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ANTHROPOLOGY

Intentional creation of carbon-rich dark earth soils in the Amazon

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Fertile soil known as Amazonian dark earth is central to the debate over the size and ecological impact of ancient human populations in the Amazon. Dark earth is typically associated with human occupation, but it is uncertain whether it was created intentionally. Dark earth may also be a substantial carbon sink, but its spatial extent and carbon inventory are unknown. We demonstrate spatial and compositional similarities between ancient and modern dark earth and document modern Indigenous practices that enrich soil, which we use to propose a model for the formation of ancient dark earth. This comparison suggests that ancient Amazonians managed soil to improve fertility and increase crop productivity. These practices also sequestered and stored carbon in the soil for centuries, and we show that some ancient sites contain as much carbon as the above-ground rainforest biomass. Our results demonstrate the intentional creation of dark earth and highlight the value of Indigenous knowledge for sustainable rainforest management.

INTRODUCTION

The size and complexity of pre-1492 Indigenous societies in the Amazon are hotly debated. Archaeological evidence has revealed a long history of human-environment interactions (*1*–*5*), but interpretations of this evidence range from a sparsely populated Amazon Basin with relatively minor human impact on the environment (*6*, *7*) to dense populations and complex societies that substantially modified the landscape (*8*, *9*). Central to this debate is dark earth—anthropic soil characterized by darker color, higher organic carbon content, and higher fertility than typical Amazonian upland soils (text S1) (*10*). The occurrence of substantial expanses of dark earth at many archaeological sites (*11*), combined with the discovery that the Amazon was a center of crop domestication (*12*), suggests that locally dense populations may have been supported by creating and farming the enriched soils, thereby overcoming the low fertility of highly weathered rainforest soils (*13*). The fertile soil is sought after today by Indigenous and non-Indigenous farmers for planting crops (*14*, *15*). Despite this evidence, the origins of dark earth remain unclear (*16*). The presence of charcoal, food remains, and artifacts indicates that humans contributed to dark earth formation (*17*, *18*), but it is unknown how they did so and whether they created it intentionally (*14*, *19*–*22*), leading some researchers to still question whether humans created it at all (*23*).

Dark earth is a widespread phenomenon with a range of characteristics (text S1). Patches of dark earth occur throughout Amazonia on diverse soil types and in different cultural and environmental contexts (*24*). The two main hypotheses for the origin of dark earth, which are not mutually exclusive, both involve human activities (*25*). One is the midden model, in which dark earth results mainly from household waste disposal. The other is the agriculture model, in which dark earth results from cultivation practices (*13*, *25*, *26*). Either mechanism could involve intentional formation of dark earth for crop production, but neither requires it. Both hypotheses originated from observations that dark earth sites typically have core areas of darker soil with higher nutrient content and abundant charcoal and artifacts—the inspiration for the midden model—surrounded by peripheral areas of lighter brown soil with relatively high organic matter and abundant charcoal but with lower nutrient content and scarce artifacts—the inspiration for the agriculture model (*25*, *26*). Rather than two distinct categories, however, dark earth commonly exhibits a continuum between these two endmembers, with soil color and other properties varying across archaeological sites (*27*, *28*).

Dark earth is not strictly an Amazonian phenomenon, as anthropic soils can be found throughout the world (*29*–*31*). However, Amazonian dark earth is notable because it contrasts so sharply with the especially poor fertility of typical highly weathered tropical upland soils in the Amazon. Unlike regions of the world

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where agriculture was viable even on unmodified soils, Amazonian dark earth formation may have played a pivotal role in enabling the development of ancient agricultural societies in the region.

Beyond the importance of dark earth to Amazonian societies and food production, it could also be a substantial carbon (C) reservoir. Tropical soils hold more than 800 Pg C, making them the second largest potential source of atmospheric carbon dioxide after fossil fuels and an important component of climate feedbacks (*32*). Estimates of tropical soil carbon content and the fate of this carbon under future climate warming and land-use change remain poorly quantified (*33*). The high soil organic carbon (SOC) and charcoal content of dark earth (*34*) mean that it could be a large additional carbon reservoir that has not been considered —and, if dark earth creation is incorporated into land management practices (*19*), a potential future carbon sink (*35*). Aside from a few investigations (*36*, *37*), the total inventory of carbon and other nutrients at dark earth sites remains largely unstudied, adding uncertainty to the potential climate impacts of soil carbon loss due to land-use change and global warming.

To address these questions about ancient humans, soil carbon, and tropical soil fertility, we combine soil analyses of modern and ancient Indigenous settlements with archaeological and ethnographic research, focusing on the Kuikuro Indigenous Territory in the Upper Xingu River basin in southeastern Amazonia (Fig. 1). Comparing ancient and modern Amazonian cultures is challenging because many Indigenous groups that survived European contact suffered severe depopulation that led to major cultural changes (*38*–*40*). In contrast, archaeological research has demonstrated cultural continuity from ancient to modern peoples in the Upper Xingu region (*41*–*44*), offering an opportunity to examine linkages between present and past activities that have modified soils. We find that spatial and compositional patterns of soil alteration in modern Indigenous villages resemble those in archaeological sites, although on a smaller scale, suggesting similar origins. Observations of daily activities and interviews with Kuikuro residents reveal intentional soil amendment to increase crop productivity. On the basis of these comparisons, we infer that ancient Amazonians in the Xingu created dark earth using similar practices to improve soil fertility. We propose a spatial model for dark earth formation in a typical Xingu village and use this model along with our soil measurements to estimate the anthropogenic carbon and nutrient inventories at ancient and modern dark earth sites. Our results demonstrate the intentional creation of dark earth, highlighting how Indigenous knowledge can provide strategies for sustainable rainforest management and carbon sequestration.

