secondary rivers of the Solimões and Madeira avoiding establishing in
11 Portuguese-defended areas of the main rivers and benefiting from previous groups
12 scattering by colonial forces. Meanwhile, Mura territories would be built deep within
13 smaller rivers from where they greatly spread (Harris et al., 2015). Mura also waged a
14 fierce and long-lasting guerrilla war with the Portuguese, preying on their ships and main
15 river villages and missions (Hemming, 1978). Seen as a response to colonial pressure, the
16 Mura expansion could actually represent a colonial rendition of a previous pattern of
17 secondary river dispersal, one that could even have benefitted from ancient Polychrome
18 routes – which would help to explain how it branched from the Lower Madeira to the
19 Upper Solimões in just a few decades. This common feature between the Mura of the
20 colonial period and the Polychrome Tradition could thus suggest a hypothesis for future
21 studies, where the latter had a part in the ethnogenesis processes of the former, an idea
22 strengthened by the known practice of the Mura of incorporating distinct ethnicities in
23 their own groups (Amoroso, 1992).

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The proposed role of the NSAM area in slowing down expansion highlights inter-
group conflict and warfare as important aspects of the Polychrome Expansion, which
correspond to the presence of evidence of ditches and palisades surrounding NSAM sites
and point to possible territorial disputes on highly prized area of intersection between
basins (Moraes and Neves, 2012). Initial expansion of Polychrome occupations
connecting Middle Solimões and the Middle Negro rivers signals to the aforementioned
ethnohistoric trade routes that stress complementary trade aspects also visualized in
pottery production (Belletti, 2016; Lopes, 2018).

The aggregate analysis of radiocarbon data presents an interesting outlook for the
final centuries of Polychrome occupations, a first drop in dates before European conquest
– that could be caused by systematic underdating – and a second one around the 17th
century. If not associated with underdating, a pre-conquest drop in both Polychrome and

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3 Arauquinoid occupations could represent late regional examples of a general process of
4 population decline and social reorganisation in Amazonia after 800BP (Moraes, 2015;
5 Arroyo-Kalin and Riris, 2020) whose causes are still undetermined. On the other hand,
6 post-colonial Polychrome occupations show resilience of these groups (especially
7 considering underdating), that persisted through colonial impact. Furthermore, it is
8 compatible with recent studies that trace persistence in practices and pottery production
9 related to Polychrome occupations up until the beginning of the 20th century in key areas
10 such as the Upper Amazon, the Middle Negro and the Middle Solimões (Lopes et al.,
11 2024).
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20 Lastly, regarding climate change and land use, recent studies (Azevedo *et al.*,
21 2019; de Souza *et al.*, 2019) using local Polychrome chronologies, have argued for a
22 relation between climate events and the Polychrome Expansion. For Azevedo and
23 colleagues, the switch between wetter to drier periods around 1150 AD significantly
24 influenced the substitution of Paredão (Incised Rim/Barrancoid) by Guarita (Polychrome)
25 occupations in the Central Amazon (Azevedo *et al.*, 2019). On the other hand, De Souza
26 (2019) and colleagues characterise Paredão occupations as more vulnerable to climate
27 change, while Guarita occupations would be more resilient. That would result particularly
28 from a distinction in land-use systems, Paredão being more intensive and specialised and
29 Guarita being more extensive and generalist. Data for the Polychrome Expansion
30 reinforces a 12th and 13th century ascension for these occupations. Nonetheless, the drop
31 in dates occurring before European arrival and at the beginning of the Little Ice Age
32 (c.1450 AD) – also a drier period in the region – casts doubt on the association between
33 Polychrome occupations and extensive land-use systems more resilient in drier periods –
34 considering limited information available on land-use for Polychrome sites for such a
35 claim (Riris, 2019). It is interesting that other contemporaneous and apparently unrelated
36 processes in the Amazon, such as Arauquinoid occupations and the Lomas in the Llanos
37 de Mojos (Prümers and Betancourt, 2014), seem to share this pre-conquest decline.
38 Therefore, we argue that association concerning the Polychrome Expansion and climate
39 events need to be better qualified and to be treated in a holistic way, as one factor that
40 relates to all others in a context of widespread social transformations.
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56 **Conclusions**

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58 Synthetizing modelled data, the Polychrome Expansion can tentatively be divided
59 in three periods, each with two phases. First period (c.1500-1000BP) marks Polychrome
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3 occupations as a relatively localized phenomenon, with an initial spread in the Middle
4 Solimões (1500-1100BP), followed by an expansion to the Caquetá-Japurá, Negro and
5 Southern and Southwestern tributaries (1100-1000BP). In the second period (1000-
6 500BP), the Polychrome Expansion reshapes Western and Central Amazonia. It starts
7 with a branching out of Polychrome occupations on main and secondary rivers and
8 interflows (1000-700BP), followed by a surge in occupations (700-500BP). Third period
9 (500-50BP) encompasses two contractions, the first one, a possible diminishment in dates
10 before European arrival (500-300BP) and the second one, the final moment of
11 Polychrome occupations (300-50BP), where it becomes a localized phenomenon in
12 colonial and postcolonial Amazonia (Lopes, 2021).
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21 This exploratory framework, gathered with the help of computational methods and
22 modelling, allows for new lines of questioning. It reinforces the value of these tools in
23 understanding ancient expansions in South America (Riris and Silva, 2021). Further,
24 these show the potential to engage in yet another central Polychrome debate: its
25 relationship with the expansion of Tupi populations (Almeida and Moraes, 2016; Belletti,
26 2016; Lopes, 2018). Although current results must be seen with caution and as data itself,
27 they provided innovative forms of viewing and interpreting data, signalling gaps and
28 possible paths of advancing discussion. Particularly, the “venous” pattern of the
29 Polychrome Expansion suggested by this study redirects focus from main rivers – that
30 oriented colonial and modern regional occupation and guided research since the
31 beginning of Amazonian archaeology – towards secondary rivers and interfluvial areas,
32 seen originally as the periphery of a peripheral region. As the transformation of
33 Amazonian archaeology allowed the region to be recentred in the ancient history of South
34 America, new studies as this paper suggest a need to recentre these areas within
35 Amazonia. On the other hand, colonial overlap with Polychrome occupations sheds light
36 on a chronological bias, the barely studied relationship of producers of Polychrome
37 Tradition pottery with Colonialism.
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Figure Captions

