Spatial Structure among the Geometric Earthworks of western Amazonia (Acre, Brazil)

Philip Riris[1]

[1]Institute for Modelling Socio-Environmental Transitions
Department of Archaeology & Anthropology
Bournemouth University
Fern Barrow
Poole BH12 5BB
priris@bournemouth.ac.uk

Highlights

- Inferring socio-political organisation among Amazonian geometric earthwork builders is a significant challenge.
- Point process modelling is adapted for detecting multi-scalar spatial structure in a sample of geometric earthworks.
- Controlling for first- and second-order spatial dependency highlights likely critical scale of spatial structure.
- This information provides the first robust regional estimates of possible territorial integration.
- Hierarchical (vertical) organisation is counter-indicated, suggesting geometric earthwork building societies more likely had non-centralised or flat structures.

Abstract

Fieldwork and desk-based research in the western Amazon basin has led to an explosive growth in the state of knowledge surrounding the pre-Columbian archaeology of this region. Previously thought to be a sparsely occupied environment, archaeologists have recorded hundreds of geometric earthworks between the Purús and Acre rivers in recent years, spurring renewed interest in understanding the distribution, age, and function of these structures. A challenge has been to identify possible relationships between sites and to place them in their broader landscape setting. The precise spatial scale, relative importance of different factors, and strength of any relationships that contributed to shaping their distributions remain an open question. This paper develops and applies an explicitly spatial framework to address this problem, drawing on a rich body of recent research in Acre state (Brazil) and advanced point

process modelling. The analytical approach, which is fully documented and reproducible with the accompanying code, infers the factors affecting geometric earthwork distribution at multiple spatial scales. This enables the first robust predictions of territorial integration in the region, which is discussed context of extant archaeological models. The findings support the interpretation that non-stratified societies likely occupied Acre during the late pre-Columbian period.

Keywords

Amazonia, spatial statistics, territoriality, social complexity, South America, earthworks

1. Introduction

The geometric earthworks of the western Amazon basin have received substantial attention in the pursuit of understanding their distribution, context, purpose, and meaning. First documented in the early 1990s, and possibly earlier (Ranzi 2003; Ranzi et al. 2007; Dias 2006; Schaan 2012), the known structures are located primarily in the interfluvial uplands of the upper Purús and Acre rivers in the modern Brazilian state of Acre. Viewed in the context of key debates in Amazonian archaeology that were coming to a head by the end of the 1990s and early 2000s (Meggers 1992; Denevan 1996; Heckenberger et al. 1999; 2001; Meggers 2001; Stahl 2002), geometric earthworks have attracted widespread interest as proof that indigenous societies could thrive far from more agriculturally-attractive sedimentary floodplains (Schaan 2012; Watling et al. 2018). With time, well over 400 individual geometric earthworks, also termed ditched enclosures or “geoglyphs”, have been documented through aerial and remote sensing surveys (Ranzi et al. 2007; Schaan 2012; Saunaluoma 2012). This number increases with every publication, in the course of which archaeologists have continued to add nuance as new information is revealed. Notably, targeted efforts to understand geometric earthwork chronology, function, and ecological context through excavation have yielded significant insights into the societies that built them, as well as their land use practices (Saunaluoma and Virtanen 2015; Watling et al. 2017). Archaeological ceramics recovered from geometric earthworks suggest their embeddedness within a broader pan-Amazonian cultural milieu and a probable ceremonial purpose in prestige-enhancing displays (Pärssinen et al. 2009; Schaan et al. 2007; Schaan et al. 2010; Saunaluoma 2012). On the other hand, the relative scarcity of cultural deposits argues against persistent occupation within these sites. They are, consequently, interpreted as unlikely to have functioned as settlements. Taken as a whole, radiocarbon assays on geometric earthworks have yielded dates spanning at least two millennia

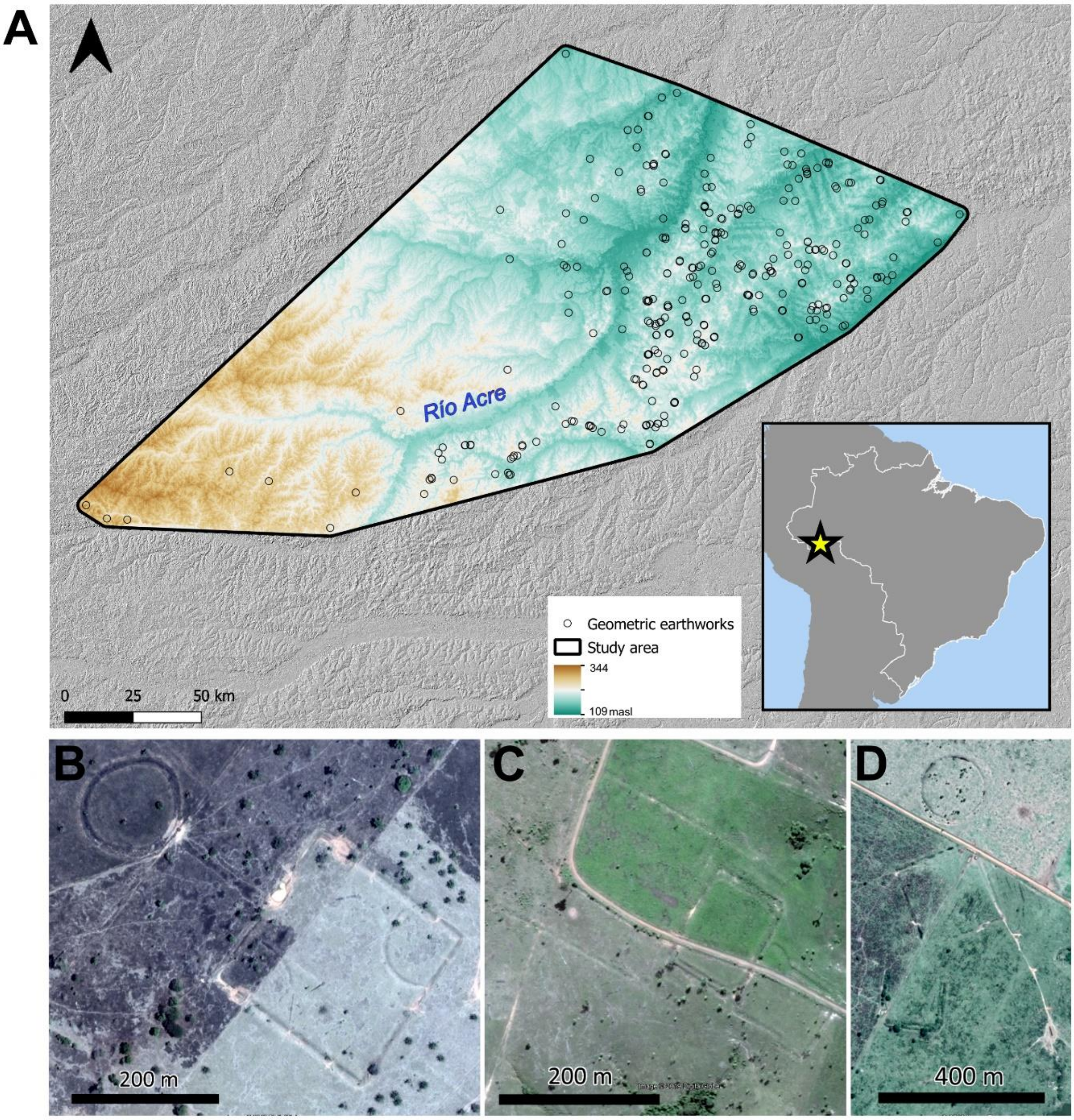

Fig. 1: Overview of geometric earthworks in the study area and location in Brazil. *A:* The study area comprises the convex hull of all earthworks located in Acre state. Note the spatial inhomogeneity of the point pattern in an east-to-west density cline. *B:* The Fazenda Atlântica site, showing internal subdivisions and inter-earthwork connections. *C:* Unnamed series of quadrangular earthworks in northern Acre, with multiple ditches and berms. *D:* The Fazenda Colorado site, showing spatial associations and alignments between circular and quadrangular earthworks. Source: ESRI & Google Earth Imagery.

from 1215-1009 cal BC to 1218-1291 cal AD (Ua-37238 and Hela-616, respectively, calibrated at 2σ with the SHCal13 curve, Saunaluoma and Schaan 2012; Hogg et al. 2013), although there are significant gaps across the set, as well as occasional unresolved inversions in individual soil profile ages (Watling et al. 2017). Terrestrial palaeoecological records reveal an apparent absence of large-scale forest clearance in the landscapes around geometric earthworks throughout their entire period of use (Watling et al. 2017). Nonetheless, microbotanical data from archaeological contexts provide evidence for subsistence practices that employed both domesticated and wild food resources, in particular palm fruit and brazil nut, suggesting that a mixed system of managed agroforestry with cultigens existed in the past (Watling et al. 2015; Watling et al. 2018). Although circular and rectangular plans predominate among geometric earthworks, a variety of shapes have been reported, including polygons, ovals, and D- and U-shaped earthworks. Rarely, causeways or "avenues" connect earthworks, while the enclosures themselves can have single or multiple ditches and berms. Within this relatively restricted range of attributes, geometric earthworks nonetheless exhibit a high degree of formal variability in their architectural characteristics and configurations. In certain rare cases, earthworks were constructed either abutting or overlaying previous earthworks, possibly indicating the long-term use of particular places and parts of the landscape. Schaan (2012), in plotting the raw distribution of earthwork shapes and sizes, has suggested that these variables might encode cultural preferences or chronological trends.