RESULTS

Soil analyses

To investigate the enrichment and distribution of modified soils, we analyzed soil samples from transects at four archaeological sites, two historic villages, and one modern village in the Upper Xingu region (Fig. 1 and fig. S1), as well as samples of background soils in areas between sites (Materials and Methods). In addition to these samples, we estimated the extent of dark earth at each site using archaeological test pits. Dates of occupation for these sites range from 5000 calibrated years before present (cal BP) to modern, with most radiocarbon ages from 1000 to 300 cal BP (Materials and Methods, fig. S26, and table S7). We collected similar measurements in two archaeological sites with dark earth in two other regions of eastern Amazonia (Materials and Methods), with dates of occupation ranging from 11,800 to 500 cal BP (Materials and Methods, figs. S27 and S28, and table S7).

Radial transects in both a modern village (Kuikuro II, Fig. 1B) and an archaeological settlement (Seku, Fig. 1C) in the Upper Xingu show soil alteration highest in middens (mounded refuse disposal areas) near the center of each site and decreasing outward (Fig. 2). The most enriched soil is more than twice as high in SOC than soil toward the distal end of the transects (Fig. 2, A and B) and less acidic by about one pH unit at Seku and two pH units at Kuikuro II (Fig. 2, C and D). Abundance measurements of nine additional elements (figs. S7 to S15) reveal that elements associated with anthropic soil enrichment (P, K, Ca, Mg, Mn, and Zn) show 10-fold or greater enrichment in the dark earth and midden areas compared to the periphery and are positively correlated with one another in a principal components analysis (PCA) of chemical concentrations (Materials and Methods and table S1). Concentrations of elements that are not generally increased by human activities (Al) or that are abundant in background soils (Fe) are inversely correlated with the enriched elements (table S1). The first principal component (Fig. 2, E and F), which explains most of the variation, shows that the overall spatial pattern of soil compositional variation is similar to the pattern of soil alteration revealed by SOC and pH individually.

Three nearby archaeological sites and a historic village show similar patterns of soil alteration, with the most enriched soil within residential areas with midden deposits (including mounds bordering plazas and roads), less modified soils in public areas including roads and plazas, and a gradual decrease in soil modification with distance from the central areas of the sites (figs. S1 to S3). Test pits indicate that less-modified brown soil extends at least 400 m outward from circumferential ditches (fig. S1A). We also observe similar patterns of soil alteration at the two other Amazonian sites we studied, one along the Tapajós River and the other in the Carajás Mountains (Materials and Methods and figs. S4 to S6). At both sites, like others in the Amazon (*45*), relatively deep dark earth deposits occur on the upper slopes of river terraces or bluff edges, with the most enriched soil found in midden deposits.

Soil measurements on the periphery of each site are consistent with highly weathered Amazonian soils, which typically contain 6 to 10 kg/m^2 of SOC in the upper 1 m (*46*). The dark earth deposits we sampled feature SOC densities of 9 to 22 kg/m^2 (table S3). These values are comparable with more fertile temperate soils rather than depleted tropical soils, and the higher values are comparable to the above-ground biomass of the Amazon rainforest (*47*). By subtracting the estimated background abundance, we estimate anthropogenic SOC enrichment of 2 to 12 kg/m^2 in archaeological sites, 1 kg/m^2 in middens from two historic villages, and 5 kg/m^2 in Kuikuro II village middens (table S3). These SOC densities are consistent with past measurements of anthropogenic SOC in dark earth, which found enrichment of 7 to 14 kg/m^2, with one outlier of 39 kg/m^2 (*35*).

We combine these estimates with mapped areas of dark earth to estimate 4500 tonnes of anthropogenic (above background) soil carbon at Seku; other ancient sites range from 410 to 2500 tonnes (table S3). The modern Kuikuro II village and the historic Kuikuro I village contain 110 and 5.3 tonnes in middens, respectively, consistent with the smaller sizes and shorter occupations of the