Figure 1: Polychrome tradition components.

Figure 2: Polychrome (dated and undated), Arauquinoid and Barrancoid sites.

Figure 3: Polychrome chronology boxplot (97 dates) according to river basins.

Figure 4: Polychrome SPD and map of dates (97 dates). Grey area represents growth rates (red line represents smoothed SPD). Crossed line signals changepoint. Map was built considering median of calibrated dates.

Figure 5: Mark permutation tests of Polychrome versus Arauquinoid ($p > 0.1$) (177 dates) and Barrancoid traditions ($p < 0.001$) (109 dates). Locally significant anomalies are in red (positive) and blue (negative).

Figure 6: Predicted latest arrival time map for best-fitting dispersal model. The shaded colours indicate the latest arrival time. Also shown are the rivers used (in blue) and the location of Vilas, which was taken to be the source of the dispersal.

Tables

Table 1: Pottery styles considered for the Polychrome Tradition.

Style	River basin

Apuaú	Lower Negro
Borba	Lower Madeira
Caimito	Ucayali
Guarita	Lower Solimões and Mid-lower Amazonas
Jatuarana	Upper Madeira
Manauacá	Middle Negro
Napo	Napo
Nofurei	Middle Caquetá
Samambaia	Middle Negro
São Joaquim	Upper Solimões
Tefé	Middle Solimões
Zebu	Upper Amazonas

Table 2: Fast Marching Δ AIC values

Dispersal Source	Vilas, Solimões	Teotônio, Upper Madeira
Model		
Model 0 (Flat)	37.08	48.37
Model 1 (All Rivers)	27.2	44.25
Model 2 (Main vs Sec)	10.20	41.93

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Model 1+D	14.25	37.94
Model 2+D	0.00	36.65

For Peer Review



Figure 1: Polychrome components.

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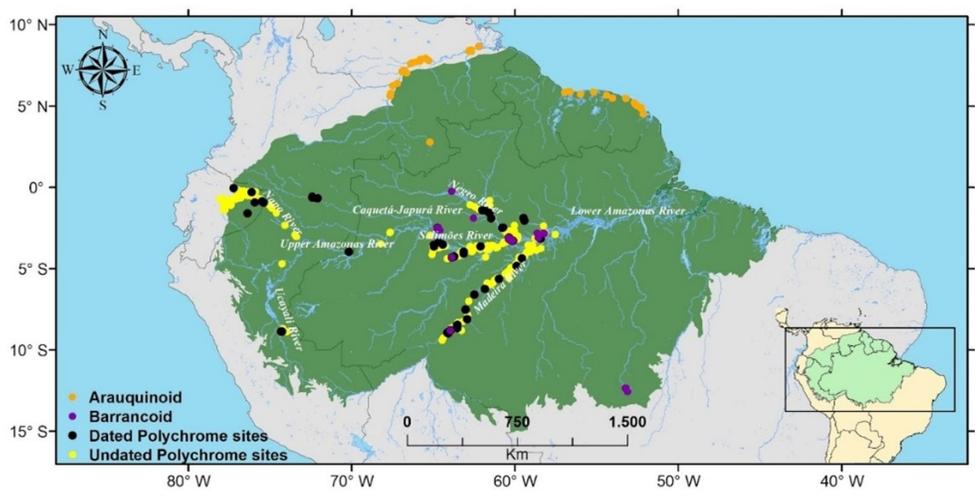


Figure 2: Polychrome (dated and undated), Arauquinoid and Barrancoid sites.

