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Predicting pre-Columbian anthropogenic soils in Amazonia

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The extent and intensity of pre-Columbian impacts on lowland Amazonia have remained uncertain and controversial. Various indicators can be used to gauge the impact of pre-Columbian societies, but the formation of nutrient-enriched *terra preta* soils has been widely accepted as an indication of long-term settlement and site fidelity. Using known and newly discovered *terra preta* sites and maximum entropy algorithms (Maxent), we determined the influence of regional environmental conditions on the likelihood that *terra pretas* would have been formed at any given location in lowland Amazonia. *Terra pretas* were most frequently found in central and eastern Amazonia along the lower courses of the major Amazonian rivers. Terrain, hydrologic and soil characteristics were more important predictors of *terra preta* distributions than climatic conditions. Our modelling efforts indicated that *terra pretas* are likely to be found throughout *ca* 154 063 km^2 or 3.2% of the forest. We also predict that *terra preta* formation was limited in most of western Amazonia. Model results suggested that the distribution of *terra preta* was highly predictable based on environmental parameters. We provided targets for future archaeological surveys under the vast forest canopy and also highlighted how few of the long-term forest inventory sites in Amazonia are able to capture the effects of historical disturbance.

1. Introduction

The perception that the entirety of the Amazon Basin was a virgin forest or 'counterfeit paradise' before European arrival to the Americas has been refuted, as recent research has documented evidence of earthwork formation, complex societies [1–3] and modified soils [4,5]. However, the overall extent to which lowland Amazonia was actively transformed into a modified landscape or cultural parkland by native people remains unknown and debated [6–10]. A newly emerging view is that pre-Columbian impacts across Amazonia were heterogeneous, both in space and degree [9,10]. However, in the areas that were occupied, the question remained: to what extent were the legacies of pre-Columbian societies evident in modern forest structure, dynamics and biodiversity patterns [6,9,11]?

Legacies of prehistoric influence in Amazonia are visible from aerial surveys and satellite imagery along the southern periphery of the basin, particularly in the Llanos de Moxos of Bolivia (e.g. [1,12–14]), the geoglyph-rich region of Acre, Brazil and northern Bolivia [3,15–18], and the Upper Xingu in Brazil [2,19] (figure 1). Whether similar impacts occur deep within the interior forests and across most of the basin remains unknown [9,10].

Potentially, one of the most telling vestiges of pre-Columbian activity in the interior forests is Amazonian black earths, known as *terra pretas*. These anthropogenic soil types were usually formed between 500 and 2500 years ago and contain significantly higher nutrient levels than typical Amazonian soils [4,20,23–28].

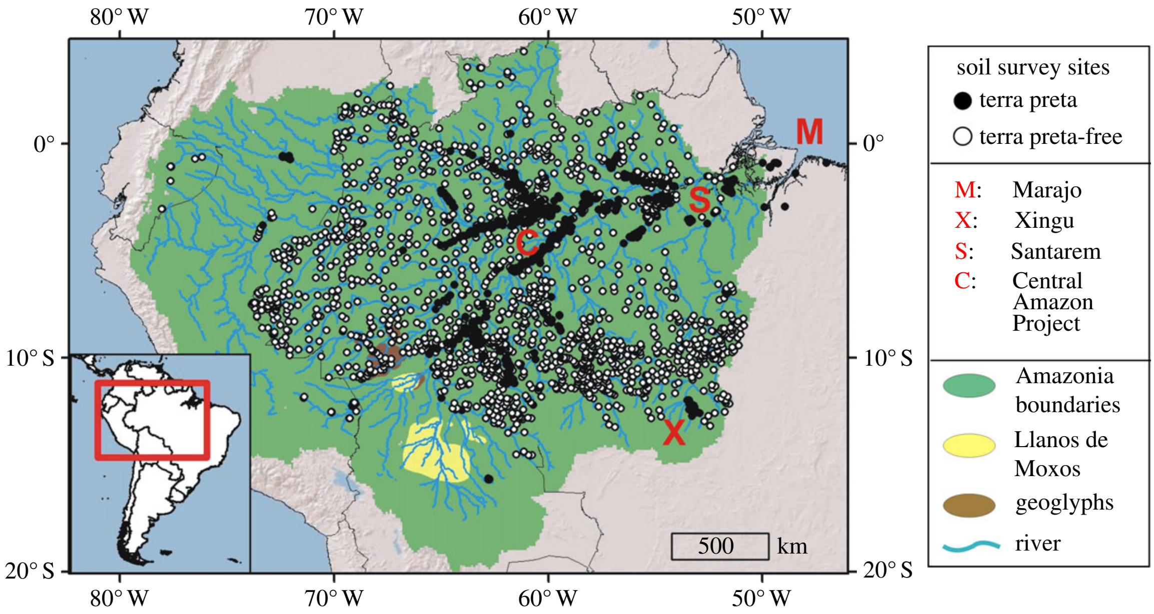

Figure 1. Locations of previously published *terra preta* and *terra preta*-free sites, major archaeological sites (references = M [20], X [2], S [21], C [22], Llanos de Moxos [12], geoglyphs [3,18]), and river systems within Amazonia.

Terra pretas indicate sedentary pre-Columbian settlements and are the most widely reported archaeological feature in Amazonia. They occur at most of the major archaeological sites in the interior forests including the Central Amazon Project [4,23], Santarem [28], Marajo [29] and the Upper Xingu [19,30] (figure 1). *Terra preta* formation has been estimated to occur in as much as 10% of the forests [6,7], but a prediction derived from empirical data and modelling is lacking.

Basin-wide soil surveys show that *terra preta* distributions are non-random (figure 1). *Terra pretas* occur throughout Amazonia, but are most commonly found in the central and eastern forests [26,31], and in riverine settings, particularly along bluffs overlooking the rivers [32]. However, the noted patterns may result from increased sampling effort in these locations. Less is known of *terra preta* occurrence in the westernmost and interfluvial forests, though most soil surveys in these areas contain no evidence of *terra pretas* [10,33–38] (figure 1).

As the potential for *terra preta* formation exists throughout Amazonia, we hypothesized that regional environmental conditions and local sociocultural practices influenced how people lived and that, in turn, affected their likelihood of creating *terra preta*. Thus, we modelled the potential distribution of *terra pretas* based on presence locations and a suite of climatic, geological, terrain and hydrological conditions across Amazonia. From our model, we determined the regional environmental factors that most strongly influence the likelihood of *terra preta* formation and estimated the spatial extent and total area of *terra preta* occurrence across Amazonia. We validated our model with additional *terra preta* presence and absence locations, and compared the output of our model with locations of previous ecological and archaeological research in Amazonia.