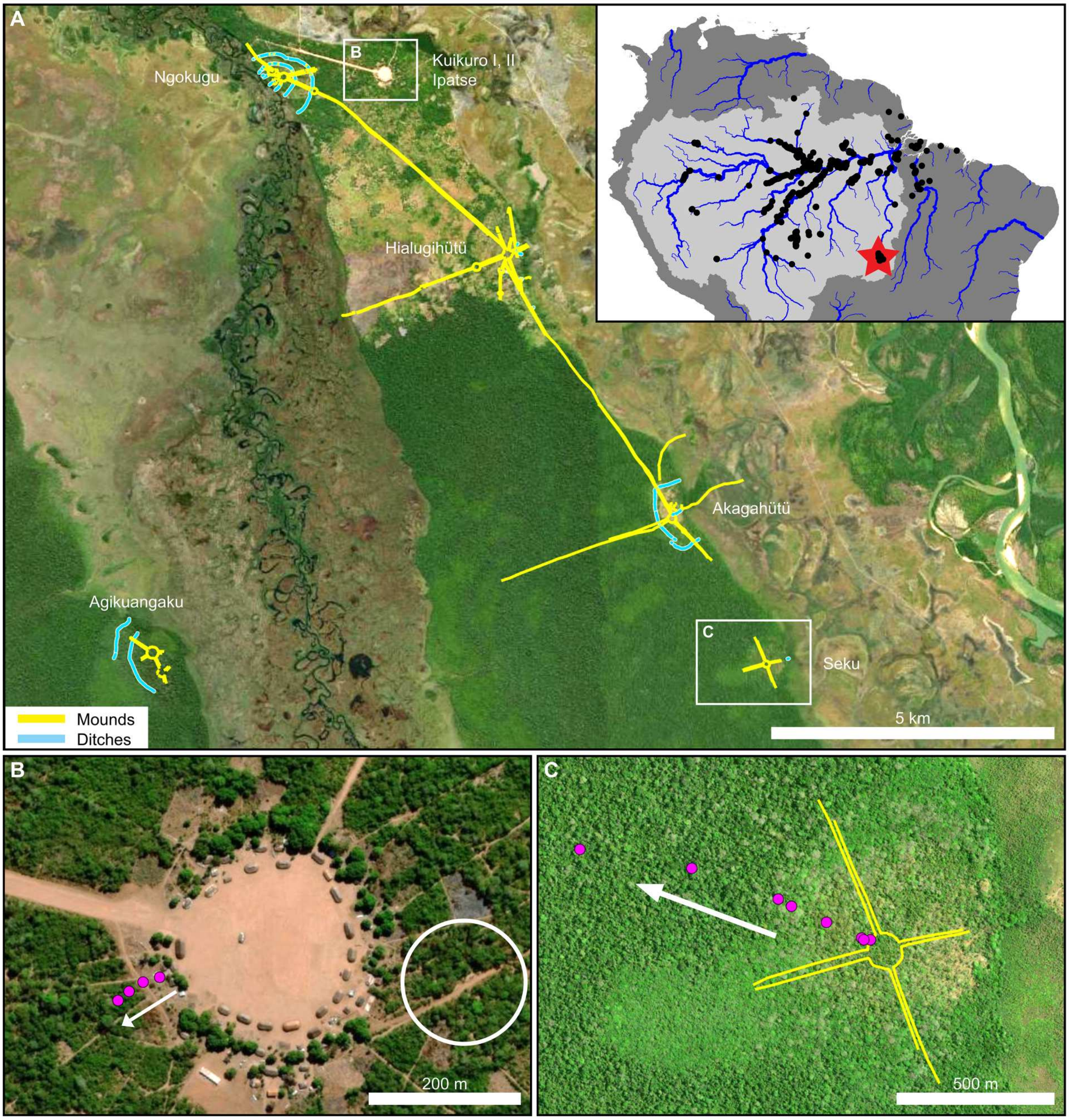

Fig. 1. Study area location, sites, and sampling transects. (**A**) Upper Xingu River study area showing locations of the modern and historic Kuikuro villages and five archaeological sites. Inset map shows the location of the study area in the Amazon Basin (red star) and locations of documented archaeological sites with dark earth (black points) (*71*). (**B**) Modern Kuikuro II village. White circle shows the location of the historic Kuikuro I village (occupied 1973–1983). (**C**) Seku archaeological site. Magenta circles in (B) and (C) mark test pit locations along the transects in Fig. 2. Arrows show the directions of the transects in Fig. 2. Satellite images: Esri, DigitalGlobe, GeoEye, i-cubed, U.S. Department of Agriculture Farm Service Agency, U.S. Geological Survey, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.

contemporary villages. We also perform similar analyses for soil phosphorus, yielding site inventories of up to 520 tonnes (table S4). Our measurements show that the recalcitrant carbon in dark earth persists for centuries in a tropical environment, demonstrating the tremendous carbon and nutrient storage of anthropogenic dark earth and the potential for further carbon sequestration by its continued formation. Extrapolating these inventories over larger geographic areas would require knowledge of the number and size of all dark earth sites. Although such estimates are not yet available, the widespread occurrence of known sites (Fig. 1A), which is a minimum bound, suggests that the total amount of anthropogenically sequestered carbon and nutrients in Amazonian dark earth could be very large. However, the stability of this stored carbon is threatened by land-use change (*35*) and climate warming (*33*). Our data show such an impact: Deforested sites under recent cultivation have lower SOC and P than forested sites (tables S3 and S4).