134x71mm (220 x 220 DPI)

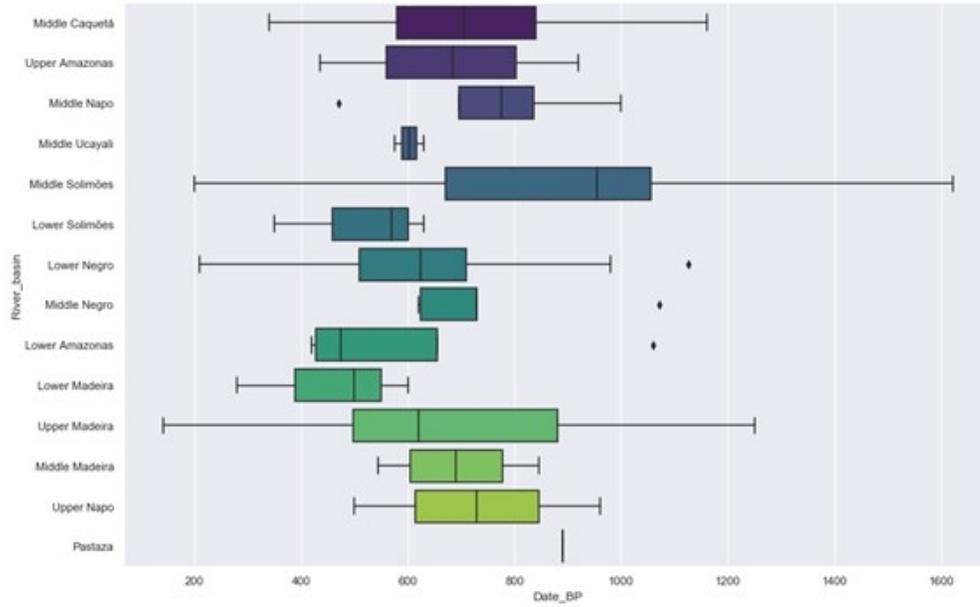


Figure 3: Polychrome chronology boxplot (97 dates) according to river basins.

150x92mm (96 x 96 DPI)

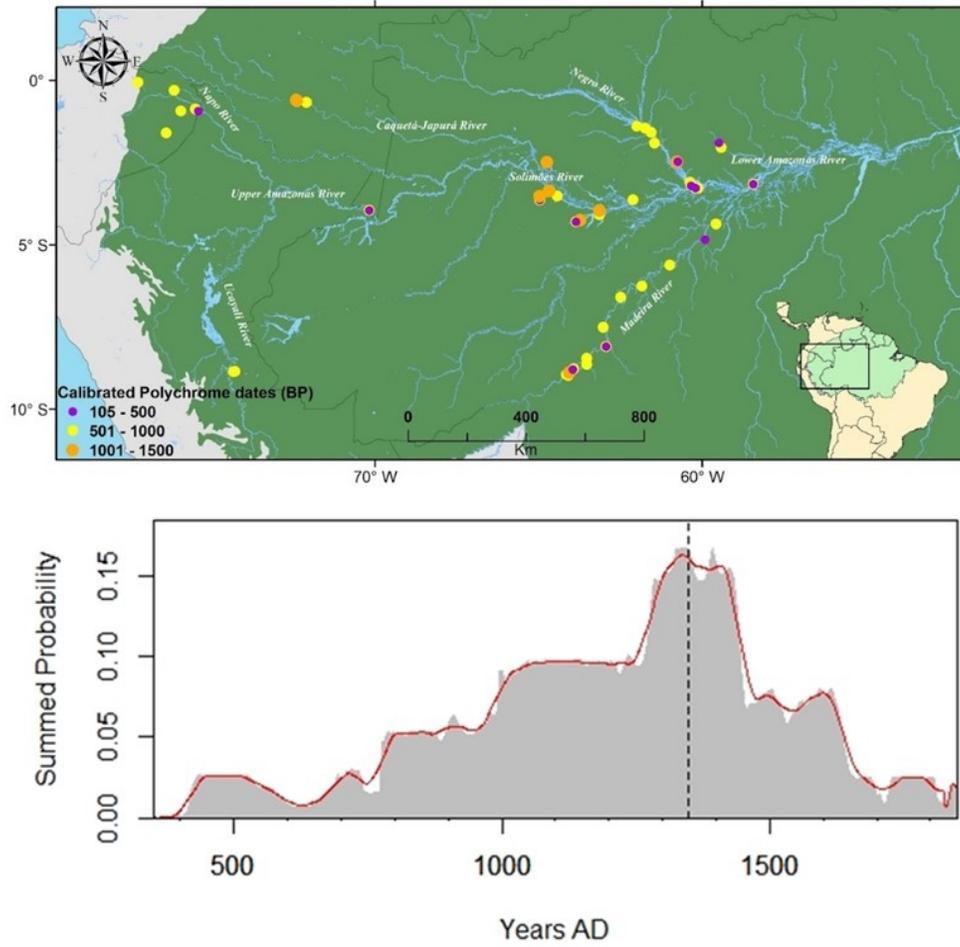


Figure 4: Polychrome SPD and map of dates (97 dates). Grey area represents growth rates (red line represents smoothed SPD). Crossed line signals changepoint. Map was built considering median of calibrated dates.

133x129mm (150 x 150 DPI)