2. Material and methods

(a) Soil surveys

Typically, archaeological researchers have not published the exact georeferenced coordinates of *terra preta* locations for a number of reasons that include the relatively recent innovation of GPS to identify locations accurately and protection of sensitive sites. However, WinklerPrins & Aldrich [39] compiled the locations of over 500 *terra preta* sites, which were classified as either high, medium or low confidence, according to the predicted accuracy of the geographical coordinates. In total, 454 sites fell within lowland Amazonia (figure 1). We combined these data points with 463 georeferenced *terra preta* sites uncovered by E.G.N. and E.K.T. in archaeological field surveys from 2008 to 2012 to obtain a total of 917 known *terra preta* locations (figure 1).

Cooper *et al*. [34] published a comprehensive database of soil surveys conducted in Brazil, with most data points originating from the field campaign of the RADAMBrasil Project (Radar in Amazonia) [33]. In total, 1791 of these sites lie within Amazonia (figure 1). No site in the database contained notes or descriptions regarding any pottery sherds or soils with the black coloration or anomalously high nutrient content of *terra pretas*. Other Amazonian soil surveys [10,37,40] also report no evidence of *terra preta*. The locations of *terra preta*-free sites from all of these surveys were combined to form a database of *terra preta* absences ($n = 1962$). The combined *terra preta* and *terra preta*-free dataset contained 2879 sites.

(b) Environmental data

Environmental data was acquired or derived for the 4 876 193 km^2 of Amazonian forests (figure 1), and if necessary, resampled to 90 m spatial resolution. All geospatial data organization and analyses was conducted using open-source python code that incorporated Geospatial Data Abstraction Library (gdal) and osgeo libraries. We compiled 45 environmental layers for possible inclusion in the model, including bioclimatic ($n = 19$), soil ($n = 16$), terrain ($n = 8$), hydrological ($n = 2$) and geological ($n = 1$) characteristics (electronic supplementary material, table S1; descriptions below). To reduce autocorrelation between variables, we performed cross-correlation analyses on the bioclimatic, terrain and soils variable groups [41] (see the electronic supplementary material, figure S1). Additional organization and data extraction were performed with ArcGIS v. 10.0.

A total of 22 variables were chosen for inclusion in the model, including nine climatic, six edaphic, four topographical, two hydrological and one geological variable (see the electronic supplementary material, table S1; described below). The WorldClim Bioclimatic variables, which include precipitation and temperature parameters across the globe at a 1 km resolution [42], were used as climatic predictors. To account for autocorrelation between variables, we reduced the 19 variables down to nine using cross-correlation matrices [41] (see the electronic supplementary material, figure S1 and table S1). We used the Harmonized World Soil Database v. 1.2 [43] for edaphic characteristics across Amazonia. As topsoil and subsoil characteristics were highly correlated with each other, we used primarily subsoil characteristics in the predictive model ($n = 6$) (see the electronic supplementary material, figure S1 and table S1). The topographic data were derived from the Shuttle Radar Topography Mission (SRTM) 90 m resolution elevation data (data available from the US Geological Survey (USGS), http://eros.usgs.gov). Elevation data were included in the model and were also used to derive metrics of terrain roughness and slope. The largest intercell difference of a central pixel and the adjacent eight pixels is defined as roughness [44] and was used to identify river bluffs. For each pixel, we also calculated the distance to the nearest terrain changes, including: (i) bluffs greater than 25 m, (ii) bluffs greater than 50 m, (iii) slopes greater than 7°, and (iv) slopes greater than 15°. These metrics were added to account for the lack of precision of some of the *terra preta* locations, and the fact that people may have formed *terra pretas* near the bluffs as opposed to directly atop them. Roughness and slope were highly correlated with each other, so only roughness metrics were used in the model (see the electronic supplementary material, figure S1 and table S1). The hydrological variables stem from the HydroSHEDS dataset (available at http://hydro sheds.cr.usgs.gov), which identifies the river networks of Amazonia [45]. 'Upcell' values are features of the HydroSHEDS dataset and represent the maximum flow accumulation at any location in the river network. We used rivers with upcell values of greater than 15 000 to delineate perennial rivers, similar to previous studies [46] (figure 1). We calculated the distance to the nearest riverbank (km) and size of the nearest river (upcell value) for each pixel across Amazonia (see the electronic supplementary material, table S1) to use as predictors of *terra preta*. The geological provinces polygon raster was obtained from the USGS (http://energy.cr.usgs.gov).

(c) Models and analysis

We modelled *terra pretas* based solely on the presence data for several reasons. First, the sampling strategies of the presence-only dataset were targeted and localized, whereas the *terra preta*-free datasets were based on landscape-scale stratified sampling designs. Second, the accuracy of locations in the RADAM dataset, which comprised the majority of points in the *terra preta*-free dataset, may be questionable as the points were collected prior to modern GPS technology. Also, RADAM and other regional Brazilian soil surveys do not contain evidence of *terra pretas*, although it is not explicit as to whether they actually searched for them. However, because of the extensive chemical analyses performed on these soil samples, *terra pretas* most likely would have been identified through the presence of abundant artefacts, charcoal or anomalous nutrient levels.

MAXENT v. 3.3.3 (http://www.cs.princeton.edu/~schapire/maxent/) was used to model *terra preta* distributions, as it commonly outperformed other modelling techniques that use presence-only or presence–absence data, especially when dealing with small sample sizes or non-random sampling [47–49]. The predictive model was produced using only the 'high confidence' sites from the WinklerPrins and Aldrich [39] database ($n = 201$), sites surveyed by Paz *et al.* [50] ($n = 8$), and the sites surveyed by E.G.N. and E.K.T. ($n = 463$; total $n = 701$). We performed 10-fold cross-validation of the model, which was advantageous because all the data points were used for model training and also for performance testing. We evaluated area under the curve (AUC) statistics, which indicated the predictive capacity of a model, and how much better (or worse) a given model performed compared with a random model, where AUC = 0.5. Response curves for each environmental variable, a table of permutation importance for each of the environmental parameters, and jackknife tests for the training and testing datasets were all used to assess the relative importance of the predictor variables.

To analyse model uncertainty, we then extracted the predicted values for each of the *terra preta* and non-*terra preta* sites ($n = 2879$) (figure 1). A probability threshold value for predicting *terra preta* presence and absence was generated based on maximizing the percentage of sites correctly classified [51]. This method allowed us to estimate false positive and false negative rates of the model. Using this threshold, we were also able to predict whether each pixel across Amazonia probably contains *terra preta* or not (i.e. predicted presence and absence). From this, we calculated the extent of forests that probably contained *terra preta* as the area of the pixels predicted as present. All statistical analyses were performed with the 'PRESENCEABSENCE' [51] and 'stats' [52] packages for R using RSTUDIO v. 0.96.331 [53].