Major advances in knowledge on the geometric earthworks have occurred in a relatively short span of time, speaking to a vigorous programmatic interest among scholars of Amazonian indigenous history. Extensive research across the southern rim of the basin has attested to other, occasionally contemporaneous, traditions of earthwork construction that performed a range of domestic, ceremonial, and subsistence roles for the societies that erected them (Denevan 1963; Arnold and Prettol 1988; Heckenberger 2005; Walker 2008; Erickson 2006; 2010; Lombardo and Prümers 2010; Carson et al. 2014; Prümers 2014; Prümers and Jaimes Betancourt 2014; De Souza et al. 2018). Archaeologists have also written extensively on the degree of social complexity among the populations involved in the construction of the geometric earthworks in the modern states of Acre, Rondônia, and Amazonas (Pärssinen et al. 2009; Schaan 2012; Saunaluoma and Schaan 2012; Saunaluoma 2012; Saunaluoma and Virtanen 2015; Saunaluoma et al. 2018; Watling et al. 2018). Taking a broad view of the above publications, certain commonalities emerge and can be summarised here briefly. First, sizeable populations, possibly totalling in the tens of thousands, are estimated to be responsible for the geometric earthworks. Concordantly, some degree of supra-local organisation may well be behind coordinating the number of people at, or close to, such an order of magnitude. The available archaeological data does not indicate the widespread or ubiquitous settlement nucleation, however, suggesting that settlement was dispersed over a relatively large area, or has at least left a less obtrusive archaeological signal (Saunaluoma et al. 2018). Political authority, as such, was likely to have been transient and derived from skilfully leveraging symbolic or ritual capital in the context of ceremonial performance associated to geometric earthworks.

Analyses of the broader landscape of geometric earthworks have proposed social processes behind their formation with direct reference to a model of organisational structure that underscores the potential interplay between hierarchy and heterarchy (Crumley 1979; 1995). The latter term implies power relations that are distributed, unranked, or marked in varying ways depending on the scale or frame of reference, emphasising the relational nature of authority derived through corporate mechanisms (Ashmore 2002; Morehart et al. 2018: 14; Furholt et al. 2019). The term is not construed as inimical or opposed to the existence of hierarchical, vertical, or ranked structures, which may co-exist or be negotiated alongside such lateral relationships (DeMarrais 2013). Indeed, the existence of multiple equivalently valued agencies or agendas in heterarchical configurations, and the societal tensions stemming from the resulting dynamics, is suggested as a major driver of social differentiation among humans (Furholt et al. 2019: 7). Prehistoric contexts across the globe provide examples for this pattern, and there are compelling empirical reasons to entertain the possibility of their existence in Amazonia too (Roosevelt 1999; Schaan 2012; Balée et al. 2014). Specifically, pre-Columbian communities are envisioned as nominally autonomous yet possessing internal social rankings that were occasionally brought to the fore. Materialised in Acre in the form of geometric earthworks, the interplay between distinctive types of organisation in the pre-Columbian period is cited as the dynamic that drove the formation of "complex" social formations (Schaan et al. 2010; Schaan 2012; Saunaluoma et al. 2018).

Formalising spatial relationships

Interpretative models of landscapes and land use provide a useful point of departure for developing the present spatial analytical approach toward geometric earthworks. This paper contends that directly investigating spatial structure at multiple scales may help elucidate the dynamics responsible for the formation of the archaeological landscape of Acre (Crumley 1979: 144). In particular, I draw on the suggestion that regional heterarchies are an inherently multiscalar, spatial phenomena (Crumley 1979, 1995; Ashmore 2002). Although formal tests of this assertion have been slow to materialise (Ashmore 2002: 1177; Smith and Schreiber 2005; Carballo et al. 2014), modern point process modelling offers the opportunity to test for the presence and type of spatial behaviour within a large sample of significant monumental sites (Baddeley and Turner 2005; Baddeley et al. 2016). The vast area and chronological span over which geometric earthworks occur pose a challenge to generalising as to their precise role among the pre-Columbian societies that constructed them. With the data currently available, we cannot at present preclude that both function and meaning also changed substantially over the two millennia or more of their existence. Multiscalar point pattern analysis has emerged as one of the solutions for direct analyses of the complexity of the archaeological record (Bevan et al. 2013; Eve and Crema 2014; Riris 2017; Dreslerová and Demján 2019). These methods offer an advantage over fixed-scale descriptive spatial statistics, such as nearest neighbour, which are easily confounded by the spatially variable nature of much archaeological data (Riris 2017; Carrero-Pazos et al. 2019). In another sense, computational modelling also offers the opportunity to test the myriad interpretations of the archaeological record. Here, incorporating a range of spatial effects and processes into formal models, including what are usually termed "first-order" (exogenously induced variables influencing the density of points) and "second-order" (the density of points as affected by the endogenous configurations of other points) effects, put these types of analyses on a robust footing for inferring socio-political dynamics. In particular, what was the spatial scale of integration among geometric earthwork building societies? To what extent does spatial structure index social structure? Is it possible to settle on just one scale, singular, or do patterns of import occur at multiple spatial scales? These questions reflect notable gaps in knowledge on the presence and strength of spatial relationships between geometric earthworks, which this paper will attempt to address employing a formal modelling approach.

Archaeologists observe marked consistencies among the settings of geometric earthworks (Schaan et al. 2010; Schaan 2012; Saunaluoma et al. 2018). Even a cursory look at the overall distribution indicates that geometric earthworks are far from randomly distributed (**Fig. 1**). To briefly summarise the locational characteristics that appear repeatedly and consistently across the abovementioned literature: geometric earthworks are typically located at elevation within the overall gently rolling topography of the Purús and Acre interfluves. Moreover, their placement also tends to be on prominent bluffs relative to their surroundings, as opposed to simply at altitude in absolute terms. Finally, while water availability is not typically thought to be a factor despite the seasonally dry (monsoonal) climate of the region, proximity to large, perennial watercourses, as potential arteries of communication and transport, likely exert some influence on the placement of these sites. Next, and temporarily leaving the landscape to one side, a closer look at the locations of geometric earthworks alone may indicate that they form clusters separated by relatively short (~5 km or less) or alternatively at much longer ranges (>10 km) too. In other words, monument locations may also depend in some way on the locations of others. Notably, Schaan (2012: 154-155) explicitly connects site size to labour mobilisation and suggests the existence of territorial interaction between clusters at a regional scale, centred on the locations of the largest of geometric earthworks. In this sense, and with reference to the inferred presence of complex heterarchical organisation here, spatial distributions have long been interpreted as indexing social relations.

A principal strength of the method developed and applied here is the explicit recognition that the factors that drive spatial phenomena (here, monument location) can also vary spatially. A basic inspection of geometric earthworks distributed within Acre indicates that, like many empirical point patterns, spatial inhomogeneity cannot be ruled out (**Fig. 1**). Previous locational models employing similar data have largely employed methods that assume a homogeneous point pattern intensity (McMichael et al. 2014a; 2014b; De Souza et al. 2018). This paper attempts to remedy this by examining the variability in spatial patterning (inhomogeneous dispersion and/or aggregation) at multiple scales simultaneously, while controlling for both induced effects and between-point interaction. This advance in method bridges the correlative (first-order) and relational (second-order) spatial properties of the archaeological record, which are frequently key factors in data that is fundamentally human in nature.

In summary, this paper uses point process modelling to explicitly control for the effects of external variables on the distribution of geometric earthworks, which are drawn from the literature. The approach also introduces a second-order (inter-site) interaction term, which together with the initial model successfully describes the majority of spatial structure among the geometric earthworks of Acre. Together, this multivariate model evaluates the relative influence of concurrent spatial phenomena on the distribution of geometric earthworks in a robust statistical framework. Additional tests on the fitted models reveal a statistically significant clustering threshold, identifying empirically-supported groups of sites in the process. A Monte Carlo test of the distribution of geometric earthwork sizes within and between these groups (Carrero-Pazos et al. 2019) is adapted to investigate if intra-cluster site hierarchies are present. Summarising, based on present information, the model-testing approach indicates that the populations responsible for the creation of geometric earthworks in western Amazonia are highly unlikely to have been hierarchically organised either at a regional scale, or within groups of sites.