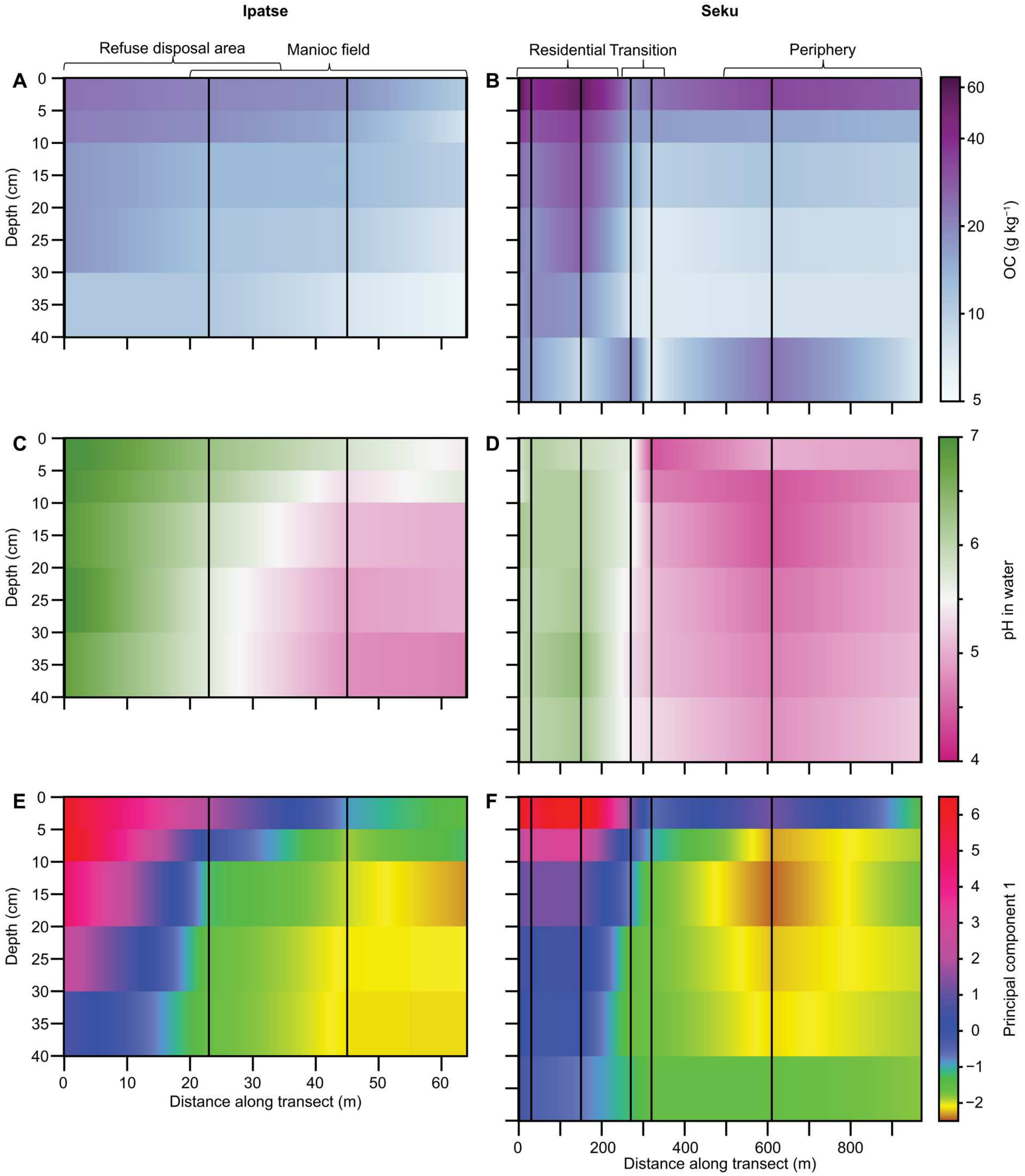

Fig. 2. Fence diagrams of soil composition along sampling transects. Transects extend radially through a modern village, Kuikuro II (**A**, **C**, and **E**) and the Seku archaeological site (**B**, **D**, and **F**). Vertical black lines correspond to sample locations in Fig. 1 (B and C). (A and B) SOC (g kg^{-1}). (C and D) Soil pH measured in water. (E and F) Principal component 1 from a PCA of the 11 measured chemical quantities, which explains 51% (Seku) and 76% (Kuikuro II) of the variation (Materials and Methods and table S1).

Generalizing these results, we find similar spatial patterns and compositional signatures of dark earth in modern and ancient settlements, with a radial pattern in which the soil enrichment is strongest in residential areas of sites, particularly in middens, and diminishes outward from the settlement. This concordance suggests that the ancient and modern dark earth deposits in the study area are the product of similar soil management practices.

Ethnographic observations

To determine what practices formed dark earth and whether it was intentionally created, we augmented our archaeological and soil analyses with ethnographic research in the present-day Kuikuro II village (Figs. 1B and 3E), which has documented enriched soils from contemporary Indigenous land management practices (Materials and Methods) (*48*). Fishing and manioc agriculture create large quantities of nutrient-rich organic waste (Fig. 3A), much of which is deposited in trash middens mounded up to ~50 to 60 cm above the original ground surface (Fig. 3B), creating the most fertile and intensely modified soil in areas surrounding residences (Fig. 2A and figs. S3, S7 to S15, and S19 to S21) (*47*). Once dark earth begins to form in these midden areas, typically within a few years, residents often exploit it for planting nutrient-demanding crops (Fig. 3C) that do not grow well on unmodified soils according to Kuikuro farmers (tables S5 and S6). We also observed farmers spreading this organic refuse, particularly ash and charcoal (Fig. 3D) and manioc waste (Fig. 3F), as well as mulching (Fig. 3G) and in-field burning (Fig. 3H), in fields on the periphery of the village (Fig. 3I).

Interviews revealed that farmers purposefully spread ash and organic waste over the ground to fertilize the soil and create dark earth, which they call *eegepe*, for later cultivation (table S5 and text S2). The locations where they spread ash are called *ilũbepe*, and a place where dark earth has already formed from spreading ash is called *ilube egepütipügü*. According to one informant, "It is the *ilũbepe* of the ancestors that we call *eegepe*" (interview with Haitsehü, text S2). Another describes how they create it today: "Charcoal and ash we sweep, gather it up and then throw it where we will plant, to turn into beautiful *eegepe*. There we can plant sweet potatoes. When you plant where there is no *eegepe*, the soil is weak. That is why we throw the ash, manioc peelings, and manioc pulp" (interview with Kanu, text S2). To quantify the level of support for the hypothesis of intentional dark earth creation, we excerpted all interview responses relevant to soil management (table S5). Of 78 statements, 42 support the hypothesis of intentional dark earth creation (54%), 11 contradict it (14%), and 25 are neutral (32%).