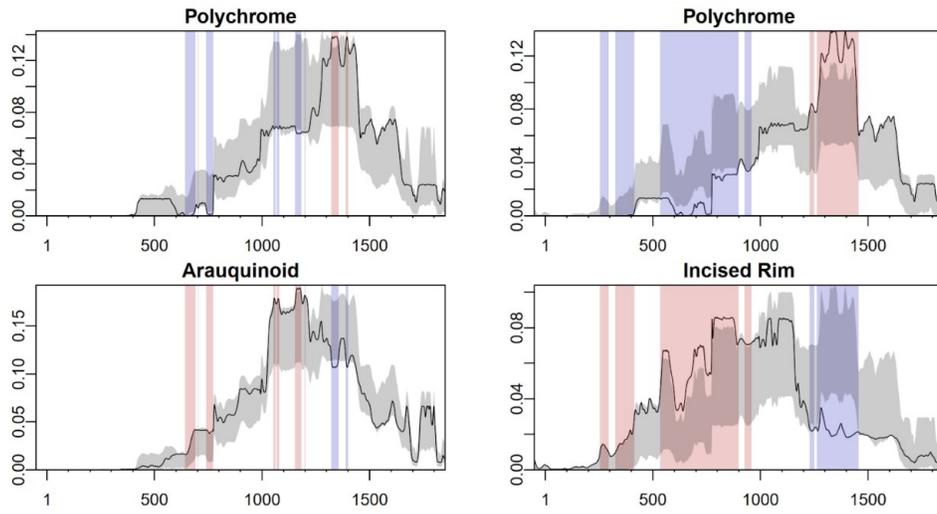


Figure 5: Mark permutation tests of Polychrome versus Arauquinoid ($p > 0.1$) (177 dates) and Barrancoid traditions ($p < 0.001$) (109 dates). Locally significant anomalies are in red (positive) and blue (negative).

149x76mm (220 x 220 DPI)

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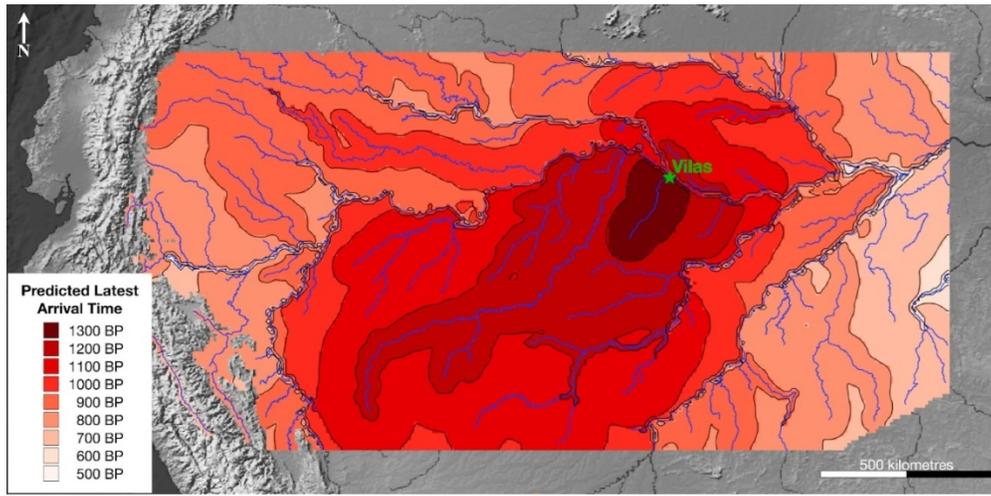


Figure 6: Predicted latest arrival time map for best-fitting dispersal model. The shaded colours indicate the latest arrival time. Also shown are the rivers used (in blue) and the location of Vilas, which was taken to be the source of the dispersal.

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Supplementary material

Methods

This document describes the data selection and palaeodemographic modelling of the Amazonian Polychrome Tradition. The code and data employed in the creation of the results are described in this document. Output files can also be accessed alongside the code and data on a dedicated GitHub (<https://github.com/philriris/m2m-bayesian>) repository.

1. AmazonArch and Polychrome data selection

Archaeological sites in AmazonArch database are georeferenced and have chronological, settlement and broad contextual data, such as site size, the presence of Amazonian Dark Earth (ADE), and which ceramic traditions have been registered. The database contains 463 archaeological sites and 60 archaeological dates related to Polychrome sites, which we expanded to 519 sites and 105 dates. Sample selection of Polychrome sites was paramount for the usage of computational methods; the addition or removal of specific styles has the potential to significantly alter possible routes and timing of this historical process. Recent studies have advanced in discerning regional components directly associated with the expansion of Polychrome occupations from others that share elements with these (such as polychromic pottery decoration) or that show signs of being influenced by it, but represent different historical trajectories (Belletti, 2016; Almeida *et al.*, 2018; 2021; Oliveira, 2022).

We follow Almeida and colleagues (2021) in distinguishing the Polychrome Expansion *sensu strictu* from polychromic ceramics. Our selection of Polychrome regional styles relies on comparisons of spatiality, chronology and elements of pottery technology and style. In reference to spatiality, contingency of components was seen as crucial, acknowledging the presence of cultural boundaries for Polychrome Expansion. The presence of Incise-Punctuate occupations between the Central and Western Amazon and the Amazon estuary around the period of the Polychrome Expansion has been used to suggest that the Eastern polychromic styles of Marajó, Koriabo, Mazagão and Aristé occupations are distinct phenomena. Furthermore, regarding chronology, the exclusion of Marajó occupations from our dataset on account to 1700BP dates in Marajó island, appears reasonable. It also rules out Tequinho occupations (Parssinen, 2021), a recently