2. Materials and Methods

This study focuses primarily on pre-Columbian geometric earthworks in Acre state, Brazil, the core area reported in the literature (Schaan 2012; Saunaluoma and Virtanen 2015; Watling et al. 2018). Hereafter, all references to earthworks refer to geometric earthworks located in Acre unless otherwise noted. The reported locations of archaeological sites were gathered through a literature survey, which formed the initial dataset. All earthwork locations were also cross-referenced with public domain satellite imagery available through the ESRI ArcGIS Online platform and Google Earth. Following analytical and interpretative precedent by Schaan (2012), earthwork surface area was directly estimated from the available imagery in the course of data collection. Surface area was consistently measured from the outer perimeter of earthwork banks or berms and the area enclosed by ditches therefore contributes to the total. In rare cases where multiple enclosures are connected through 'avenues', and sequences of construction cannot be discerned, their combined area is reported. Furthermore, for the handful of earthworks (<5) that *directly* abut or overlay each other, and where the sequence of construction cannot be discerned from remotely sensed imagery alone, their location is reported as a single centroid of the combined outlines. Other aspects of geometric earthwork monumentality, such as berm height and ditch depth or indices of architectural complexity, may conceivably be relevant to understanding the energetics and relative configuration of the archaeological landscape of Acre. In this paper, I limit analysis to area enclosed as a first order approximation of earthwork size as a possible index of elaboration (Schaan 2012).

Data collection resulted in a total of 420 point locations that could be derived directly from published maps, with associated information. The majority of earthworks (n = 312) lie within the state of Acre, where agribusiness-led deforestation, centred on the town of Rio Branco, is most extensive. The remaining 108 earthworks were encountered in Rondônia and Amazonas states. Absent widely available canopy-penetrating remote sensing technology (Prümers and Jaimes Betancourt 2014), it must be cautioned that the representativity of the sample is essentially dictated by the extent of deforestation. As this process is decidedly more advanced in Acre compared to neighbouring states, the data affords improved control and explanatory power over the areas of Amazonas and Rondônia where forest removal is less complete. To avoid spurious results due to uneven sampling, this study is restricted to the area formed by the convex hull of earthworks within Acre, buffered by 3 km to mitigate edge effects. This approach withholds sites located in Rondônia and Amazonas from the study, pending verification of the extent to which this subset of western Amazonian earthworks is representative of a broader pattern beyond Acre.

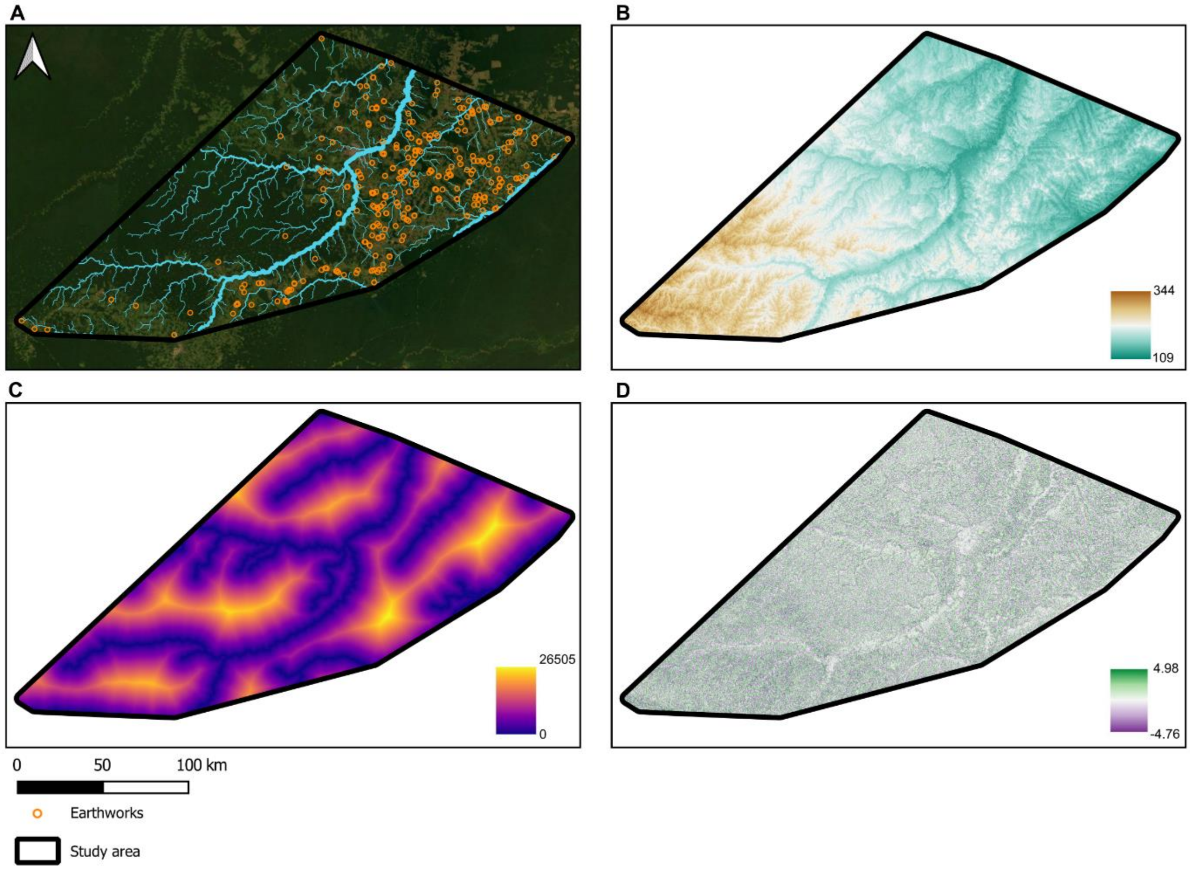

Fig. 2: Earthwork distribution and covariate data. *A:* Earthwork locations within the study area overlaid on satellite imagery, *B:* elevation raster (metres above sea level) derived from SRTM data, *C:* Euclidean distance (metres) from permanent watercourses, *D:* topographical position index (TPI, dimensionless).

As noted, point pattern analysis distinguishes primarily between first- and second-order spatial trends, that is, structure induced by external processes, and the degree of attraction or repulsion between points within a pattern (Diggle 2013). Bearing in mind the abovementioned explanatory frameworks for the distribution of Amazonian earthworks, this paper leverages modern spatial statistics and point process modelling to evaluate the degree to which archaeological patterns might be influenced by both induced *and* internal spatial structure concurrently. The principal findings are briefly summarised here, and the procedure is fully described in the accompanying code (**Supplementary Information**). Employing archaeological interpretations as a point of departure, the approach initially builds a model to control for the presence and strength of first-order spatial trends among Amazonian geometric earthworks. Next, a second-order interaction term is incorporated to account for spatial interaction not explained by the null and baseline first-order models. The results and insight gained from the modelling exercise detailed below reveals yet further statistically significant spatial structure that neither model fully accounts for, individually or in tandem. Based on these findings, a combination of machine learning algorithms (Ester et al. 1996) and additional spatial statistical analysis integrating earthwork attribute data (Carrero-Pazos et al. 2019), yields robust estimates for possible western Amazonian territorial units. Moreover, this procedure conservatively identifies zones where archaeological data is presently lacking enough detail to make confident inferences, in particular where sites are exceptionally sparse.

Fitting covariate spatial data

The covariate spatial data (**Fig. 2**) are consistently highlighted in the archaeological literature as relevant to understanding geometric earthwork distributions across Acre (Schaan et al. 2010; Schaan 2012; Saunaluoma et al. 2018). Here, I assess the interplay and relative influence, if any, of each dataset. First, a multicollinearity test with Pearson's R reveals that there are no collinear effects between the datasets, indicating that they are suitable as independent model terms. Next, the observed point pattern of geometric earthworks is fitted to a Poisson point process model, equivalent to an initial null hypothesis of complete spatial randomness (CSR). At the same, using the Bayesian Information Criterion (BIC) as a guideline for information gain per added model term, a stepwise model selection procedure rejects none of the covariates in isolation or in combination. The BIC suggests that a combination of all three covariates provides the best starting point for modelling earthwork locations. Together, elevation, topographical prominence, distance from water, and the assumed Poisson process comprise the multivariate first-order model. The spatial intensity (density) of archaeological sites in Acre, as described by the interaction of these parameters, is a function of their combined maximum logistic likelihood. Third, to evaluate the possible effects of interaction at a landscape level between earthworks, a second-order term is incorporated into the fitted first-order model to generate a combined model. Such a model statistically accounts for induced and internal spatial dynamics simultaneously. Here, following precedent for handling archaeological data in this manner (Bevan et al. 2013), the area-interaction point process model is advanced to replace CSR as the null and to capture the range of observed variability in the empirical point pattern. Area-interaction is attractive due to its relative flexibility, generality, and lack of complex free parameters. Alternatives such as the Hard Core, Matérn cluster, or Thomas process describe processes that presume rather more about the formation of geometric earthwork distributions than is presently known (Baddeley and Turner 2005). To obtain the best fit for the second-order term, the joint probability distribution is estimated by log pseudolikelihood.