DISCUSSION

Our ethnographic observations demonstrate that modern Kuikuro villagers intentionally create dark earth through traditional practices. Our archaeological and soil data show that ancient and modern dark earth deposits have similar compositions and spatial

Fig. 3. Some activities that contribute to dark earth creation. (**A**) Processing manioc. (**B**) Discarding refuse in mounded middens. (**C**) Backyard crop cultivation. (**D**) Sweeping ash and charcoal from a hearth. (**E**) Kuikuro II village with locations of other photos indicated. (**F**) Spreading manioc waste. (**G**) Spreading ash and charcoal around trees. (**H**) Burning in fields and in backyard refuse disposal areas. (**I**) In-field manioc processing and burning of waste and crop residue.

distributions. These similarities are consistent with the hypothesis that ancient peoples created dark earth deposits through intentional soil management. Combining these results, we formulate a general model for the anthropogenic origins of ancient dark earth and its spatial distribution in upland sites (Fig. 4). We propose that soils were intentionally modified over time in settlements and the surrounding land. The greatest impact on the soil was through organic refuse disposal in mounded trash middens. As a result, the most highly modified soil is generally concentrated in refuse middens surrounding houses, along linear mounds bordering plazas, roads, and paths, and concentrated on slopes at the periphery of settlements (*45*). Middens generally become shallower and more dispersed with distance from the site's center, reflecting more dispersed homes and/or reduced concentration of organic refuse. Beyond the residential areas, where soil management and cultivation can occur, the soil gradually lightens in color and diminishes in degree of modification with distance.

Managing tropical soils is vital to feeding the world's population (*49*), mitigating climate change (*19*), and conserving biodiversity and ecosystems (*50*). Dark earth soils in the Amazon are evidence for past resource management that may have sustained large populations despite naturally low soil nutrients. Our results suggest that much of the dark earth found in the Upper Xingu region of the Amazon was intentionally created in ancient times and show that it is still being created today by Indigenous people with traditional knowledge. These soil management practices have fostered food production in low-fertility soils and sequestered carbon in the soil for centuries. We consider it likely that dark earth soils in other regions of Amazonia were also created intentionally through similar practices. Our results support the idea that managing soil to increase organic carbon content and incorporate charcoal is one of the most effective and readily available means to remove excess atmospheric carbon (*51*, *52*). Modern sustainable agriculture and climate change mitigation efforts, inspired by the persistent fertility of ancient dark earth, can draw on traditional methods practiced to this day by Indigenous Amazonians.

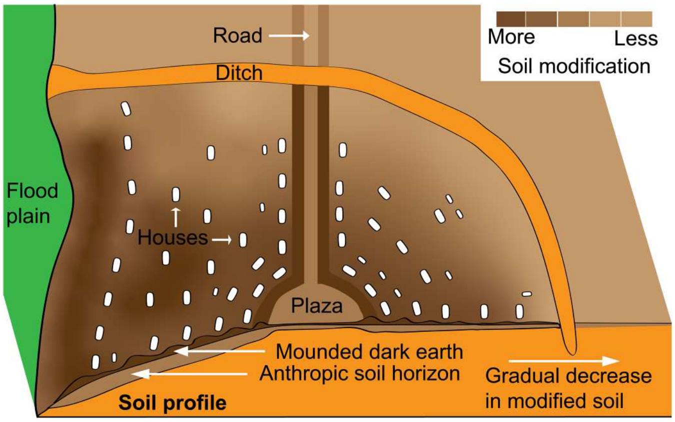

Fig. 4. Conceptual model of an ancient village showing locations of middens and enriched soils in relation to structures, earthworks, and the landscape. Not all sites contain all features shown.

MATERIALS AND METHODS

Study areas

Research was carried out in three study areas. The primary focus is on the Upper Xingu Basin (Fig. 1 and fig. S1), and additional case studies are presented for study areas on the Tapajós River (figs. S4 and S6) and in the Carajás Mountains (figs. S5 and S6).

The Upper Xingu Basin is a flat, low-lying sedimentary basin to the north of the central Brazilian highlands. The landscape is a mosaic of river channels, oxbow lakes, natural levees, low-lying floodplain, seasonal streams, ponds, seasonal floodplain lakes, large permanent lakes, and forested uplands. The Upper Xingu basin lies in a transitional floristic zone between the Amazon rainforest and the savanna (*cerrado*) of central Brazil. The annual average temperature is 25°C with 1800 mm/year of rainfall concentrated between October and April and a pronounced dry season from June to September (*41*). Upland soils in the study area are similar to soils that have been studied in nearby regions like the Suia-Missu river basin (*53*). They are predominately Oxisols (red latosols), highly weathered soils that are prevalent over extensive areas of the Amazon Basin characterized by low fertility, high acidity, phosphorous fixation, and aluminum toxicity. Soil texture in the Upper Xingu study area was found to be sandy clay or sandy clay loam, determined by grain size analysis for several locations under forest that were chosen to characterize background soils in the study area (*27*).