3. Results

The outputs of the maximum entropy model included probabilities of finding *terra preta* for each pixel across Amazonia (figure 2). The probabilities ranged from 6.2×10^{-9} to 0.96, with most of Amazonia at the low end of that range. The average AUC value obtained from the 10-fold cross-validation of the model was 0.957, with a standard deviation of ± 0.006, which was much higher than that of a random prediction (0.5), and indicated that the model fitted the data well and had a high predictive capacity.

Terrain, geological and hydrological characteristics were more important in shaping *terra preta* distributions than were climatic ones (table 1 and figures 3–5). Elevation was the most important factor in the model, and the potential distribution was constrained to areas primarily between 0 and 100 m elevation (figure 3). The second most important predictor was geological province, and *terra pretas* are most likely to be found in the Solimões Basin, Ucayali Basin and Brazilian Shield regions (figure 3). As expected, riverine settings were also important in the model. Our model suggested that *terra pretas* are also most probable within 10 km of a river, and near bluffs more than 25 m (figure 3). The type of river does not seem to be as important, as areas of high *terra preta* probability fall along black-water (including the Rio Negro), white-water (including the Amazon) and clear-water rivers (including the Tapajos) [26,55].

Model results also indicated that the probability of finding *terra preta* is almost zero at the major archaeological sites in Bolivia, including the Llanos de Moxos and the geoglyph-rich region (figure 2). Similarly, the model predicted that *terra pretas* are very unlikely to be found in the forests in close proximity to the western Amazonian earthworks. An absence of *terra preta* was also predicted across most of western Amazonia and in the upper catchment areas of southeastern Amazonia.

When considering the predicted probabilities of all known *terra preta* presence and absence points (figure 1), a probability threshold of 0.25 was able to correctly classify the highest percentage of known sites. Using the 0.25 threshold, 89% of all cases were predicted correctly, with a false negative rate of 6.5% and a false positive rate of 4.7%. When this probability

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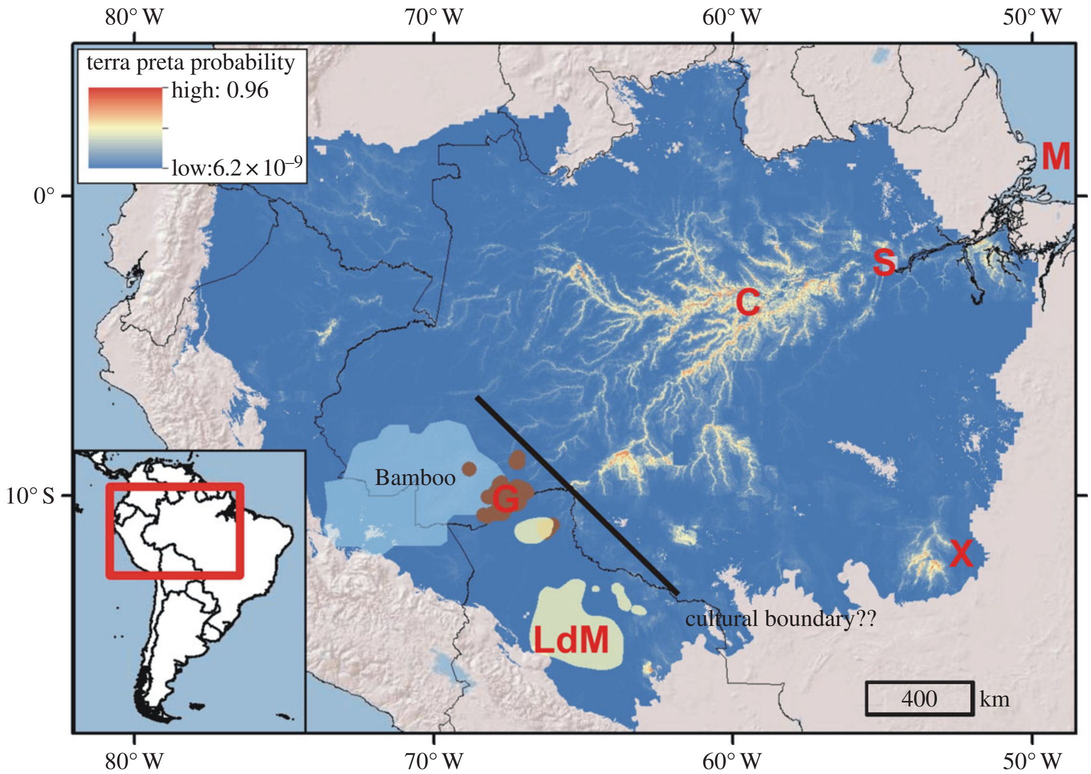

Figure 2. Probabilities of *terra preta* occurrence based on predictive models. Legend of archaeological sites is the same as in figure 1. The black line indicates a potential cultural boundary where the probability of *terra preta* formation decreases and disappears and is replaced by alternative subsistence strategies in south-western Amazonia (see text for details).

Table 1. Permutation importance (%), AUC of model with variable excluded (AUC minus predictor), and AUC of model with only individual predictors included (AUC only predictor) for each environmental layer used in Maxent models.

description	permutation importance	AUC minus predictor	AUC only predictor
elevation	61.4945	0.9552	0.8794
geological province polygon	5.6174	0.9568	0.8335
distance to bluff (roughness) greater than 25 m	4.8146	0.9571	0.6858
distance to the nearest river	4.6613	0.9566	0.8082
precipitation seasonality (coefficient of variation)	3.4576	0.9573	0.7711
minimum temperature of the coldest month	2.7401	0.9569	0.8111
precipitation of the driest month	2.67	0.957	0.7698
subsoil organic carbon	2.6332	0.9566	0.8377
mean temperature of the driest quarter	2.3904	0.9569	0.7803
subsoil gravel	1.9065	0.9567	0.6336
precipitation of the warmest quarter	1.3017	0.9573	0.7569
isothermality (BIO2/BIO7) (*100)	1.1918	0.9571	0.6485
subsoil bulk density	0.9513	0.9565	0.8208
the size (flow accumulation) of the nearest river from a given pixel	0.8351	0.9568	0.8157
distance to bluff (roughness) greater than 50 m	0.767	0.9566	0.6232
roughness	0.6853	0.9571	0.6272
precipitation of the wettest month	0.6278	0.957	0.6293
subsoil pH	0.4795	0.957	0.8135
temperature seasonality (standard deviation *100)	0.4294	0.9576	0.6682
topsoil organic carbon	0.1886	0.9571	0.8219
subsoil cation exchange content	0.1027	0.9574	0.7997
precipitation of the driest quarter	0.0543	0.9576	0.7712