Finally, the goodness-of-fit of each of the three models is assessed comparatively employing the pair correlation function. This statistic has some especial advantages in the context of the goals of this study. For fitted models and point patterns, the statistic estimates the presence and degree of spatial clustering and repulsion at multiple scales within the window of observation. Unlike the classic Ripley's *K* statistic, which employs discs to count and measure spatial structure, the pair correlation function employs rings with outer and inner boundaries. Consequently, patterning at different scales is more easily discerned visually (Stoyan and Stoyan 1994; Baddeley et al. 2016). The fact that the function does not accumulate also provides a more intuitive result (Wiegand and Moloney 2004: 225; Jacquemyn et al: 2007, 451). Rather than the more common spatially uniform version of this statistic, the *inhomogeneous* variant used here accounts for differences in the density of the point pattern across the study. In other words, it assumes that the point pattern has an underlying spatial trend. Density-dependent variation is a well-known quality of earthwork locations (Schaan 2012; Saunaluoma et al. 2018) and controlling for this source of spatial structure can be considered an initial step in uncovering the possible drivers of the formation of the archaeological record.

To illustrate the critical scales where geometric earthworks attract or inhibit one another, significance bands are derived via Monte Carlo simulations of point patterns drawn from the null (random), first-, and second order models. Envelopes are generated by simulating 999 point patterns for each application of the pair-correlation function to the fitted models (Baddeley and Turner 2005; Jacquemyn et al. 2007: 451). Rather than expressing confidence to a chosen level (e.g. 95%), they estimate the likelihood of incorrectly rejecting the null hypothesis of no spatial structure as a function of the number of simulated runs. For the envelopes generated here, this value (α) corresponds to 0.002, which can be considered highly robust for the purposes of the modelling exercise. It must be acknowledged that the null model of complete spatial randomness (CSR) is unlikely to adequately reflect the empirical data, but it is nonetheless presented for completeness. As described above, the first-order model also assumes an underlying Poisson distribution, while the second-order model replaces this with an Area Interaction term. The workflow is fully implemented as R code in the supplementary information, with accompanying archaeological data, and draws extensively on functions in the package 'spatstat' version 1.60-1 (Baddeley and Turner 2005).

3. Spatial point process modelling

Spatial structure between geometric earthworks is well-illustrated by the initial application of the pair correlation function to the point pattern (**Fig. 3, top left**). Attending to the first maximum and minimum outside the simulation envelope, these values correspond to the typical range at which points are most strongly attracted or repelled by one another, respectively (Strand et al. 2007). For Acre earthworks, this occurs below 500 m for clustering and at approximately 13000 m for dispersion, with the observed value falling just outside the envelope

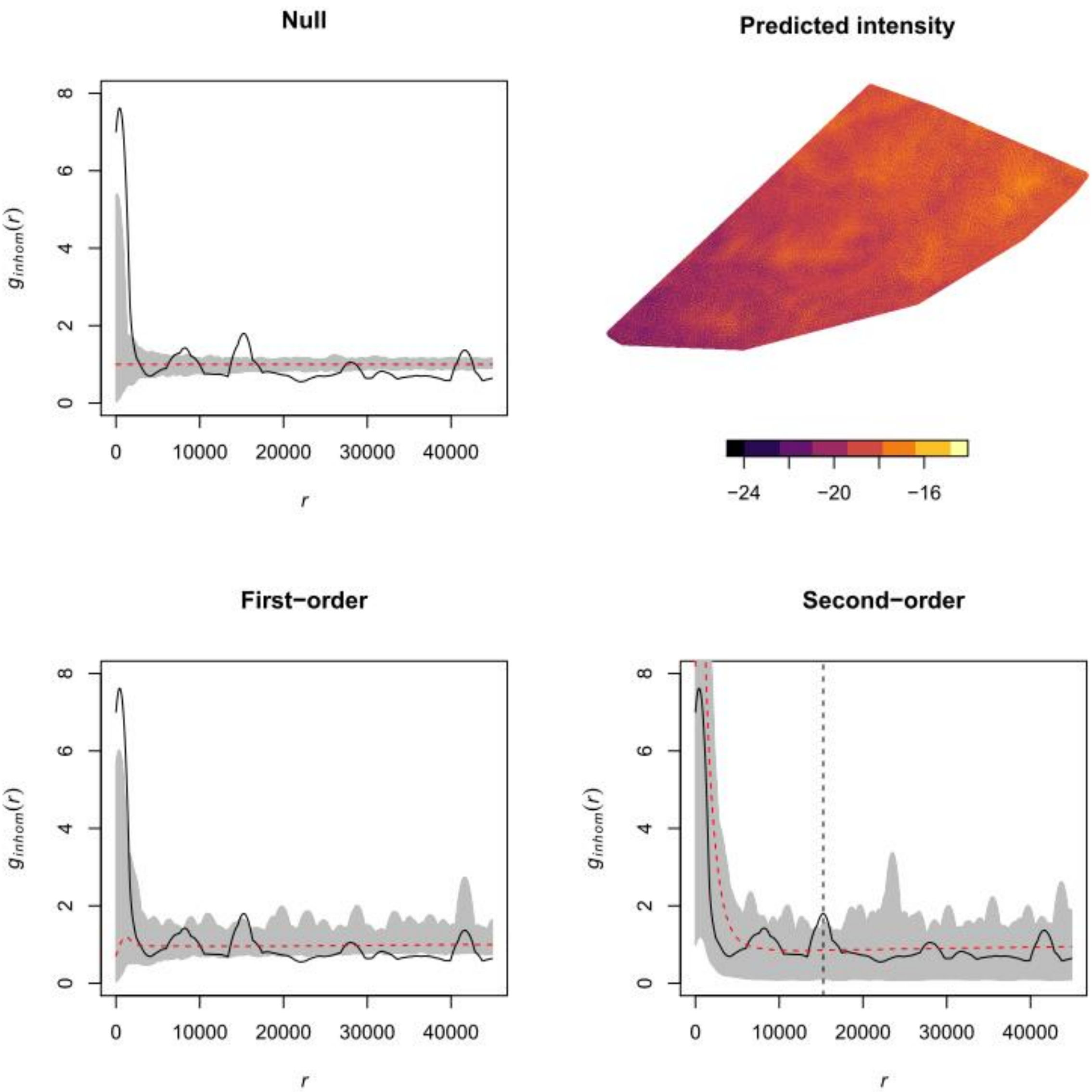

Fig. 3: Results of point process modelling. *Null*: The pair correlation function estimated on an assumption of complete spatial randomness, illustrating statistically significant clustering and repulsion that alternate at varying ranges (x-axes in metres). *Predicted intensity*: log-odds prediction surface of earthworks based on elevation, distance from major watercourses, and topographical prominence. *First-order*: the pair correlation function with a critical envelope conditioned on the covariate data as first-order variables, accounting for a greater range of spatial variability. *Second-order*: the final model, incorporating a point interaction term in the first-order model, accounting for all spatial variability except significant clustering at $r \approx 15000$ m (vertical line). Y-axes have been rescaled to a common range.

at this range. This initial finding suggests a variety of spatial processes may be at play, inducing strong short-range clustering and somewhat weaker longer-range repulsion between earthworks. Without further supporting information, such as fitted covariate data or point process models beyond the null expectation of CSR, it must be underscored that this baseline assessment lacks sufficient context to adequately explore the implications of these findings in further detail. The analysis now turns to fitting the point pattern to covariate datasets derived from close readings of the archaeological literature.

First-order model

The first-order model (**Fig. 3, bottom left**) provides a much improved fit over the CSR null model, controlling for most of the weaker signals of spatial autocorrelation at all ranges from >40 km to below 10 km. All three covariate datasets (**Table 1**) were found to be highly significant. Nonetheless, the strong patterns of short-range clustering and long-range repulsion of earthworks (beyond ~22 km) persist in this iteration. The predicted intensity (log-odds of points per unit of area) from this model (**Fig. 3, top right**) provides an illustrative summary of the degree to which this model explains spatial structure among geometric earthworks. Although clearly spatially variable (inhomogeneous), the predicted spatial trend is weak, with few zones showing values at the high end of the scale. Consequently, in agreement with the results of the pair correlation function, the fitted first-order model indicates that a relatively large proportion of spatial variation remains unaccounted for, in spite of the overall improved fit. Rather than risk overfitting this model with covariate data beyond what is supported by archaeological inference, the next step directly incorporates a model term to control for between-point interaction, noting the exceptionally strong clustering found at ~450 m and below.

Table 1: Fitted covariate datasets for the first-order model.