The Xingu Indigenous Territory covers more than 28,000 km^2 in northern Mato Grosso state. There are currently over 7000 inhabitants in the Territory from 16 different ethnic groups. The study area is centered around the principal village of the Kuikuro community and approximates the Kuikuro's traditional territory. Villages and archaeological sites are located on non-flooding uplands bordering the floodplains of the Culuene River (upper reach of the Xingu River) to the east and Angahuku (Buriti) River to the west. Archaeological research has documented cultural continuity in ceramic technology, settlement patterns, and overall use of the landscape throughout a chronological sequence spanning more than a millennium (*41*, *42*, *44*, *54*). It provides one of the best-studied examples of large, densely settled pre-European populations and intensive resource management in complex, built environments with ethnographic analogues from descendent populations, presenting a unique opportunity to address questions about the range of activities that produced the soil variation found in archaeological sites. Thirty-seven available calibrated radiocarbon dates from five Upper Xingu archaeological sites (Ngokugu, Heulugihütü, Akagahütü, Kuhikugu, and Seku) range from 2400 cal BP to modern, with one outlier at Ngokugu at ~cal 5000 BP (fig. S27 and table S7). Most dates fall between 1000 and 300 cal BP (*9*, *42*). Results are presented for research carried out at one current and two historic Kuikuro villages. The current village is referred to as Kuikuro II (Fig. 1) (*41*) and has been occupied from 1983 to the present. The previous village (Kuikuro I) (Fig. 1 and fig. S3) was occupied from 1973 to 1983. The historic village of Ipatse, located adjacent to Lake Ipatse, east of Kuikuro I, was occupied by the Kuikuro circa 1920–1940. Dates for the historic villages are known from previous researchers and Kuikuro oral history (*41*, *54*–*56*).

The Terra Preta do Mangabal (TPM) archaeological site is located on a high forested bluff on the left bank of the Upper Tapajós River within the traditionally occupied territory of riverine (*beiradeiro*) communities (fig. S4). Much of the dark earth at the TPM site is concentrated on the edge of the bluff and in the most elevated area. The site was used as a homestead in the recent past and a small area on the edge of the bluff is currently being cultivated with bananas. It appears that cultivation covered a small part of the site along the bluff edge in the recent past. The northern half of the site consists of old-growth forest with canopy emergent trees, resulting in the high organic carbon levels near the surface in the middle of the soil transect due to the thick forest litter layer. We excavated 70 auger holes at distance intervals of 25 to 50 m to delimit the archaeological deposits at the site. Our excavations indicate a reduction of artifacts northward as the landscape transitions to grassland, indicating an estimated area of at least 20 ha. The TPM site contains a large quantity of ceramic and lithic remains, as well as wood charcoal, carbonized seeds, and faunal remains. The average depth of dark earth at the site is 50 cm, although areas of middens and mounded deposits contain deeper dark earth horizons (*57*, *58*). Available radiocarbon ages range from 1260 to 940 cal BP (fig. S28 and table S7) (*57*, *58*), while available OSL dates range between 1572 ± 188 before present (BP) and 1135 ± 81 BP (table S8). These dates are interpreted to be from a single, continuous occupation that has been related to Tupian speakers ancestral to the Munduruku people (*59*).

The Mangangá archaeological site is a forested site in a valley in the Carajás Mountains located along the Sossego River (a mountain stream with headwaters on the nearby plateau) near the confluence of a small tributary (fig. S5) (*60*). The riverbank is a few meters high with a narrow floodplain, 20 to 30 m wide, on the southeast and south side of the site and an upper terrace where most of the archaeological deposits were found. The transect presented here is 100 m long with sampled profiles every 10 m. It begins at the river′s edge, crosses the narrow floodplain (20 m), and traverses the slope and upper terrace through archaeological deposits with dark earth (*61*, *62*). Radiocarbon dates on and near the transect range from 3700 to 500 BP, but the lower levels of excavations in other areas of the site were dated to as early as 11,800 BP, including early Holocene soil enrichment (fig. S29 and table S7) (*60*).

Mapping

Mapping of archaeological features and excavations in the Upper Xingu was carried out with a Trimble XRS Global Positioning System (GPS) receiver with real-time correction (*41*, *42*). Mapped features include ditches, plazas, roads, and water access locations. Plazas and roads are bordered by linear mounds up to 1 m high. These features were mapped by collecting points at intervals of several meters in the approximate center of the mound or ditch. Additional sample locations were recorded with a Garmin hand-held GPS. At the TPM site, sample locations were mapped with a total station and georeferenced with a Garmin hand-held GPS. Contours were derived from the Multi-Error-Removed Improved-Terrain (MERIT) digital elevation model (*63*). At Mangangá, the topography and sample locations were mapped with a total station and georeferenced with a Garmin hand-held GPS.

Soil sample collection

Soil samples were collected during archaeological excavations or in transects using a bucket auger. Excavations included 1-m-wide trenches that bisect archaeological features, 1-m^2 excavation units (including block excavations), or 50 × 50 cm test pits. Samples were collected from excavation walls with a trowel in a vertical column in 5- or 10-cm increments. Additional samples were collected at 1-m intervals in transects within or outside excavations using an 8-cm bucket auger to extract a core in 5- or 10-cm depth intervals up to 2-m deep.

At Kuikuro II, samples were collected from four test pits along a 60-m transect beginning in a backyard refuse disposal area and ending in a manioc field outside of the village (Fig. 1B). Additional samples were collected at 1-m intervals on transects within village zones (plaza, house, backyard, and refuse middens) and activity areas (hearths and manioc processing) (*27*). Samples were collected from a transect in the center of and parallel to an old midden that was formerly on the edge of a backyard at the Ipatse village site (occupied ca. 1920–1940). At the historic village site Kuikuro I (occupied ca. 1973–1983), samples were collected in the former plaza, domestic areas, middens, and trails (*27*). One 52-m transect, with samples at 1-m intervals to a depth of 30 cm, began in the plaza, passed through a former house and backyard, and lastly over a mounded midden (fig. S3).