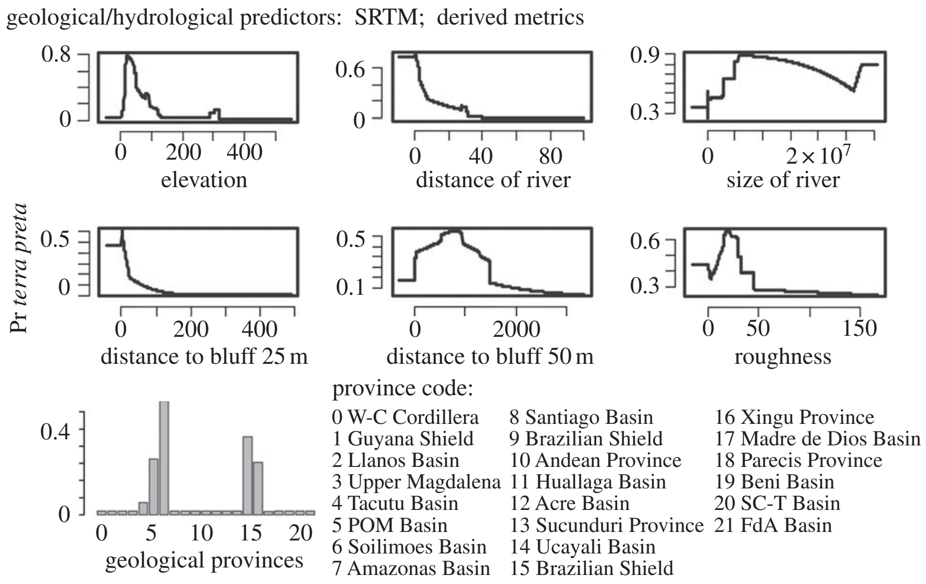

Figure 3. Response curves for the geological and geographical variables (see Material and methods) included in the predictive model. Because many of these variables are correlated with each other (see the electronic supplementary material, figure S4), these response curves are based on a MAXENT model using only the corresponding variable [54].

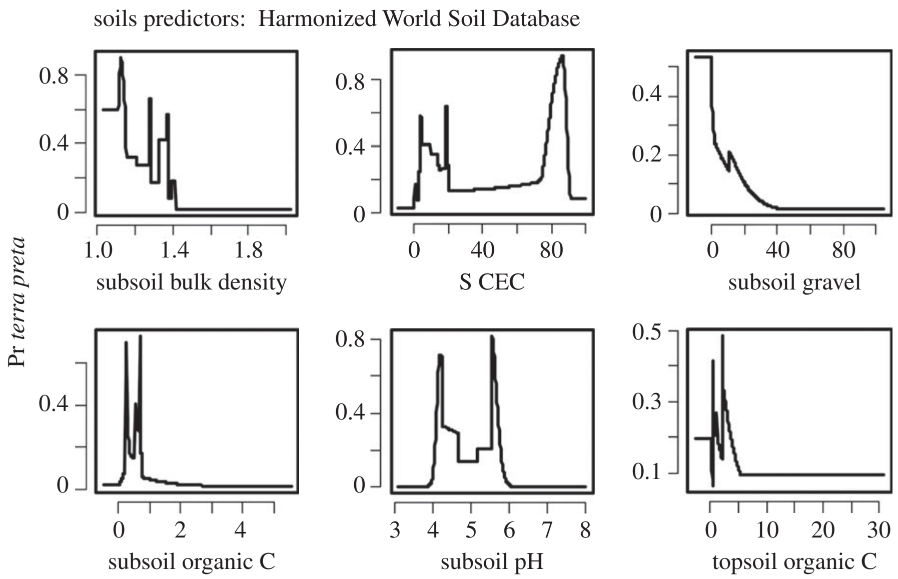

Figure 4. Response curves for the soil variables [43] included in the predictive model. Because many of these variables are correlated with each other (see the electronic supplementary material, figure S4), these response curves are based on a MAXENT model using only the corresponding variable [54]. S CEC, subsoil cation exchange content.

threshold was applied across the basin, *ca* 154 063 km^2 or 3.2% of the forest was predicted as having conditions that made *terra preta* formation likely.

4. Discussion

(a) Spatio-temporal heterogeneity of pre-Columbian peoples

Terra preta formation was most probable in eastern and central Amazonia, and in association with the lower courses of major rivers (figures 2 and 6). The older and highly weathered cratonic soils of eastern Amazonia were particularly nutrient-poor [37,56], and *terra preta* formation increased fertility in soils and afforded repeatable harvests in nutrient-poor areas at higher population densities. The larger acreage *terra pretas*, discovered to date, also lay near the Amazon River channel and its major tributaries, but smaller *terra pretas* occurred on the floodplains and in upper catchment areas [5,26,32,39,55,57–59]. This distribution may indicate a settlement preference for larger rivers, but may also be related to flood conditions, which are longer but not as deep in the lower courses. Furthermore, the eastern sections of the Amazon River are less turbid and have slower flow and meander rates compared with the western sections [60]. This stability may have also favoured larger and more permanent settlements in eastern Amazonia, particularly in regions such as Santarem, where some of the oldest records of human occupation in Amazonia have been identified [21,25]. The first European account of travel

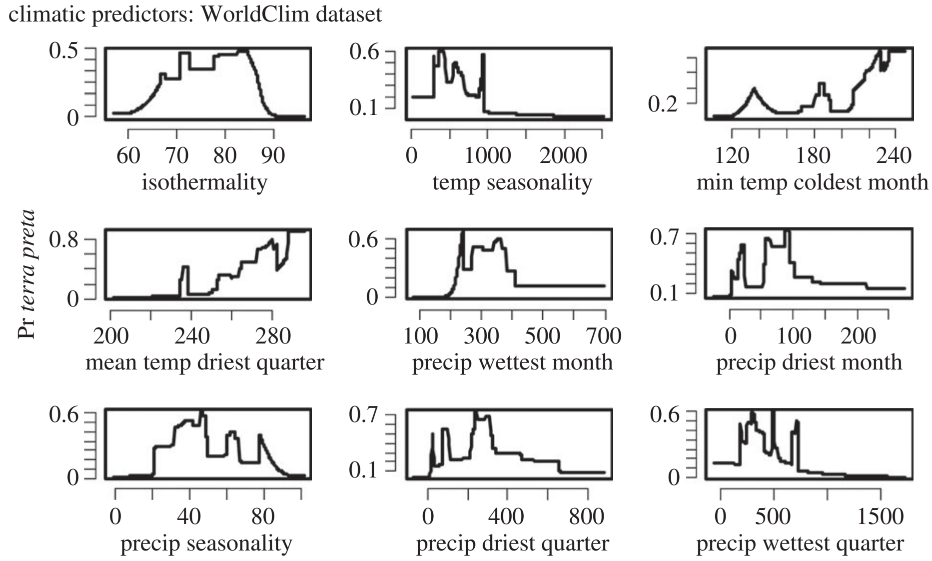

Figure 5. Response curves for the climatic variables [42] included in the predictive model. Because many of these variables are correlated with each other (see Material and methods and the electronic supplementary material, figure S4), these response curves are based on a MAXENT model using only the corresponding variable [54].