Covariates	Estimate	Standard error	Z value	Significant
(Intercept)	-15.6934100	0.408140	-38.4511	***
Elevation	-0.0183163	0.002307	-7.93976	***
Topographical prominence	0.9620874	0.085621	11.23655	***
Distance to watercourses	0.0000689	0.000011	6.341012	***

Second-order model

The area-interaction process, as outlined above, is fitted by maximising the profile information entropy with respect to a series of fixed spatial interaction distances (Baddeley and van Lieshout 1995; Baddeley et al. 2016). The analysis is permuted in 100-metre intervals from 100 m to 2500 m to produce 25 candidate models, rather than impose a single arbitrary interaction value. According to Akaike's Information Criterion, this procedure provides a best fit for the area interaction parameter at r = 2100 meters. The second model also incorporates the first-order model as a trend parameter. This combined first- and second-order model thus successfully controls for both exogenous and endogenous processes within the point pattern of geometric earthworks. Conditioning the simulation envelope for the pair correlation function on the combined null model (**Fig. 3,** bottom right) illustrates the effect of incorporating between-point interaction. The results reveal most variability in spatial structure among geometric earthworks can be explained by controlling for these factors. While models with a better goodness-of-fit could be derived from alternative readings of the archaeological record, the data is nonetheless satisfactorily explained by the combined model. The model terms are derived from close readings of the archaeological record, which reduces need to develop a more complex model that risks overfitting against the data.

A notable exception of spatial structure for which the combined model does not account is the presence of statistically significant clustering in the range ~14500 – 15900 at a significance level of 0.002 (above), with a local maximum at r = 15264 m. This indicates spatial patterning among geometric earthworks that may be particularly relevant for understanding distributional trends of broader importance among the earthworks analysed here and, ultimately, the decision-making processes that led to the formation of the archaeological landscape of Acre. This information is now used to draw further inferences on landscape-level patterns among geometric earthworks through further tests of their properties and configurations.

4. Geometric earthwork clusters and size ranking

Building a point process model of earthworks in Acre has proven informative in several regards. First, interpretations of their locational properties, expressed informally by archaeologists, have been statistically expressed and validated. The importance of this should not be understated. Drawing reliable conclusions as to the structure, formational processes, and wider distributional patterns of geometric earthworks is key to building robust models of pre-Columbian social organisation and going beyond the plain-language explanations typically favoured by archaeologists. Additionally, while first-order factors do not explain the structure of the archaeological point pattern on their own, the incorporation of a term to directly address point interaction both provides a model with a good fit for the majority of the variability in the Acre earthworks, and also hints towards resolving an elusive property of these structures. Specifically, this discussion now draws attention to the spatial scale at which patterning among geometric earthworks manifests most strongly (**Fig. 3, bottom right**). What might this imply for the organisation and landscape-level structure of pre-Columbian societies in Acre and western Amazonia more broadly?

This question is far from trivial, since direct connections have been drawn between the level of regional integration, anthropic landscape history, and the size and elaboration of geometric earthworks (Saunaluoma et al. 2018; Watling et al. 2018). A salient point first underlined by Schaan (2012: 154-155) is that the distribution of the largest earthworks may reflect some aspect of locally marked hierarchies, which interacted at a regional scale through horizontal power relations. The knowledge gained from the point process modelling can be incorporated into further exploratory analyses to this end. In summary: the results demonstrate that significant spatial autocorrelation exists between earthworks in intervals of approximately ~15 km, or more precisely, a neighbourhood radius of around 7.5 km (7632 m, to be exact; **Fig. 3D**).

Using the neighbourhood radius as a distance threshold (ε) in DBSCAN (Density-Based Spatial Clustering of Applications with Noise; see Ester et al. 1996), a data-clustering algorithm particularly suited to point patterns of arbitrary shape and density, groupings of earthworks should emerge that reflect archaeologically meaningful units. Minimum group size is somewhat arbitrarily set at three earthworks, a value that conservatively excludes most sites that are located close to the edges of forest clearances (**Fig. 2A**). This minimum group size threshold approximates a subset of earthworks on the study area boundaries that lack sufficient context for robust interpretations for the time being. Undoubtedly there are more earthworks waiting to be uncovered under the canopy. Finally, potential variation in group membership was also considered by permuting the DBSCAN algorithm through the range of statistically significant clustering (14500 – 15900 m in 100-metre intervals, **Fig. 3D**). This procedure (**Supplementary Fig. 1**) illustrates that varying ε primarily alters the relative proportion of "noisy" points with no group. While total number of groups varies between 17 and 21, most shifts in membership occur overwhelmingly among the smallest permissible groups (3 earthworks), which either “become noisy” or join larger groups as the distance threshold decreases or increases, respectively. Most of the groups detected by the algorithm are robust across thresholds and do not have large alterations to their membership.

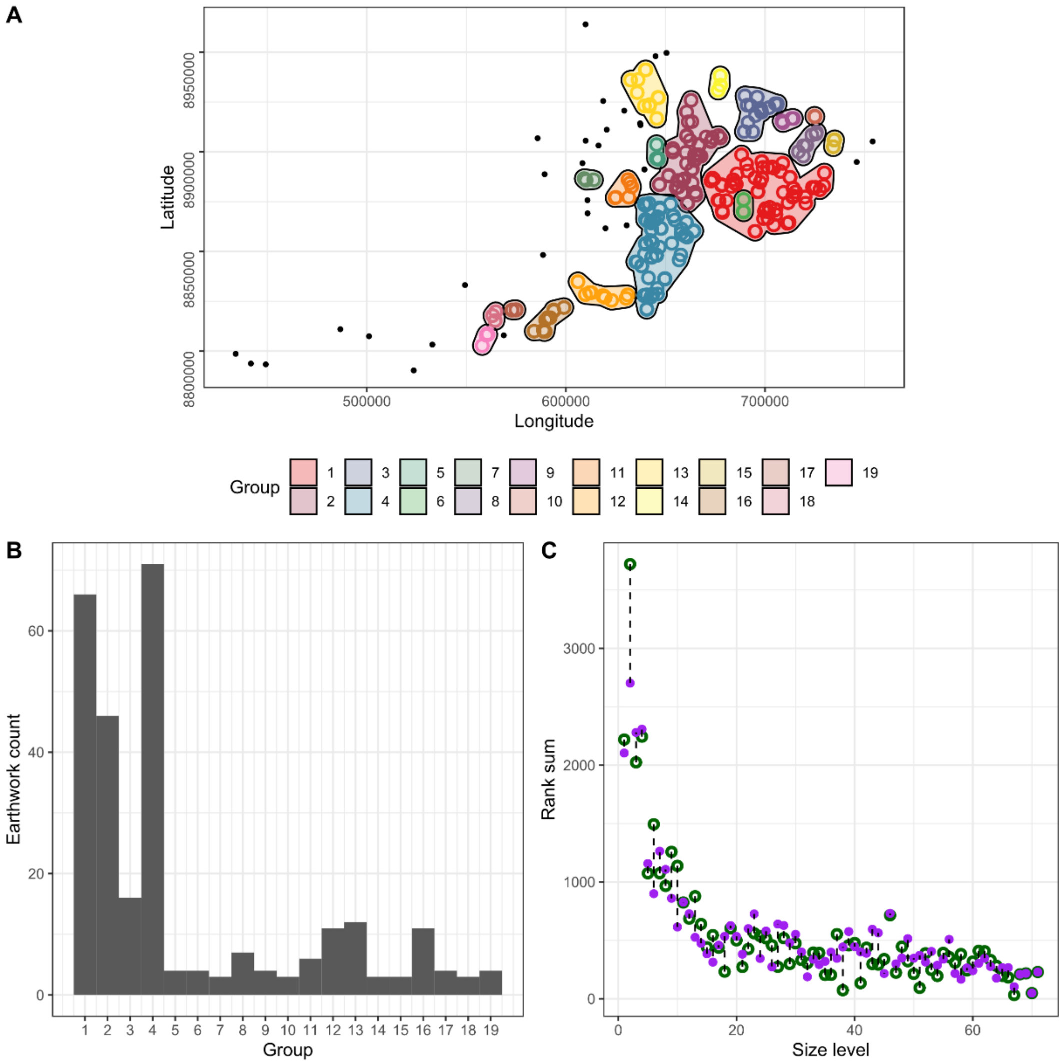

Fig. 4: Non-hierarchical organisation of Amazonian geometric earthworks. *A:* The DBSCAN algorithm defines 19 discrete clusters, highlighted with their convex hulls, with clusters defined at a threshold of ε = 7632 metres. Convex hulls do not imply territorial extent, but are presented as a visual aid. Non-clustered points are represented as black dots. *B:* Count of earthworks by group, *minimum group size* = 3. *C:* Differences in rank sums of site area between an ideal hierarchy (green) and the observed distribution (purple) given the same number of earthworks and groups. Further permutation testing indicates that these differences are overwhelmingly likely due to chance rather than within-group hierarchies.