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3 discovered polychromic occupation dated between 300-500 AD in the Upper Purus area.
4 Regarding technology and style, the cohesion of ceramic attributes, that includes the
5 presence or absence of decorative elements – especially highly diagnostic features such
6 as grooving, *horror vacui*, and snake-anthropomorphic motifs – and of other traits as
7 morphological variability were observed. Most characteristic aspects of Polychrome
8 pottery are red, brown and/or black painting on white or beige slips summed with incised,
9 excised decorations, but relying heavily in grooving (Barreto, Lima and Betancourt,
10 2016, pp. 591–592). Regarding morphology, anthropomorphic burial urns, square plates
11 and mid-rim vessels are emblematic. Besides those, the high recognizability of
12 Polychrome pottery lies in the structure and ordering of iconographic patterns and themes.
13 Decorative fields are formed by lines and strips that combine curves and stepping in
14 symmetric graphical patterns of anthropomorphic and zoomorphic elements that display
15 *horror vacui*. Complex motifs present especially quimeric beings formed from diadem-
16 wearing anthropomorphs, serpents and birds. Patterning and stability of these traits gives
17 way for relating and comparing regional components (Oliveira, 2022).
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30 The combination of these elements weakens the case for inclusion of
31 Aceipa/Palmeras and San Roque occupations in the Napo basin (Arellano, 2009) and of
32 Nofurei occupations in the Caquetá River, previously suggested by Arroyo-Kalin and
33 colleagues (Arroyo-Kalin *et al.*, 2019). In these three cases, the absence of morphological
34 aspects such as mid-rim vessels, as well as specific decorative combinations was key for
35 highlighting differences.
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41 In case of Tequinho and Marajó, similarities suggest that they originate in a
42 common stylistic source possibly associated with Pocó pottery (3000-500BP), which
43 incorporates most decorative aspects that in later styles are included: polychromic
44 painting, incise and excise decorations and production of mid-rim vessels (Almeida,
45 Lopes and Stampanoni Bassi, 2021). On the other hand, Aceipa/Palmeras, Nofurei,
46 Koriabo, Mazagão and Aristé present chronological and stylistic similarities, and
47 maintain internal cohesion that differs from that of the Polychrome. Aceipa/Palmeras
48 present clear Napo influences, while also maintaining technological and stylistic
49 distinctions, such as a high frequency of brown slips. Late San Roque occupations also
50 present Napo pottery in between red-on-brown painting. Aceipa/Palmeras and San Roque
51 also seem to correspond to historical developments of earlier Tivacuno pottery (Arroyo-
52 Kalin and Rivas Panduro, 2016). Nofurei pottery contains anthropomorphic and snakelike
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3 motifs but executed in an emblematic red painting with incised contours, that indicate
4 more of a balance between Polychrome influence and regional development.
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8 Nofurei data was kept on behalf of ongoing debates on its position on the
9 Polychrome Expansion and for exploratory purposes, to consider how a Polychrome
10 sphere of influence could spread from an initial Middle Solimões origin.
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14 Koriabo shows polychromic paintings and mid-rim vessels (with scraped motifs,
15 instead of Polychrome grooving) as components amidst highly diverse techniques and
16 morphologies. Anthropomorphic and zoomorphic modelling are present but applied to
17 different forms than Polychrome. Mazagão is a ceramic phase still poorly understood,
18 located in a zone of possible multiethnic exchange networks between the modern state of
19 Amapá and the Guianas, being recently related to the Caviana phase, with
20 anthropomorphic and polychromic urns (Saldanha *et al.*, 2016). Aristé pottery is also
21 known for the presence of anthropomorphic urns, polychrome painting, zoomorphic
22 modeling, painting and incisions with curvilinear patterns and textures, but those differ
23 considerably from the classic Polychrome patterns. Aristé, Caviana, Mazagão and
24 Marajoara, in addition to being isolated in the Amazon estuary from the rest of
25 Polychrome components, are located in an area known ethnographically for wide
26 networks of exchange, that materialize different processes of sharing of ceramic styles.
27 In addition, the occupations linked to these different phases exhibit different forms of
28 occupation and management of the environment (Almeida *et al.*, 2018). Shaft graves,
29 megaliths, tesos and hydrological management earthworks indicate specific regional
30 aspects of environmental use, forms of sociability and funerary behaviors, not found in
31 Polychrome contexts (Saldanha *et al.*, 2016).
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46 Marajoara is perhaps the ceramic industry with the greatest variability in terms of
47 technology and decorative patterns. With chronologically differentiated styles, it
48 combines techniques such as incision, excision, modeling, channeling, red and black
49 paint, white and red slip, zoomorphic and anthropomorphic decorations, including
50 appliques and a wide variety of beings modeled among birds, snakes, amphibians, insects,
51 among others. Despite its exclusion from the Polychrome Tradition, there is the
52 hypothesis of a late Polychrome influence in the Marajoara pottery, expressed in the
53 Pacoval and Anajás Inciso styles. Late Marajoara styles highlight an understudied issue
54 not addressed in the present paper: the spheres of influence that proportionate similarities
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3 in pottery styles across Amazonia around AD 1000, of which the presence of a diverse
4 range of anthropomorphic burial urns are the most emblematic remnant (Barreto, 2016).
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7 Finally, Zapotal sites were considered, but its three radiocarbon dates were
8 discarded on account of ambiguous descriptions of results as both BP and AD (Morales,
9 2019).
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14 15 *2. Summed probability distributions of calibrated radiocarbon dates*