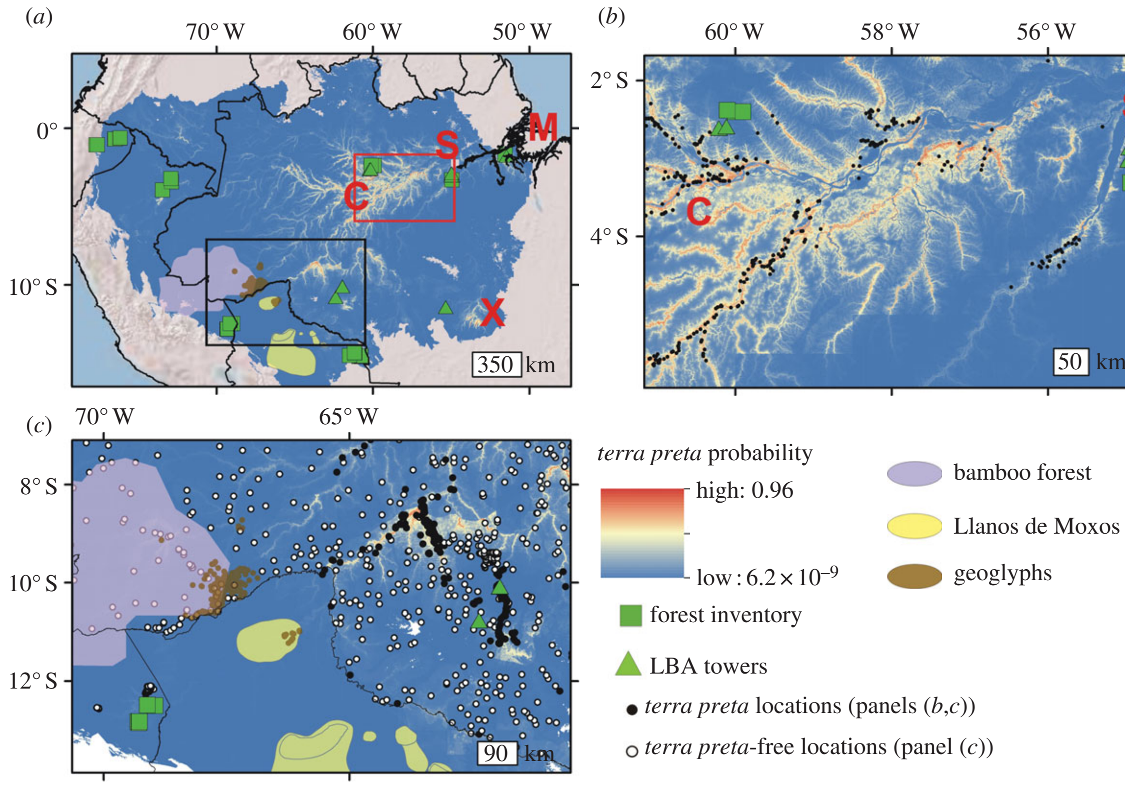

Figure 6. (*a*) *Terra preta* probabilities in relation to locations of long-term forest inventories, large scale biosphere-atmosphere experiment in Amazonia (LBA) C-flux towers, geoglyphs, bamboo-dominated forests and major archaeological sites. The legend of archaeological sites is shown in figure 1. The location and spatial extent of panels (*b*) and (*c*) are shown as the red and black rectangles respectively. (*b*) Regional view of areas with forest inventory data and an increased probability of *terra pretas*. (*c*) Regional-scale view of the potential cultural boundary between ancient cultures that formed *terra preta*, and those that used alternative subsistence practices.

down the Amazon River in 1541–1542, written by Gaspar de Carvajal, described flourishing and fruitful societies in the easternmost sections of river, although at least some aspects of these accounts are of dubious reliability, i.e. the description of a nation of warrior women—the Amazons [61].

The lack of *terra pretas* in western Amazonia may be because the Andean-derived soils of western Amazonia did not require nutrient enrichment, or because the human footprint in western Amazonia is for the most part smaller than that in the east. These possibilities are not mutually exclusive, although multiple lines of palaeoecological evidence suggest heterogeneous and localized low-impact human activity in much of western Amazonia [10]. Also, Carvajal's account describes the western river sections as desolate, with the expedition starving to the point of eating shoe leather [61]. That is not to say people were absent from western Amazonia; most evidence indicates that with the exception of the earthwork-rich areas in southwestern Amazonia, people were sparsely scattered through the landscape, clearing small tracts of land and growing crops on localized scales.

Cultural differences undoubtedly contributed to the distribution of *terra preta* formation, and these boundaries may have been just as important as environmental conditions (figure 2). The Llanos de Moxos regions of Bolivia is located in seasonally inundated forests at the forest–savannah transition, and instead of *terra preta* formation, large societies sustained themselves by using techniques such as fish weirs and raised-field agriculture (e.g. [12]). In the nearby geoglyph-rich regions of Acre, Brazil and northern Bolivia, our model predicts an absence of *terra preta* (figures 2 and 3). These predictions are concordant with archaeological surveys which report an absence of *terra pretas* within the region [18]. The forests surrounding both sites were also predicted to be *terra preta*-free. Thus, the geoglyph builders may have been more culturally similar to people of the Beni. Interestingly, the geoglyph-rich region at least partially overlaps with expansive bamboo-dominated forests in Amazonia (figure 2) [62] that have persisted in the landscape for thousands of years [36]. A direct connection between these features has not yet been demonstrated with empirical data.

We suggest that aside from the areas that lie near ecotonal boundaries, such as Marajo, Xingu and the Llanos de Moxos (figures 1 and 2), our model predicts the areas of lowland interior Amazonia that experienced the most intensive pre-Columbian disturbances. Our reasoning is owing to the fact that *terra pretas* are found throughout all of the major archaeological sites in the interior of the Amazon Basin, including areas near the Central Amazon Project and Santarem (figures 1 and 2). Our estimates of potential *terra preta* sites were significantly less than the previous estimates of 10% [6,7] and did not support the assertion that most of Amazonia was a transformed landscape or cultural parkland before European arrival. Instead, these data suggested that pre-Columbian Amazonia was a heterogeneous landscape, with varying degrees of human impacts across the mosaic.