The 19 clusters defined among the earthworks at the strongest clustering threshold is shown in **Fig. 4A**. The groups vary substantially in size from 71 earthworks, enclosing a total of 94.48 ha, to the minimum of three individual sites. The resulting output is visually intuitive, in the sense that borders between clusters are readily apparent, as well as between the outliers. Groups

1, 2, and 4 clearly dominate the clusters in terms of sheer numbers, presenting a relatively skewed distribution (**Fig. 4B**) with a few large groups and many smaller ones. Group 1 wholly surrounds the much smaller Group 6. Nonetheless, the meaningful clusters generated by combining the point process model with DBSCAN, though having highly uneven membership, do not directly inform on whether relative rankings exist within them. Bearing in mind the role of earthwork size in indexing relative site importance (Schaan 2012), if this attribute is a possible marker of hierarchical social relations and community structure, the groupings detected here may provide a useful point of departure for further analyses. To help approximate a solution, the final part of this paper adapts a permutation test developed by Carrero-Pazos et al. (2019) to examine if earthwork area is distributed more unevenly than would be expected by random chance both between and within groups/clusters.

In outline (Carrero-Pazos et al. 2019: 6-7), the method orders all earthworks by size and creates a ranking of site sizes *within* each group: the largest site in each cluster is graded 1, the second largest is graded 2, and so on. The sum of *observed* grades by group is compared to the sum of the *ideal* distribution of grades if a perfect site hierarchy were present, given the same number of ranks. Consistently ideal size distributions within groups are expected to represent internally ranked social formations. Here, the number of grades is 71, corresponding to the group size of the largest group. **Fig. 4C** demonstrates that observed rankings overall tend to deviate from the ideal rankings. Notably, size grades 1 and 2 (the largest earthworks, thought to be dominant with each group) lie well below the rank sum that would be expected if a strong hierarchy of sites were present within the groups of earthworks. Below the largest size grades, however, the rank sums tend to exceed the expectations of the ideal ranking, suggesting that small-to-medium earthworks are over-represented relative to the large or exceptionally large earthworks in the sample. Initially, at least, an internal hierarchy of monuments is counter-indicated by this test. In other words, if the clusters of geometric earthworks can be interpreted as reflecting community organisation, it does not at present seem probable that they were strongly stratified.

To establish whether the differences between observation and expectation are greater than could occur chance, the size grades can be randomly shuffled independent of group membership. This is performed 999 times. The observed ranking can then be compared to the simulated shuffled rankings, with an associated *p*-value. This procedure indicates that at almost every grade, the distribution of earthwork sizes in the 19 groups (**Fig. 4A**) cannot be distinguished from the null hypothesis of no internal rankings (**Supplementary Table 1**). Two exceptions are at rank 10 and 32, which return a result significant to $p < 0.05$, but no lower. The implication of this specific finding is not straightforward to interpret. The high *p*-values suggest this is an artefact of the underlying data, particularly in the latter case, as only three groups contain 32 earthworks or more. Overall, it can be suggested that the earthwork groups defined through point pattern analysis are far from hierarchically distributed in terms of their size. While the construction of *individual* earthworks may have been guided by people with the knowledge or authority to do so, there is little evidence at present that centralised control structured the monumental landscape of Acre, either between or within clusters, over time. This has broad-ranging implications for interpreting the formation of this archaeological landscape.

5. The structure and organisation of geometric earthworks

Pärssinen et al. (2009) cautioned a decade ago that archaeologists are only just beginning to understand the earthwork builders of the Amazon, and at the time estimated that no more than 10% of all sites in the western Amazon had been documented. Far fewer have ever been visited by an archaeologist. Findings such as those presented here are therefore understood to be subject to testing with field data. The approach is deliberately couched in the language of probability, examining problems in Amazonian archaeology in the light of a formalised model-testing approach. This paper has demonstrated that archaeological hypotheses on geometric earthworks are informative and appropriate for direct statistical scrutiny, an increasingly prominent practice in the humanities more broadly (Epstein 2006; Kohler and Van der Leeuw 2007) and in landscape archaeology specifically (Bevan et al. 2013). This procedure estimated the relative importance of known variables and detected conditions under which they do not apply, which were controlled for through further testing. Bearing in mind our nascent understanding of western Amazonian societies, the methods provide a rigorous point of departure for extensions and alternative approaches in future work. Social dynamics, whether vertical or horizontal, may be theorised on extensively, but ultimately must be subjected to rigorous scrutiny if they are to improve our understanding of the past (Smith and Schrieber 2005: 205).

In this regard, 'complexity' in the abstract is frequently invoked to frame the emergence and endurance of earthwork building as a cultural practice across the Neotropics (Roosevelt 1999; Stahl 2002; Balée and Erickson 2006; Heckenberger and Neves 2009; De Souza et al. 2018), however, operationalising a common definition and testing it in formal, comparative terms has been less forthcoming (Smith and Schreiber 2005). Reflecting on this broader issue of model testing in lowland South America, this paper has argued that archaeological accounts of human-environmental relations would benefit from the systematic application of computational methods. The approach advocated here is not antithetical to frameworks that emphasise the dynamics of social behaviour or political organisation, but build usefully upon existing hypothesis with complementary, probabilistic analytical tools. Point process modelling enables multiple effects to be directly integrated in explanatory frameworks (McMichael et al. 2014a; 2014b). Statistically informative gains were achieved through a synthesis of model terms that encapsulated both first- and second-order interaction within the material record. The former class of effects collectively reflected consistent elements of geometric earthwork configurations in relation to the landscape, while the latter stood in as a proxy for potential social processes guiding the placement of these monuments in relation to one another. Achieving a multifactorial fit to data in this manner demonstrates that archaeological models expressed in plain language are tractable to robust statistical analysis. Formal simulation-based models of complex archaeological realities are useful in drawing out salient elements of the material record at the landscape scale (Wobst 1974; Lake 2015), and ought to be standard. This paper provides a point of departure for further advances in point process modelling (**Supplementary Information**), for example of other traditions of earthwork building among the indigenous societies of pre-Columbian South America (Arnold and Prettol 1988; Heckenberger et al. 1999; Roosevelt 1999; Prümers et al. 2006; Walker 2008; Lombardo and Prümers 2010; Prümers 2014; De Souza et al. 2018).

Although it appears unlikely that time-transgressive or ascribed political status was a factor in behind the construction of geometric earthworks, their distribution and groupings may instead reflect other aspects of society in the pre-Columbian period, as well as biogeographical factors (McMichael et al. 2014a; Watling et al. 2017). Bearing in mind the link that has repeatedly been made between labour mobilisation and earthwork size, it can be tentatively suggested that a demographic dimension to their distribution and degree of elaboration may exist. As noted in the introduction, the period of geometric earthwork construction spans some two millennia. If a certain degree of population fluctuation is assumed over such a lengthy time span, the interplay between population growth and contraction would suggest, in theory, that the presence of larger sites simply reflects there being more people to mobilise at a given point in time, and smaller sites the reverse. On the other hand, Saunaluoma and Virtanen (2015: 36) do not believe there is an association between increased geometric earthwork elaboration and the advance of time. This link therefore remains somewhat conjectural, and its confirmation or rejection ought to rest on far more extensive sampling of radiocarbon data from both monumental sites and the few settlement sites that are known in the western Amazon. Future investigations may also benefit from direct estimates of other geometric earthwork parameters, such as the energetics involved in construction: berm height, ditch depth, total volume of soil movement, and/or new indices of architectural complexity. Such variables, should they be collected, could prove informative in renewed modelling efforts and permutation testing. Additionally, the acquisition of high-resolution chronometric data would enable spatio-temporal point process models to be fitted to archaeological patterns, turning the type of analysis developed here from synchronic to diachronic (Baddeley and Turner 2005). Extensions of the pair-correlation function that test for patterning among categorical subsets of points, usually termed bi- or multi-variate spatial statistics would directly address phenomena such as the reported cline in geometric earthwork morphology identified by Schaan (2012) along a north-south axis.

Returning to the present research: the combined model highlighted hereto-unrecognised spatial structure among geometric earthworks in Acre. Further examination of these patterns with the simulation and permutation testing enabled specific inferences on the types of societies that likely lived in this part of western Amazonia during the Late Holocene. Second, in a broader methodological and theoretical scope, the analysis provided valuable insight into the development of spatial analytical approaches in indigenous Amazonian contexts. The basic null model (**Fig. 3**) illustrates that statistically significant clustering *and* dispersion occurs between geometric earthworks at a variety of ranges. Furthermore, the additional controls on the observed pattern (**Fig. 2**, **Table 1**) produced major insights into where the significant, "extraordinary" patterns are in the data. Armed with this knowledge, we can affirm that analysis at arbitrary spatial scales would fail to capture the diversity of the archaeological point pattern. The results make it clear that fixed-scale summary statistics under a null assumption of spatial homogeneity will not succeed in adequately describing data that are spatial palimpsests (Davies et al. 2016). With reference to the study of "complexity", a pervasive rhetorical device in the archaeology of the Amazon basin, there are clear benefits to using analytical strategies that can detect and account for non-linear interactions of this nature at multiple spatial scales.

On one level, the findings presented here suggest that stratified or ranked societies are unlikely to have been behind the construction of groups of geometric earthworks in western Amazonia.