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18 We use summed probability distributions of calibrated radiocarbon dates (SPDs)
19 pertaining to the Amazonian Polychrome Tradition and the Incised Rim and Arauquinoid
20 Series as a proxy of relative levels of activity within these cultural phenomena. In outline,
21 SPDs are a widespread method of visualising changes in the aggregate probability density
22 of a sample of dates. Together with alternatives such as kernel density estimates (Brown
23 2017) or radiocarbon event counts (Carleton 2021), they enable the visualisation of trends
24 over time within a dataset of radiocarbon dates. Approaches typically employ the
25 combined total of all dates in a geographical region, however, specific types of activity
26 (Schauer et al. 2019) or class of evidence (Solheim 2021; Crema et al. 2022) have also
27 been targets for investigation. SPDs have seen prior use in the South American lowlands
28 to investigate carrying capacity, cultural resilience, and sensitivity to hydroclimatic
29 variations at various timescales, among other topics (Azevedo et al. 2019; De Souza et al.
30 2019; Arroyo-Kalin and Riris 2021; Riris and De Souza 2021). Our aim is to use SPDs
31 to examine and compare the trajectories of the three abovementioned Late Holocene
32 cultural traditions, and to apply this new information in the context of existing
33 archaeological evidence on the characteristics of the Polychrome Expansion. We are
34 specifically interested in comparing frequencies in time, and rates of growth and decline
35 in the dated evidence of the Polychrome, Incised Rim, and Arauquinoid. We also seek to
36 estimate the timing of the transition between these two states.
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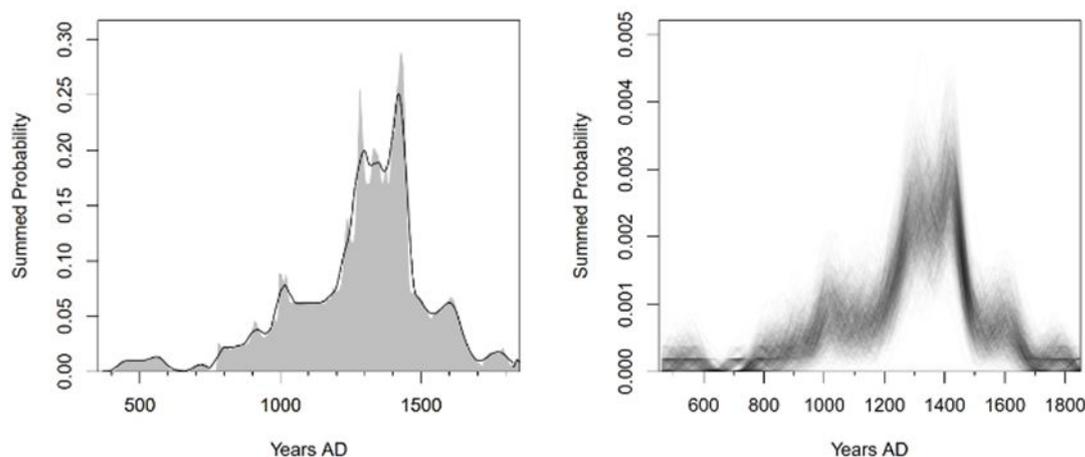


Figure 1: SPD and cKDE of Polychrome Tradition dates, AD 450-1850. *Left:* Raw SPD (grey) is presented with a 50-year running mean (black line). *Right:* Bootstrapped cKDE illustrating the potential uncertainty over time associated to this dataset.

Our approach employs standard protocols in the aggregate analysis of radiocarbon dates. We calibrate our sample of dates from radiocarbon years to calendar years using a custom calibration curve that combines the northern and southern hemisphere curves in equal proportion (Marsh et al. 2018). Calibrated dates are not normalised, to avoid spikes in probability caused by steep portions of the calibration curve within our windows of analysis (for example around 1200 cal BP; Reimer et al. 2020). Before summing, we first thin our dates by randomly sampling single dates from “bins” where dates fall within 50 radiocarbon years of one another in the same site, to minimise the overrepresentation of well-dated sites. We present both the raw SPD and a 50-year running average. For illustrative purposes, a composite kernel density estimate (cKDE) computed from 1000 bootstrap sampled dates with a smoothing bandwidth of 25 years is shown alongside (Figure S1). The cKDE effectively illustrates the considerable uncertainty associated to variation over time in the dataset, which the SPD does not capture sufficiently on its own.

Used in isolation or as a simple graphical summary, SPDs are therefore unreliable indices of anything but the broadest of trends – for example, a general rise and fall of Polychrome-affiliated dates centred approximately on AD1350. To distinguish genuine trends over time from artefacts arising from multiple sources of error (sampling bias, calibration effects, and/or taphonomy), additional statistical modelling is essential (Crema and Bevan 2021), particularly in a relatively modest dataset such as this.

3. Mark permutation testing

To evaluate differences in time between the frequencies of dates associated to the three ceramic traditions, we apply a mark permutation test to our combined dataset (Crema et al. 2016). This approach, implemented in the R package ‘rcarbon’ (Crema and Bevan 2021), statistically compares the distributions of three SPDs against one another to assess whether there are significant differences between each sub-sample, under the null hypothesis of “no significant difference”. In our case the null implies that the three ceramic traditions have identical trajectories. By repeatedly shuffling the affiliation of each date and producing an SPD (here, 1000 times), the permutation test produces a confidence envelope against which to compare the empirical SPDs and assess local and global divergences from expectations. As a non-parametric test, it is relatively robust to small sample sizes (Crema and Bevan 2021). The same calibration, binning, and aggregation procedure as above is employed for the mark permutation test. Results are presented and discussed in the main text, as well as shown in **Figure S2**.