Also, our model probably overestimates the areas where *terra pretas* will be found at any given time because it predicts the summed distribution taken across all ages. Dates from *terra pretas* are not always contemporaneous, and range from 3000 to 500 years ago. Most recorded dates are from 1000 to 2000 years ago [22], and the spatial extent of *terra pretas* probably expanded significantly during this time. Whether *terra preta* sites were continuously occupied after the original formation remains unknown. Some sites, particularly the smaller ones, may have been used only briefly. Further dating of *terra preta* sites could determine whether age is associated with size or a particular geographical region. Potentially, with enough dates, the spread of *terra preta* culture through time could be reconstructed.

Our model contradicts recent assertions that pre-Columbian human disturbance increased Amazonian biodiversity through promoting preferred species [11]. None of the predicted highly impacted areas are as biodiverse as the forests of northwestern Amazonia, which contain the highest tree-species diversity per unit area. Consistent with this view, the western, and particularly the northwestern, forests contain limited, if any, evidence of pre-Columbian human presence [10,63].

(b) Archaeological and ecological implications

Many archaeological sites are discovered accidentally through deforestation [3,15] or as a result of conversations with local people. Our model predicts where ancient impacts should be the most intense, even under the forest canopy, and provides basin-wide target locations for archaeologists who study the rich culture of ancient societies within the vast Amazonian rainforests (figure 6). Distribution models such as the one presented here, could also be applied to other archaeological features, for example geoglyphs, allowing examinations of cultural boundaries and areas of potential cultural overlap (figure 6*c*).

We do note, however, that because most *terra preta* and *terra preta*-free sites lie in Brazil, our most confident predictions are for this country. Elsewhere in Amazonia, the predictions are based on larger interpolations and are less certain. Increased sampling will refine our estimates of *terra preta* prevalence outside of Brazil.

A huge investment has been made by ecologists towards understanding ecosystem patterns and processes. Most ecological data collection and field surveys, particularly in the Neotropics, have been conducted over recent timescales, i.e. the past 50 years. Although these data have been immensely valuable in deciphering many of the underlying mechanisms that shape forest composition, structure and change, they lack a historical perspective. It has been suggested that the historical contingency, or historical trajectory, can play just as large a role in shaping observed ecological phenomena as modern climatic and abiotic conditions [64,65]. Our model provides a basis for linking historical trajectories of forest change with forest inventory data and ecological surveys conducted in Amazonia over modern timescales.

Most of the previous forest inventory research occurred in areas that most probably do not contain *terra pretas*, but the long-term study sites near Manaus and Santarem are particularly promising for local-scale evaluations of pre-Columbian disturbance on forest structure (sites C and S in figure 6). Many tree species in Amazonia live several hundred years [66], and forest burning and clearing associated with *terra pretas* from 2000 to 500 years ago, and in many cases again at the turn of the twentieth century, may have significantly contributed to patterns and dynamics documented in the modern forests. Previous field reports have documented that *terra pretas* are often associated with lower canopy height [28], denser understory [28], increased frequencies of lianas [67] and are often identified by locals as secondary forests with a predictable suite of species, many of which are domesticated (e.g. [68,69]). Other 'anthropogenic' forests that were formed in pre-Columbian periods may be identifiable within the forest today, as some species, including some palms, were heavily promoted species [6,70–72].

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Data accessibility. All *terra preta* locations reported in this study will be added to the existing online database of WinklerPrins and Aldrich [39].