At Seku, a transect with seven test pits begins in the mound surrounding the plaza and extends for 970 m between two major roads (Fig. 1C). At Akagahütü, we sampled a transect traversing the site from the edge of the floodplain, adjacent to a probable excavated pond, to the peripheral earthwork (ditch), and four additional test pits were excavated beginning on the outside of the ditch and leading away from the site between two major roads (fig. S1A). At Ngokugu, a 100-m transect, with cores every 5 m, begins on the outer edge of the circular central plaza, traverses the plaza mound, and crosses a residential area before terminating near the inner ditch (fig. S1B). Additional test pit transects traverse residential areas within the inner ditch and between the inner and outer ditches (*27*). Test pit transects at Heulugihütü pass through residential areas outside of the central plaza (fig. S1C) (*27*). At TPM, the 400-m transect begins on the upper slope of a steep bluff overlooking the Tapajós River, heads inland (north-northwest) crossing the relatively flat central area of the site until it leaves the forest and enters an adjacent savannah (fig. S4). The 100-m transect at Mangangá begins at the river′s edge, crosses a narrow floodplain, goes up a low slope with deposited dark earth, crosses a flat area devoid of dark earth, and then passes through a second deposit of dark earth before lastly entering an area of decreased enrichment beyond the second deposit (fig. S5) (*61*, *62*).

Soil laboratory analysis

We analyzed 3532 soil samples from 1176 individual locations (dataset S1). Each sample corresponds to a discrete depth range (e.g., 10 to 20 cm) from the excavation, test pit, or auger core. Laboratory analyses of soil samples were carried out at EMBRAPA Soils in Rio de Janeiro, EMBRAPA Amazonia Oriental in Belém, the Luiz de Queiroz College of Agriculture (ESALQ)/University of São Paulo in Piracicaba, the Department of Ecology at the Emilio Goeldi Museum (MPEG) in Belém, and the environmental laboratory of Eletronorte in Belém.

Samples were air-dried and screened through 2-mm mesh in preparation for chemical and physical analyses. For selected samples, particle-size analysis was performed on the <2 mm fraction. The sand fraction was measured by wet sieving, and the pipette method was used with 20 g of soil in 100 ml of distilled water plus 10 ml of 1 M sodium hydroxide (NaOH) for measuring clay and silt fractions. Physical analyses included measurement of magnetic susceptibility (MS) and apparent electrical conductivity (ECa) using a Terraplus (Canada) model KT10 SC instrument. To standardize the samples for analysis of MS and ECa, samples were placed in petri dishes 9 cm in diameter and 1.7 cm deep, holding approximately 150 g of soil.

All samples were analyzed for SOC using the modified Walkley-Black method, and soil pH was determined in distilled water (1:2.5 soil:solution) (*64*). A total of 193 samples were analyzed for fertility including measurements of pH in potassium chloride (KCl), exchangeable Al, Ca, and Mg by 1 M KCl extraction, and available P, K, Na, Cu, Fe, Mn, and Zn extracted with the Mehlich-1 solution [0.05 M hydrochloric acid (HCl) and 0.0125 M sulfuric acid, (H_2SO_4)] method (*64*, *65*). For 3339 samples, a standard hydrofluoric acid (HF) digestion was used in a closed-vessel microwave system to extract total elements from 0.1 g of sample (*27*, *66*). The mass concentration C_m of Al, Ba, Ca, Co, Cr, Cu, Fe, K, Mg, Mn, Na, Ni, P, Pb, Sr, Ti, V, and Zn was measured by inductively coupled plasma atomic emission spectroscopy (Varian Vista Pro simultaneous) with axial viewing, a radio frequency of 40 MHz, and charge-coupled device detection.

Soil data analysis

Fence diagrams of SOC, pH, and elemental mass concentration (Fig. 2 and figs. S2, S3, and S6 to S15) were generated by linearly interpolating along transects between sampled test pits. We assumed that each sample is representative of its associated depth range and that quantities are uniform across that range. For one missing sample (Seku, 970 m along transect, 30- to 40-cm depth), we estimated values by averaging the samples immediately above and below in the same test pit.

PCA was performed separately for each site using soil data normalized to a common mean and variance. PCA of the Kuikuro II, Seku, Mangangá, and TPM transects included pH, SOC, and available or extractable elemental concentrations. PCA of Akagahütü, Ngokugu, and Kuikuro I transects included pH, SOC, and total element concentrations. We plot fence diagrams of the first principal component as described above and give the weighting coefficients in tables S1 and S2.

To estimate SOC and phosphorous inventories, we used the average concentration in the upper 1 m of soil at each site. To compute this average, we used a depth-integrated approach. At each depth horizon between 0 and 1 m, we computed the average of all samples whose depth range includes this horizon. We combined these averages to estimate an average depth-concentration curve for each site (figs. S16 to S26), which we integrated to a depth of 1 m to compute the average concentration. Because of the nature of the sampling, this approach typically results in fewer samples representing deeper levels than shallower levels. We performed a similar calculation for samples collected outside dark earth sites to compute background soil properties. This calculation yields the average mass concentration C_m (M/M, dimensionless) in the upper 1 m of the soil. We report these values in tables S3 and S4.