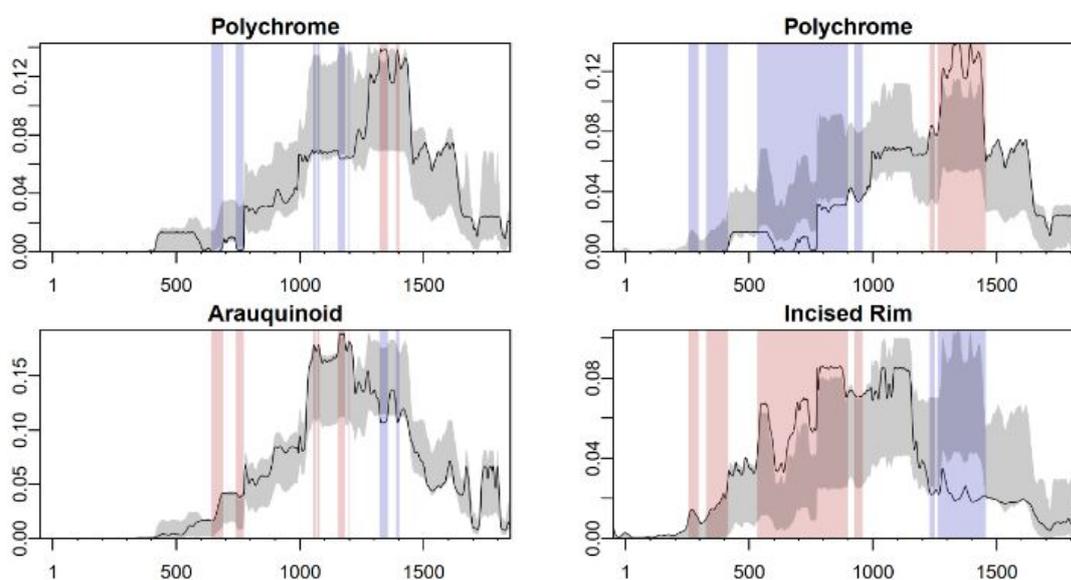


Figure 2: Mark permutation tests for Amazonian ceramic traditions. Left column: Polychrome versus Arauquinoid ($p > 0.1$). Right column: Polychrome versus Incised Rim ($p < 0.001$).

4. Palaeodemographic modelling

To estimate the rates of growth and decline in the production of Polychrome ceramics, we employ a Bayesian population model fitting framework implemented in the

R package ‘nimbleCarbon’ (Crema and Shoda 2021). Following visual examination of our SPDs, we elected to define a bounded double-exponential growth model as a prior, with three target parameters: the growth rates r_1 and r_2 , and the point of transition between them. This approach treats the aggregate variation over time in our dataset as a probability mass, and accounts separately for calibration effects and variation in sampling intensity. We set the start and end points for this analysis to 1600 cal BP and 150 cal BP, respectively, sensible ranges that are designed to capture the full duration of the radiocarbon dataset. We set weakly informative normally distributed priors for the growth rates that are designed to capture a broad range of both positive and negative values, noting the increase-to-decrease trend over time that is present in all our datasets:

$$r_1 \sim \text{Normal}(\mu=0, \sigma=0.0004)$$

$$r_2 \sim \text{Normal}(\mu=0, \sigma=0.0004)$$

For the change points between growth rates, we set a truncated normal distribution that is approximately centred on the peak in the SPD and cKDE (in cal BP), with a standard deviation of a century, which is relatively broad in the context of the window of analysis:

$$chp \sim \text{TruncatedNormal}(a=1600, b=150, \mu=600, \sigma=100)$$

We executed three chains over 50,000 iterations, with a burn-in of 5000 iterations and a thinning interval of 2. Following inspection of model diagnostics, the obtained posterior parameters were employed in a predictive check. By comparing the empirical SPDs against confidence envelopes generated from 1000 parameter samples, locally significant departures from expectations can be detected and visualised.

Table S1: Bayesian MCMC diagnostics and highest posterior density values for the posterior samples. Dates in BC/AD are shown in parentheses.

Parameter	R'	ESS	HPD _{lower}	Median	HPD _{upper}
<i>r1</i>	1.023088	11225.74	0.00046	0.00135	0.00225
<i>r2</i>	1.000880	16307.51	-0.00560	-0.00282	-0.00043
<i>chp</i>	1.001912	14734.40	492 (1458)	588 (1362)	701 (1249)

Results of the posterior predictive checks are presented and discussed in the main text, as well as shown in **Figure S3**. MCMC diagnostics are shown in **Figure S4** and summarised in **Table S1**. Traceplots and the Gelman-Rubin diagnostic R^* indicate convergence and adequate mixing of the MCMC samples of the parameters for each ceramic tradition.