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References

1. Erickson CL. 2006 The domesticated landscapes of the Bolivian Amazon. In *Time and complexity in historical ecology* (eds W Balee, CL Erickson), pp. 235–278. New York, NY: Columbia University Press.
2. Heckenberger M, Russell J, Fausto C, Toney J, Schmidt M, Pereira E, Franchetto B, Kuikuro A. 2008 Pre-Columbian urbanism, anthropogenic landscapes, and the future of the Amazon. *Science* **321**, 1214–1217. (doi:10.1126/science.1159769)
3. Pärssinen M, Schaan D, Ranzi A. 2009 Pre-Columbian geometric earthworks in the upper Purús: a complex society in western Amazonia. *Antiquity* **83**, 1084–1095.
4. Neves E, Petersen J. 2006 Political economy and pre-Columbian landscape transformation in central Amazonia. In *Time and complexity in historical ecology: studies in the neotropical lowlands* (eds W Balee, CL Erickson), pp. 279–310. New York, NY: Columbia University Press.
5. Glaser B, Woods WI. 2004 *Amazonian dark earths: explorations in space and time*. Berlin, Germany: Springer.
6. Erickson CL. 2008 Amazonia: the historical ecology of a domesticated landscape. In *The handbook of South American archaeology* (eds H Silverman, WH Isbell), pp. 157–183. New York, NY: Springer.
7. Mann CC. 2002 The real dirt on rainforest fertility. *Science* **297**, 920–923. (doi:10.1126/science.297.5583.920)
8. Romero S. 2012 Once hidden by forest, carvings in land attest to Amazon's lost world. *New York Times*. January 15; Sect. A6.
9. Barlow J, Gardner TA, Lees AC, Parry L, Peres CA. 2012 How pristine are tropical forests? An ecological perspective on the pre-Columbian human footprint in Amazonia and implications for contemporary conservation. *Biol. Conserv.* **151**, 45–49. (doi:10.1016/j.biocon.2011.10.013)
10. McMichael C, Piperno DR, Bush MB, Silman MR, Zimmerman AR, Raczka MF, Lobato LC. 2012 Sparse pre-Columbian human habitation in western Amazonia. *Science* **336**, 1429–1431. (doi:10.1126/science.1219982)
11. Balée W. 1993 *Indigenous transformation of Amazonian forests: an example from Maranhao, Brazil*. *L'Homme* **33**, 231–254.
12. Erickson CL. 2000 An artificial landscape-scale fishery in the Bolivian Amazon. *Nature* **408**, 190–193. (doi:10.1038/35041555)
13. Lombardo U, Canal-Beeby E, Fehr S, Veit H. 2011 Raised fields in the Bolivian Amazonia: a prehistoric green revolution or a flood risk mitigation strategy? *J. Archaeol. Sci.* **38**, 502–512. (doi:10.1016/j.jas.2010.09.022)
14. Lombardo U, Prümers H. 2010 Pre-Columbian human occupation patterns in the eastern plains of the Llanos de Moxos, Bolivian Amazonia. *J. Archaeol. Sci.* **37**, 1875–1885. (doi:10.1016/j.jas.2010.02.011)
15. Ranzi A, Feres R, Brown F. 2007 Internet software programs aid in search for Amazonian geoglyphs. *EOS Trans.* **88**, 226–229. (doi:10.1029/2007EO210003)
16. Saunaluoma S. 2010 Pre-Columbian earthworks in the Riberalta region of the Bolivian Amazon. *Amazônica-Revista de Antropologia*. **2**, 104–138.
17. Saunaluoma S, Schaan D. 2012 Monumentality in Western Amazonian formative societies: geometric ditched enclosures in the Brazilian state of Acre. *Antiqua* **2**, e1. (doi:10.4081/antiqua.2012.e1)
18. Schaan D, Pärssinen M, Saunaluoma S, Ranzi A, Bueno M, Barbosa A. 2012 New radiometric dates for pre-Columbian (2000–700 BP) earthworks in western Amazonia, Brazil. *J. Field Archaeol.* **37**, 132–142. (doi:10.1179/0093469012Z.00000000012)
19. Heckenberger MJ, Kuikuro A, Kuikuro UT, Russell JC, Schmidt MJ, Fausto C, Franchetto B. 2003 Amazonia 1492? Pristine forest or cultural parkland. *Science* **301**, 1710–1714. (doi:10.1126/science.1086112)
20. Roosevelt AC. 1991 *Moundbuilders of the Amazon: geophysical archaeology on Marajó Island*. San Diego, CA: Academic Press.
21. Roosevelt AC, Housley RA, Imazio da Siveira M, Maranca S, Johnson R. 1991 Eighth millenium pottery from a prehistoric shell midden in the Brazilian Amazon. *Science* **254**, 1621–1624. (doi:10.1126/science.254.5038.1621)
22. Neves EG, Petersen JB, Bartone RN, Heckenberger MJ. 2004 The timing of *terra preta* formation in the Central Amazon: archaeological data from three sites. In *Amazonian dark earths: explorations in space and time* (eds B Glaser, WI Woods), pp. 125–134. Berlin, Germany: Springer.
23. Neves E, Petersen J, Bartone R, Augusto Da Silva C. 2004 Historical and socio-cultural origins of Amazonian dark earth. In *Amazonian dark earths: origins, properties, management* (eds J Lehmann, DC Kern, B Glaser, WI Woods), pp. 29–50. The Netherlands: Kluwer Academic Publisher.
24. Roosevelt AC. 1993 *The rise and fall of the Amazon chiefdoms*. *L'Homme* **33**, 255–283.
25. Roosevelt AC *et al*. 1996 Paleoindian cave dwellers in the Amazon: the peopling of the Americas. *Science* **272**, 373–384. (doi:10.1126/science.272.5260.373)
26. Sombroek W, Kern D, Rodrigues T, Cravo MS, Jarbas TC, Woods W, Glaser B (eds). 2002 *Terra preta* and *terra mulata*: pre-Columbian Amazon kitchen middens and agricultural fields, their sustainability and their replication. In *Proc. 17th World Congress of Soil Science, Bangkok, Thailand*.
27. Sombroek WG. 1966 *Amazon soils: a reconnaissance of the soils of the Brazilian Amazon region*. Wageningen, The Netherlands: Centre for Agricultural Publications and Documentation.
28. Woods WI, McCann JM. 1999 The anthropogenic origin and persistence of Amazonian dark earths. *Yearb. Conf. Latin Am. Geogr.* **25**, 7–14.
29. Schaan D, Kern D, Frazão F. 2009 An assessment of the cultural practices behind the formation (or not) of Amazonian dark earths in Marajó island archaeological sites. In *Amazonian Dark Earths: Wim Sombroek's Vision* (eds W Woods, W Teixeira, J Lehmann, C Steiner, A WinklerPrins, L Rebellato), pp. 127–141. Dordrecht, The Netherlands: Springer.
30. Heckenberger MJ, Petersen JB, Neves EG. 1999 Village size and permanence in Amazonia: two archaeological examples from Brazil. *Latin Am. Antiquity* **10**, 353–376. (doi:10.2307/971962)
31. Glaser B, Birk JJ. 2012 State of the scientific knowledge on properties and genesis of Anthropogenic dark earths in central Amazonia (terra preta de Índio). *Geochim. Cosmochim. Acta* **82**, 39–51. (doi:10.1016/j.gca.2010.11.029)
32. Denevan WM. 1996 A bluff model of riverine settlement in prehistoric Amazonia. *Ann. Assoc. Am. Geogr.* **86**, 654–681. (doi:10.1111/j.1467-8306.1996.tb01771.x)
33. Brazil MdMeE, Departamento Nacional de Producão Mineral (DNPM). 1973–1983 Projeto RADAMBRASIL: 1973–1983, Levantamento de Recursos Naturais. DNPM, Rio de Janeiro.
34. Cooper M, Mendes LMS, Silva WLC, Sparovek G. 2005 A national soil profile database for Brazil available to international scientists. *Soil Sci. Soc. Am. J.* **69**, 649–652. (doi:10.2136/sssaj2004.0140)
35. McMichael C, Bush MB, Piperno D, Silman MR, Zimmerman AR, Anderson C. 2012 Scales of pre-Columbian disturbance associated with western Amazonian lakes. *Holocene* **22**, 131–141. (doi:10.1177/0959683611414932)
36. McMichael CH, Bush MB, Silman MR, Piperno DR, Raczka M, Lobato LC, Zimmerman M, Hagen S, Palace M. 2012 Historical fire and bamboo dynamics in western Amazonia. *J. Biogeogr.* **40**, 299–309. (doi:10.1111/jbi.12002)
37. Quesada C, Lloyd J, Anderson L, Fyllas N, Schwarz M, Czimczik C. 2011 Soils of Amazonia with particular reference to the RAINFOR sites. *Biogeosciences* **8**, 1415–1440. (doi:10.5194/bg-8-1415-2011)
38. Quesada C *et al*. 2009 Regional and large-scale patterns in Amazon forest structure and function are mediated by variations in soil physical and chemical properties. *Biogeosci. Discuss.* **6**, 3993–4057. (doi:10.5194/bgd-6-3993-2009)
39. WinklerPrins AMGA, Aldrich SP. 2010 Locating Amazonian dark earths: creating an interactive GIS of known locations. *J. Latin Am. Geogr.* **9**, 33–50. (doi:10.1353/lag.2010.0029)
40. McMichael CH, Correa Metrio A, Bush MB. 2012 Pre-Columbian fire regimes in lowland tropical rainforests of southeastern Peru. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **342–343**, 73–83. (doi:10.1016/j.palaeo.2012.05.004)
41. Buermann W, Saatchi S, Smith TB, Zutta BR, Chaves JA, Milá B, Graham CH. 2008 Predicting species distributions across the Amazonian and Andean

regions using remote sensing data. *J. Biogeogr.* **35**, 1160–1176. (doi:10.1111/j.1365-2699.2007.01858.x)