We convert the mass fraction C_m to a volumetric concentration C_v (M/L^3) by multiplying by the bulk density r_b (M/L^3), $C_v = r_b C_m$, assuming a soil bulk density of 1100 kg/m^3 (*67*). This expression gives the average mass per unit volume of a soil quantity (e.g., SOC or P). By multiplying by a depth of 1 m, we calculate the areal density (M/L^2); this is the average mass per unit area contained within the upper 1 m. To estimate the total mass (M) contained within an archaeological site, we then multiplied this average by the area of the site (L^2), which we estimated using a combination of field mapping, test pits, earthworks, and vegetation patterns in satellite imagery (tables S3 and S4). For the modern Kuikuro II village, we calculated carbon and phosphorus inventories from measured concentrations and mapped areas of middens in 2002 (*27*). In the historic Kuikuro I village, we used measured concentrations and mapped areas of middens in 1993 (*41*). We report the areal densities, the mapped areas, and the total inventories in tables S3 and S4.

Upper Xingu sites differ in forest cover and recent land use history, as many of the ancient dark earth sites have been used for cultivating crops within living memory. Each site was designated as forested or deforested; in this case, only Seku was designated as a forested site. To account for the lower naturally occurring SOC and nutrient concentrations in deforested settings, we computed background concentrations separately for forested and deforested samples away from archaeological sites (9.2 g/kg SOC and 856 mg/kg total P in forested areas; 6.8 g/kg SOC and 277 mg/kg total P in deforested areas). We subtracted the appropriate value from each dark earth sample to estimate the anthropogenic contribution (tables S3 and S4).

Mass concentration data in the supplementary table were standardized to mg kg^{-1}. Results that were reported in cmol$_c$ or mmol$_c$ were converted to mg by multiplying mmol$_c$ by the atomic weight of the appropriate element. For results reported in volumetric units (dm^3) (Mangangá samples), a pedofunction was used that estimates the fine earth density (<2-mm grain size) based on the quantity of organic carbon (*68*).

Geochronological analysis

We collected samples for radiocarbon dating from charcoal in situ in archaeological test pits and excavations at Akagahütü, Seku, and areas between archaeological sites (table S7). Samples were measured by accelerator mass spectrometer at Beta Analytic in Miami, Florida. We converted radiocarbon dates to calibrated ages with the SHCal20 calibration curve (*69*) using OxCal 4.4 (*70*). We also compiled previously published radiocarbon dates from Ngokugu, Heulugihütü, Kuhikugu (*9*), Mangabal (*57*), and Mangangá (*60*) and recalibrated these dates with the updated calibration curve. We report all radiocarbon dates and calibrated ages in figures S27 and S29 and table S7.

Optically stimulated luminescence (OSL) dating (table S8) was performed at the Laboratory of Gamma Spectrometry and Luminescence at the Institute of Geosciences, University of São Paulo. The dose rate was estimated by gamma spectrometry with a high-purity germanium detector using ultralow background shielding. The dose equivalent was determined by single-aliquot regenerative-dose protocols with multigrain aliquots of quartz. The OSL measurements were carried out with a Lexsyg Smart detector equipped with a beta radiation source (Sr/Y) with a dose rate of 0.116 Gy/s. The preparation of quartz aliquots included the following steps: First, detrital grains in the size range of 180 to 250 μm and 125 to 250 μm (sample 5522) fractions were recovered by wet sieving; second, the target fraction was treated with hydrogen peroxide (H_2O_2, 27%) to eliminate organic matter and hydrochloric acid (HCl, 10%) to remove carbonate minerals; third, a heavy liquid separation with lithium metatungstate (LMT) was used to separate heavy and light minerals (LMT = 2.75 g/cm^3) and quartz (LMT = 2.62 g/cm^3); fourth, the samples were etched in HF (30%) for 40 min to eliminate the external layer of quartz grains and feldspar remnants. Equivalent doses of samples were calculated using the Central Age Model, Minimum Age Model (overdispersion > 30%), and simple mean average (aliquots with dose saturation) (sample 5522). Only aliquots with a recycling ratio between 0.9 and 1.1, a recuperation <5%, and no contamination of feldspar (IR signal) were considered for the calculation of equivalent dose. A dose recovery test was made on sample 5024 (preheating to 220°C, administering doses of 2.5, 5, and 10 Gy).

Ethnographic research

Ethnographic and ethnoarchaeological research consisted of observations, mapping, sampling, and recording interviews carried out over 12 months of fieldwork between 2002 and 2019 in collaboration with the Kuikuro community. Informed consent was obtained from all study participants. Observations were used to determine the spatial distribution of activities in the village, which were then mapped using GPS. Soil cores were collected and analyzed in the different activity areas. Interviews were carried out with elder agricultural specialists in the community in the native Kuikuro language. Video recordings of nine interviews were translated into Portuguese by experienced Kuikuro translators and then translated to English (text S2). Portuguese text received minor edits to improve readability but was otherwise left in the translator′s words.

We analyzed the interview texts by excerpting and tabulating interviewee responses related to two topics: soil management (table S5) and dark earth fertility and cultivation (table S6). We scored each response related to soil management according to whether it supports the hypothesis of intentional dark earth creation, contradicts intentionality, or neither supports nor contradicts intentionality (table S5). Text S2 provides additional information on the interviews, a glossary of key terms in the Kuikuro language, and the complete translations of the interviews in Portuguese and English.

Supplementary Materials

This PDF file includes:
Text S1 and S2
Figs. S1 to S29
Tables S1 to S8
Legend for dataset S1
References

Other Supplementary Material for this manuscript includes the following:
Dataset S1

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