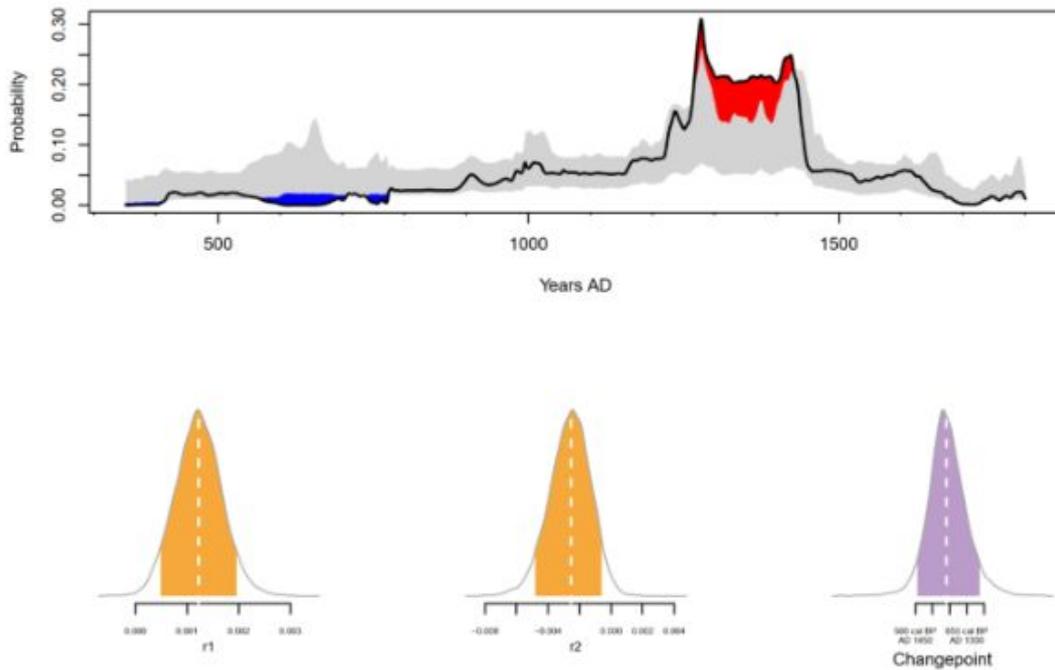


Figure 3: Posterior predictive check and highest posterior density estimates for growth rates and change point.

5. Dispersal Modelling Framework

Our approach to dispersal modelling is inspired by procedures used to explicitly and quantitatively compare the predictions of different source locations and dispersal trajectories against the empirical data for the case of the spread of rice in Asia (Silva *et al.*, 2015; 2018). Specifically, there are 4 stages to this framework, each with their own methodology.

5.1 Modelling different dispersal hypotheses

The different dispersal hypotheses are explicitly and spatially modelled using rasters that divide the region into sections where the dispersal may have occurred at different speeds (see Silva and Stelle 2012; 2014 for details). Here we have restricted the

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3 modelling region to the convex hull around the dated sites (with a buffer of 100km to
4 extend and smooth the convex hull). Rivers within this region were coded as Main or
5 Secondary based on their Strahler number: when the Strahler number was equal to or
6 above 8 the river was considered Main, whereas those with Strahler number below 8 were
7 considered Secondary. Finally, the defended area around the Negro-Solimões and
8 Amazon-Madeira (NSAM) meeting was constructed by buffering out 10km either side of
9 the rivers in the NSAM area. These spatial layers are then converted to rasters and input
10 into the Fast Marching algorithm (Silva and Steele 2012, 2014) which, together with a
11 source location and baseline speed, then calculates the cost-distance to each cell in the
12 chosen domain.
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22 *5.2 Comparing predictions with the empirical data*

23 This is done using the same quantile regression approach developed in Silva et al. (2015).
24 Essentially, the model's predicted cost-distance from the source of the dispersal to each
25 of the archaeological sites is queried from the Fast Marching output and then used,
26 together with the chronometric data for said sites, to perform a quantile regression. As
27 argued elsewhere a good dispersal model will result in a quantile regression that is a
28 better-fit to the chronometric data (Silva et al. 2015), using Akaike's Information Criteria
29 (AIC) (Akaike 1973) as our fitting index.
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38 *5.3 Optimising model parameters*

39 However, the dispersal model will have parameters (the speeds in the different regions)
40 which can have different values and, depending on these, the model can have a good or a
41 bad fit to the data. To address this issue we have implemented a Particle Swarm
42 Optimization (PSO) algorithm that efficiently searches the parameter space to find the
43 parameter combination that maximises a given fitness function (Gad 2022). The fitness
44 function here was chosen to be the inverse of Akaike's Information Criteria (AIC) since
45 the better the fit the lower the AIC value.
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53 *5.4 Model selection*

54 Finally, there is the issue of choosing between the different dispersal scenarios. This was
55 done using a model selection approach based on Akaike's Information Criteria (Burnham
56 and Anderson 2002). The AIC values of all models are compared, identifying the one
57 with the lowest value (the best-fitting model) and then calculating the difference in AIC
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3 value for all other models (Δ AIC). Only models with Δ AIC below 4 should be retained
4 since they all provide a significant fit to the data, despite the fact that the one with the
5 lowest DAIC value is the best-fitting (see also Silva et al 2015; 2018).
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10 5.5 Implementation

11 This framework was implemented in R (R Core Team 2022) using packages *rcarbon*
12 (Crema and Bevan 2021), *quantreg* (Koenker 2022), *hydroPSO* (Zambrano-Bigiarini and
13 Rojas 2013; 2020), and *fastmaRching* (Silva 2022). The source code is provided as
14 supplementary material. QGIS (QGIS Development Team 2022) was also used for
15 handling the different raster and vector files.
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