Patterning within groups, whose definition is derived through robust inference, is more evocative of non-hierarchical societies. It follows that interactions *between* groups of earthwork-builders may have transiently expressed localised authority, materialised through place-making practices in the form of geometric earthworks (Saunaluoma and Virtanen 2015). Emergent forms of political control, in Acre as in many places in the world, were likely historically variable and actively negotiated (Furholt et al. 2019). Ultimately, however, the establishment of such relationships were not necessarily leveraged to form time-transgressive, top-down political control over extended social groups. This accords with theory (Crumley 1979, 1995) and the archaeological record of Acre, which has thus far not produced evidence typically associated with assigned social rank, such as structured access to resources, elite burials, or as established here, a clear site hierarchy. Tentatively, an absence of centralised control at any scale may also explain the diversity of geometric earthwork shapes, degree of elaboration (Saunaluoma et al. 2018), and probably cluster size too. Anthropic changes to vegetation community structure are evident at a landscape level in Acre since at least 4000 cal BP, with major alterations to the relative abundance of comestible and economically useful species (Watling et al. 2017, 2018). Without falling into unhelpful dichotomies between intentional niche construction versus accidental forest enrichment, I note that evidence for systematic, coordinated efforts at environmental modification is also lacking in Acre (McMichael et al. 2012; Watling et al. 2017). This contrasts with neighbouring regions of Amazonia, where both social stratification and large-scale labour coordination are reported in association (Erickson 2006; Lombardo and Prümers 2010; Prümers and Jaimes Betancourt 2014). Despite the relative geographic proximity of geometric earthworks to other, diverse earthmoving cultures of the Llanos de Moxos, their different organisational trajectories caution against over-generalising the drivers and mechanisms behind the formation of extensive pre-Columbian built environments without accounting for local trajectories first. In closing, the observed diversity in their configurations and spatial structure likely possesses a chronological element, as well as cultural and possibly demographic dimensions. These issues, highlighted by the fitted point process models presented here, can only be resolved through further excavation and recovery of data on their life histories.

Acknowledgements

I gratefully acknowledge the helpful input from colleagues during the development of this research, in particular Adrian Baddeley and Miguel Carrero-Pazos. Fabio Silva also provided useful feedback. This research was funded by a British Academy Postdoctoral Fellowship

(PF2\180065). The analyses presented in this paper were carried out in QGIS 3.8, ArcGIS 10.5, and the R statistical modelling environment version 3.60, in particular the package ‘spatstat’ version 1.60-1. Three reviewers provided welcome critical feedback on two versions of the manuscript.

Bibliography

Arnold, D.E., Prettol, K.A. 1988. Field Reports: Aboriginal Earthworks near the Mouth of the Beni, Bolivia. *Journal of Field Archaeology* 15: 457-465

Ashmore, W. 2002. “Decisions and Dispositions”: Socializing Spatial Archaeology. *American Anthropologist* 104: 1172-1183.

Baddeley, A., Van Lieshout, M.N.M., 1995. Area-Interaction point processes. *Annals of the Institute of Statistical Mathematics*. 47: 601–619.

Baddeley, A., Turner, R. 2005. spatstat: An R Package for Analyzing Spatial Point Patterns. *Journal of Statistical Software* 12: 1-42. http://www.jstatsoft.org/v12/i06/.

Baddeley, A., Møller, J., Waagepetersen, R. 2000. Non-and semi-parametric estimation of interaction in inhomogeneous point patterns. *Statistica Neerlandica* 54: 329–350.

Baddeley, A., Rubak, E., Turner, R., 2016. *Spatial Point Patterns: Methodology and Applications with R*. London: CRC Press.

Balée W., Erickson C.L. (eds.) 2006. *Time and Complexity in Historical Ecology: Studies from the Neotropical Lowlands*. New York: Columbia University Press.

Baleé, W., Schaan, D.P., Whitaker, J.A., Holanda, R. 2014. Florestas Antrópicas no Acre: Inventário florestal no geoglifo Três Vertentes, Acrelândia. *Amazônica – Revista de Antropología* 6: 140-169.

Bevan, A., Crema, E., Li, X., Palmisano, A. 2013. Intensities, interactions and uncertainties: some new approaches to archaeological distributions. In: Bevan, A., Lake, M. (eds.), *Computational Approaches to Archaeological Spaces.* Walnut Creek: Left Coast Press. 27–52.

Carballo, D.M., Roscoe, P., Feinman, G.M. 2014. Cooperative and Collective Action in the Cultural Evolution of Complex Societies. *Journal of Archaeological Method and Theory* 21: 98-133.

Carrero-Pazos, M., Bevan, A., Lake, M.W. 2019. The spatial structure of Galician megalithic landscapes (NW Iberia): A case study from the Monte Penide region. *Journal of Archaeological Science* 108: 104968.

Carson, J.F., Whitney, B.S., Mayle, F.E., Iriarte, J., Prümers, H., Soto, J.D., Watling, J. 2014. Environmental impact of geometric earthwork construction in pre-Columbian Amazonia. *PNAS* 111: 10497-10502.

Crumley, C.L. 1979. Three Locational Models: An Epistemological Assessment for Anthropology and Archaeology. *Advances in Archaeological Method and Theory* 2: 141-173.

Crumley, C.L. 1995. Heterarchy and the Analysis of Complex Societies. In: R.M. Ehrenreich, C.L. Crumley, J.E. Levy. (eds.), *Heterarchy and the Analysis of Complex Societies*. Anthropological Papers of the American Anthropological Association.

Davies, B., Holdaway, S.J. and Fanning, P.C. 2016. Modelling the palimpsest: an exploratory agent-based model of surface archaeological deposit formation in a fluvial arid Australian landscape. *The Holocene* 26: 450-463.

DeMarrais, E. 2013. Understanding Heterarchy: Crafting and Social Projects in Pre-Hispanic Northwest Argentina. *Cambridge Archaeological Journal* 23: 345-362.

Denevan, W.M. 1963. Additional Comments on the Earthworks of Mojos in Northeastern Bolivia. *American Antiquity* 28: 540-545.

Denevan, W.M. 1996. A Bluff Model of Riverine Settlement in Prehistoric Amazonia. *Annals of the Association of American Geographers* 86: 654-681.

de Souza, J.G., Schaan, D.P., Robinson, M., Barbosa, A.D., Aragão, L.E., Marimon Jr, B.H., Marimon, B.S., da Silva, I.B., Khan, S.S., Nakahara, F.R., Iriarte, J. 2018. Pre-Columbian earth-builders settled along the entire southern rim of the Amazon. *Nature Communications* 9: 1125.

Dias, O. 2006. As Estruturas Arqueológicas de Terra no Estado do Acre— Amazônia Ocidental, Brasil. Um Caso de Resiliência? In: M. Días, E. Carvalho, M. Zimmerman (eds.), *Estudos Contemporâneos de arqueología*. Palmas: Insituto de Arqueologia Brasileira, Universidade do Tocantins. 59–168.

Diggle, P.J. 2013. *Statistical Analysis of Spatial and Spatio-Temporal Point Patterns*. London: CRC Press.

Dreslerová, D., Demján, P. 2019. Modelling prehistoric settlement activities based on surface and subsurface surveys. *Archaeological and Anthropological Sciences:* 1-25.

Epstein, J.M. 2006 *Generative Social Science: Studies in Agent-Based Computational Modeling*. Princeton Studies in Complexity. Princeton: Princeton University Press.

Erickson, C.L. 2006. The Domesticated Landscapes of the Bolivian Amazon. In: W. Balée & C.L. Erickson (eds.), *Time and Complexity in Historical Ecology*. New York: Columbia University Press. 235-278.

Erickson, C.L. 2010. The Transformation of Environment into Landscape: The Historical Ecology of Monumental Earthwork Construction in the Bolivian Amazon. *Diversity* 2: 618-652.

Ester, M., Kriegel, H.-P., Sander, J., Xu, X. 1996. A density-based algorithm for discovering clusters in large spatial databases with noise. In: Simoudis, E., Han, J., Fayyad, U.M. (eds.), *Proceedings of 2nd International Conference on Knowledge Discovery and Data Mining (KDD-96).* AAAI Press, Portland, 226–231.

Eve, S., Crema, E.R. 2014. A house with a view? Multi-model inference, visibility fields, and point process analysis of a Bronze Age settlement on Leskernick Hill (Cornwall, UK). *Journal of Archaeological Science* 43: 267-277.

Furholt, M., Grier, C., Spriggs, M., Earle, T. 2019. Political Economy in the Archaeology of Emergent Complexity: A Synthesis of Bottom-Up and Top-Down Approaches. *Journal of Archaeological Method and Theory*, 1-35.

Heckenberger, M. 2005. *The Ecology of Power. Culture, Place and Personhood in the Southern Amazon A.D. 1000-2000*. New York: Routledge.