42. Hijmans RJ, Cameron SE, Parra JL, Jones PG, Jarvis A. 2005 Very high resolution interpolated climate surfaces for global land areas. *Int. J. Climatol.* **25**, 1965–1978. (doi:10.1002/joc.1276)
43. FAO/IIASA/ISRIC/ISS-CAS/JRC. 2008 Harmonized World Soil Database (version 1.0). FAO, Rome, Italy, and Laxenburg, Austria.
44. Wilson MFJ, O'Connell B, Brown C, Guinan JC, Grehan AJ. 2007 Multiscale terrain analysis of multibeam bathymetry data for habitat mapping on the continental slope. *Mar. Geodesy* **30**, 3–35. (doi:10.1080/01490410701295962)
45. Lehner B, Verdin K, Jarvis A. 2006 HydroSHEDS technical documentation. US WWF, Washington, DC. See http://hydrosheds.cr.usgs.gov.
46. Bow J, Josse C, Sayre R, Sotomayor L, Touval J. 2008 *Terrestrial ecosystems of South America*. Arlington, Virginia: The Nature Conservancy and Natureserve.
47. Phillips SJ, Dudík M. 2008 Modeling of species distributions with Maxent: new extensions and a comprehensive evaluation. *Ecography* **31**, 161–175. (doi:10.1111/j.0906-7590.2008.5203.x)
48. Elith J, Phillips SJ, Hastie T, Dudík M, Chee YE, Yates CJ. 2011 A statistical explanation of Maxent for ecologists. *Divers. Distrib.* **17**, 43–57. (doi:10.1111/j.1472-4642.2010.00725.x)
49. Phillips SJ, Anderson RP, Schapire RE. 2006 Maximum entropy modeling of species geographic distributions. *Ecol. Model.* **190**, 231–259. (doi:10.1016/j.ecolmodel.2005.03.026)
50. Paz-Rivera C, Putz FE. 2009 Anthropogenic soils and tree distributions in a lowland forest in Bolivia. *Biotropica* **41**, 665–675. (doi:10.1111/j.1744-7429.2009.00521.x)
51. Freeman EA, Moisen G. 2008 PresenceAbsence: an R package for presence absence analysis. *Statist. Softw.* **23**, 1–31.
52. R Development Core Team. 2011 *R: a language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing.
53. RStudio. 2012 *RStudio: integrated development environment for R* (*version 0.96.331*). RStudio: Boston, MA.
54. Phillips S. 2006 A brief tutorial on Maxent. See http://www.cs.princeton.edu/~schapire/maxent/tutorial/tutorial.doc.
55. Kern DC, Aquino GD, Rodrigues TE, Frazao FJL, Sombroek W, Myers TP, Neves EG. 2003 Distribution of Amazonian dark earths in the Brazilian Amazon. In *Amazonian dark earths: origins, properties, management* (eds J Lehmann, DC Kern, B Glaser, WI Woods), pp. 51–75. Dordrecht, The Netherlands: Kluwer Academic Publishers.
56. Hoorn C *et al*. 2010 Amazonia through time: Andean uplift, climate change, landscape evolution, and biodiversity. *Science* **330**, 927–931. (doi:10.1126/science.1194585)
57. Denevan WM. 1976 The aboriginal population of Amazonia. In *The native population of the Americas in 1492* (ed. WM Denevan), pp. 205–234. Madison, WI: University of Wisconsin Press.
58. Denevan WM. 1992 The pristine myth: the landscape of the Americas in 1492. *Ann. Assoc. Am. Geogr.* **82**, 369–385. (doi:10.1111/j.1467-8306.1992.tb01965.x)
59. Smith NJH. 1980 Anthrosols and human carrying capacity in Amazonia. *Ann. Assoc. Am. Geogr.* **70**, 553–566. (doi:10.1111/j.1467-8306.1980.tb01332.x)
60. Mertes LAK, Dunne T, Martinelli LA. 1996 Channel-floodplain geomorphology along the Solimoes-Amazon River, Brazil. *GSA Bull.* **108**, 1089–1107. (doi:10.1130/0016-7606(1996)108<1089:CFGATS>2.3.CO;2)
61. Medina J. 1934 *The discovery of the Amazon according to the account of Friar Caspar de Carvajal and other documents*. New York, NY: American Geographical Society.
62. de Carvalho AL, Nelson BW, Bianchini MC, Plagnol D, Kuplich TM, Daly DC. 2013 Bamboo-dominated forests of the southwest Amazon: detection, spatial extent, life cycle length and flowering waves. *PLoS ONE* **8**, e54852. (doi:10.1371/journal.pone.0054852)
63. Roucoux KH, Lawson IT, Jones TD, Baker TR, Coronado ENH, Gosling WD, Lähteenoja O. 2013 Vegetation development in an Amazonian peatland. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **374**, 242–255. (doi:10.1016/j.palaeo.2013.01.023)
64. Ricklefs RE, Latham RE, Qian H. 1999 Global patterns of tree species richness in moist forests: distinguishing ecological influences and historical contingency. *OIKOS* **86**, 369–373. (doi:10.2307/3546454)
65. Ricklefs RE, Schluter D. 1993 *Species diversity in ecological communities: historical and geographical perspectives*. Chicago, IL: University of Chicago Press.
66. Hartshorn G, Zimmerman M. 1978 Tree falls and tropical forest dynamics. In *Tropical trees as living systems* (eds PB Tomlinson, MH Zimmerman), pp. 617–638. Cambridge, UK: Cambridge University Press.
67. Balee W, Campbell DG. 1990 Evidence for the successional status of liana forest (Xingu river basin, Amazonian Brazil). *Biotropica* **22**, 36–47. (doi:10.2307/2388717)
68. Clement C, McCann J, Smith N. 2004 Agrobiodiversity in Amazonia and its relationship with dark earths. In *Amazonian dark earths* (eds B Glaser, WI Woods), pp. 159–178. Berlin, Germany: Springer.
69. Junqueira AB, Shepard GH, Clement CR. 2011 Secondary forests on anthropogenic soils of the middle Madeira river: valuation, local knowledge, and landscape domestication in Brazilian Amazonia. *Econ. Bot.* **65**, 1–15. (doi:10.1007/s12231-010-9138-8)
70. Balee W. 1989 The culture of Amazonian forests. In *Resource management in Amazonia: indigenous and folk strategies* (eds DA Posey, W Balee), pp. 1–21. New York, NY: New York Botanical Garden.
71. Balee W. 2010 Contingent diversity on anthropic landscapes. *Diversity* **2**, 163–181. (doi:10.3390/d2020163)
72. Levis C, de Souza PF, Schietti J, Emilio T, da Veiga Pinto JLP, Clement CR, Costa FRC, Hart JP. 2012 Historical human footprint on modern tree species composition in the Purus-Madeira Interfluve, central Amazonia. *PLoS ONE* **7**, e48559. (doi:10.1371/journal.pone.0048559)