Heckenberger, M.J., Petersen, J.B., Neves, E.G. 1999. Villages size and permanence in Amazonia: Two archaeological examples from Brazil. *Latin American Antiquity* 10: 353-376.

Heckenberger, M.J., Petersen, J.B., Neves, E.G. 2001. Of lost civilizations and primitive tribes, Amazonia: Reply to Meggers. *Latin American Antiquity* 12: 328-333.

Heckenberger, M.J., Neves, E.G. 2009. Amazonian Archaeology. *Annual Review of Anthropology* 38: 251-266.

Hogg, A.G., Hua, Q., Blackwell, P.G., Niu, M., Buck, C.E., Guilderson, T.P., Heaton, T.J., Palmer, J.G., Reimer, P.J., Reimer, R.W., Turney, C.S. 2013. SHCal13 Southern Hemisphere calibration, 0–50,000 years cal BP. *Radiocarbon* 55: 1889-1903.

Jacquemyn, H., Brys, R., Vandepitte, K., Honnay, O., Roldán-Ruiz, I., Wiegand, T. 2007. "A spatially explicit analysis of seedling recruitment in the terrestrial orchid *Orchis purpurea*" *New Phytologist* 176: 448-459.

Kohler, T.A. and van der Leeuw, S.E. (eds.) 2007. *The Model-based Archaeology of Socionatural Systems*. Santa Fe: School for Advanced Research Press.

Lake, M.W. 2015. Explaining the Past with ABM: On Modelling Philosophy. In: Wurzer G., Kowarik, K., Reschreiter H. (eds.), *Agent-Based Modeling and Simulation in Archaeology*. Vienna: Springer International. 3-28

Lombardo, U., Prümers, H. 2010. Pre-Columbian human occupation patterns in the eastern plains of the Llanos de Moxos, Bolivian Amazonia. *Journal of Archaeological Science* 37: 1875-1885.

McMichael, C.H., Piperno, D.R., Bush, M.B., Silman, M.R., Zimmerman, A.R., Raczka, M.F., Lobato, L.C. 2012. Sparse pre-Columbian Human Habitation in Western Amazonia. *Science* 336: 1429-1431.

McMichael, C.H., Palace, M.W., Golightly, M. 2014a. Bamboo-dominated forests and pre-Columbian earthwork formations in south-western Amazonia. *Journal of Biogeography* 41: 1733-1745.

McMichael, C.H., Palace, M.W., Bush, M.B., Braswell, B., Hagen, S., Neves, E.G., Silman, M.R., Tamanaha, E.K., Czarnecki, C. 2014b. Predicting pre-Columbian anthropogenic soils in Amazonia. *Proceedings of the Royal Society B: Biological Sciences* 281: 20132475.

Meggers, B.J. 1992. Amazonia: Real or counterfeit paradise. *The Review of Archaeology* 13: 25-50.

Meggers, B.J. 2001. The Continuing Quest for El Dorado: Round Two. *Latin American Antiquity* 12: 304-325.

Morehardt, C.T., Millhauser, J.K., Juarez, S. 2018. Archaeologies of Political Ecology – Genealogies, Problems, and Orientations. *Archeological Papers of the American Anthropological Association* 29: 5-29.

Nordenskiöld, E. (trans. Denevan, W.M.) 1916 [2009]. Indian Adaptations in Flooded Regions of South America. *Journal of Latin American Geography*. 8: 209-224.

Pärssinen, M., Schaan, D., Ranzi, A. 2009. Pre-Columbian geometric earthworks in the upper Purus: a complex society in western Amazonia. *Antiquity* 83: 1084-1095.

Premo, L. 2004. Local spatial autocorrelation statistics quantify multi-scale patterns in distributional data: an example from the Maya Lowlands. *Journal of Archaeological Science* 31: 855–866.

Prümers, H., 2014. Sitios prehispánicos com zanjas en Bella Vista, Provincia Iténez, Bolivia. Antes de Orellana. In: Rostain, S. (ed.), *Actas Del 3er Encuentro Internacional de Arqueología Amazônica*. Quito: Instituto Francés de Estudios Andinos. 73-91.

Prümers, H., Jaimes Betancourt, C., Martinez, R.P. 2006. Algunas tumbas prehispánicas de Bella Vista, Prov. Iténez, Bolivia. *Zeitschrift für Archäologie Außereuropäischer Kulturen* 1: 251-284.

Prümers, H., Jaimes Betancourt, C. 2014. 100 años de investigación arqueológica en los Llanos de Mojos. *Arqueoantropológicas* 4: 11-54.

Ranzi, A. 2003. Geoglifos: Patrimônio cultural do Acre. In: M. Pärssinen, A. Korpisaari (ed.), *Western Amazonia – Amazônia occidental*. Helsinki: Renvall Institute for Area and Cultural Studies, University of Helsinki. 135-72.

Ranzi, A., Feres, R., Brown, F. 2007. Internet software programs aid in search for Amazonian geoglyphs. *EOS, Transactions of the American Geophysical Union* 88.

Riris, P. 2017. Toward’s an artefact’s-eye view: Non-site analysis of discard patterns and lithic technology in Neotropical settings with a case from Misiones province, Argentina. *Journal of Archaeological Science: Reports* 11: 626-638.

Roosevelt, A.C. 1999. The Development of Prehistoric Complex Societies: Amazonia, A Tropical Forest. In: E.A. Bacus, L.J. Lucero (eds.), *Complex Polities of the Ancient Tropical World*, 13-33. Washington, DC: American Anthropological Association.

Saunaluoma, S. 2012. Geometric earthworks in the state of Acre, Brazil: excavations at the Fazenda Atlântica and Quinauá sites. *Latin American Antiquity* 23: 565-583.

Saunaluoma, S., Schaan, D. 2012. Monumentality in Western Amazonian formative societies: geometric ditched enclosures in the Brazilian state of Acre. *Antiqua* 2: e1.

Saunaluoma, S. Virtanen, P.K. 2015. Variable Models for Organization of Earthworking Communities in Upper Purus, Southwestern Amazonia: Archaeological and Ethnographic Perspectives. *Tipití* 13: 23-42.

Saunaluoma, S., Pärssinen, M., Schaan, D. 2018. Diversity of Pre-colonial Earthworks in the Brazilian State of Acre, Southwestern Amazonia. *Journal of Field Archaeology* 43: 362-379.

Schaan, D. 2012. *Sacred Geographies of Ancient Amazonia*. Walnut Creek: Left Coast Press.

Schaan, D., Pärssinen, M., Ranzi, A., Piccoli, J. 2007. Geoglifos da Amazônia Ocidental: Evidência de Complexidade Social Entre Povos da Terra Firme. *Revista de Arqueología* 20: 67–82.

Schaan, D., Bueno, M., Ranzi, A., Barbosa, A., Silva, A., Casagrande, E., Rodrigues, A., Dantas, A., Rampanelli, I. 2010. Construindo Paisagens Como Espaços Sociais: O Caso dos Geoglifos do Acre. *Revista de Arqueología* 23: 30–41.

Smith, M.E., Schreiber, K.J. 2005. New World States and Empires: Economic and Social Organization. *Journal of Archaeological Research* 13: 189-229.

Stahl, P.W. 2002. Paradigms in Paradise: Revising Standard Amazonian Prehistory. *The Review of Archaeology* 23: 39-51.

Stahl, P.W. 2015. Interpreting interfluvial landscape transformations in the pre-Columbian Amazon. *The Holocene* 25: 1598-1603.

Stoyan, D. and Stoyan, H. 1994. *Fractals, random shapes and point fields*. Chichester: John Wiley & Sons.

Strand, E.K., Robinson, A.P., Bunting, S.C. 2007. Spatial patterns on the sagebrush steppe/Western juniper ecotone. *Plant Ecology* 190: 159-173.

Tilley, C., 1994. *A Phenomenology of Landscape.* Oxford: Berg Publishers.

Walker, J.H. 2008. Pre-Columbian ring ditches along the Yacuma and Rapulo Rivers, Beni, Bolivia: A preliminary review. *Journal of Field Archaeology* 33: 413-427.

Watling, J., Saunaluoma, S., Pärssinen, M., Schaan, D. 2015. Subsistence practices among earthwork builders: Phytolith evidence from archaeological sites in the southwest Amazonian interfluves. *Journal of Archaeological Science: Reports* 4: 541-551.

Watling, J., Iriarte, J., Mayle, F.E., Schaan, D., Pessenda, L.C.R., Loader, N.J., Street-Perrott, F.A., Dickau, R.E., Damasceno, A., Ranzi, A. 2017. Impact of pre-Columbian "geoglyph" builders on Amazonian forests. *PNAS* 114: 1868-1873.

Watling, J., Mayle, F.E., 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.

Wiegand, T., Moloney, K.A. 2004. Rings, circles, and null-models for point pattern analysis in ecology. *Oikos* 104: 209-229.

Wobst, H.M. 1974. Boundary conditions for Palaeolithic social systems: a simulation approach. *American Antiquity* 39: 147-178.