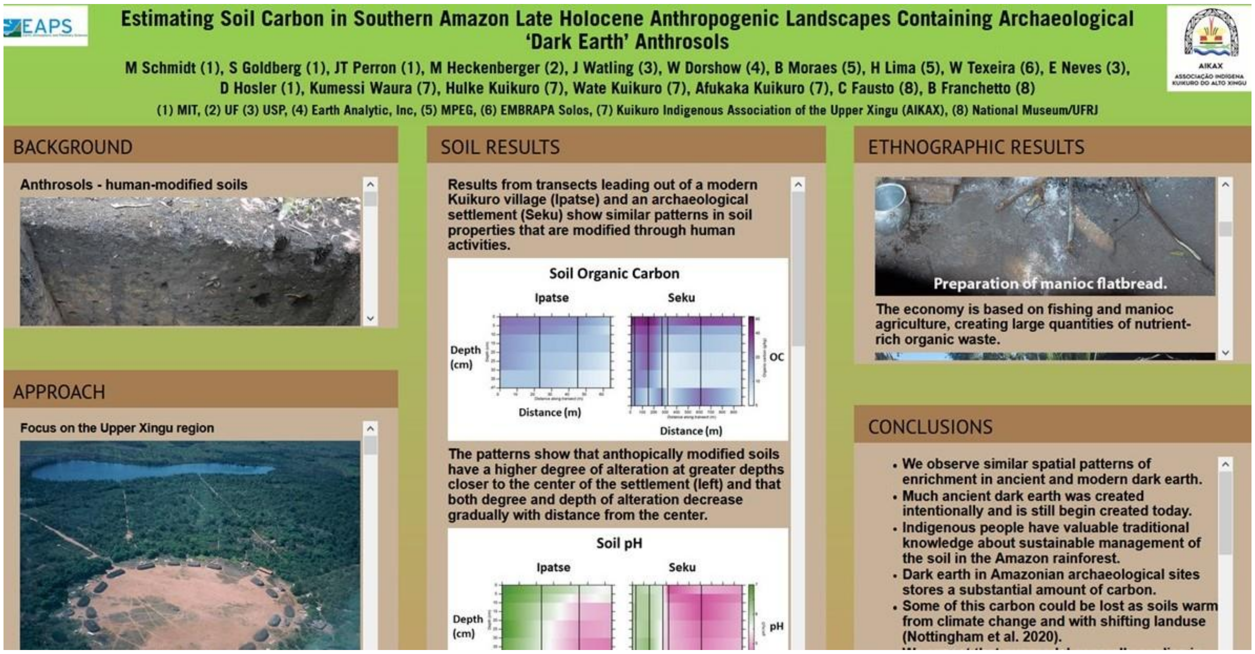
# Estimating Soil Carbon in Southern Amazon Late Holocene Anthropogenic Landscapes Containing Archaeological 'Dark Earth' Anthrosols

Morgan J. Schmidt[1], Samuel Lukens Goldberg[1], J Taylor Perron[1], Michael Heckenberger[2], Jennifer Watling[3,4], Wetherbee Bryan Dorshow[5,6], Bruno Moraes[7,8], Helena Lima[8], Wenceslau Texeira[9], Eduardo Neves[3,4], Dorothy Hosler[10,11], Kumessi Waura[12], Hulke Kuikuro[12], Wate Kuikuro[12] Afukaka Kuikuro[12], Carlos Fausto[13], Bruna Franchetto[13]

(1) Massachusetts Institute of Technology, Earth, Atmospheric and Planetary Sciences, Cambridge, MA, United States, (2) University of Florida, Anthropology, Gainesville, FL, United States, (3) University of Sao Paulo, Sao Paulo, Brazil, (4) Museu de Arqueologia e Etnologia, Sao Paulo, Brazil, (5) Earth Analytic, Inc, Santa Fe, NM, United States, (6) Puente Institute, Santa Fe, NM, United States, (7) University of Pittsburgh, Anthropology, Pittsburgh, United States, (8) Museu Paraense Emilio Goeldi, Belem, Brazil, (9) EMBRAPA Solos, Rio de Janeiro, Brazil, (10) Massachusetts Institute of Technology, Materials Science and Engineering, Cambridge, MA, United States, (11) Center for Materials Research in Archaeology, Cambridge, MA, United States, (12) Kuikuro Indigenous Association of the Upper Xingu (AIKAX), Ipatse, Brazil, (13) National Museum/ Federal University of Rio de Janeiro.

## Plain Language Summary

Amazonian dark earths (ADE) are extremely fertile soils with concentrated carbon and nutrients that formed mainly over the past few thousand years, prior to the arrival of Europeans, but are still forming on a more limited scale up to the present in indigenous communities. Our research aims to shed light on the distribution of modified soils in distinct regions of the Amazon in relation to landforms and the environment. Scientists studying ADE soils discovered that charcoal is an important part of what keeps them so fertile for so long. Many believe that putting charcoal into the ground could help to remove excess carbon from the atmosphere and thereby reduce global warming. However, no one really knows how much extra carbon is stored in the ground in these ancient human-made soils. We collected several thousand soil samples in an indigenous territory of the southeastern Amazon in the region of the headwaters of the Xingu River. The samples are from many different areas including modern villages and archaeological sites. We aim to discover how the modified ADE soil is created and distributed around the landscape and how much extra carbon is stored there.




Cite as: Schmidt, MJ, Goldberg SL, Perron JT, Heckenberger MJ, Watling J, Dorshow WB, Moraes B, Lima H, Texeira W, Neves EG, Hosler D, Kumessi Waura, Hulke Kuikuro, Wate Kuikuro, Afukaka Kuikuro, Fausto C, Franchetto B. Estimating Soil Carbon in Southern Amazon Late Holocene Anthropogenic Landscapes Containing Archaeological 'Dark Earth' Anthrosols. Poster presented at the American Geophysical Union (AGU) Fall Meeting, San Francisco, CA, December 1-17, 2020.


## Abstract

ADE, a result of domestic, economic, and agricultural activities in and around human settlements, are noted for their extraordinary fertility and resilience and for the significant quantities of organic carbon, much in the form of charcoal. The deepest and most extensive areas of ADE are generally located on the bluffs of major rivers adjacent to floodplains, but significant areas of ADE have also been found in floodplains and in headwater and interfluvial areas. Our research aims to shed light on the distribution of modified soils in distinct regions of the Amazon in relation to landforms and the environment. Although research on ADE has led to a proliferation of studies on charcoal in soil management and the development of a 'biochar' industry that promotes the incorporation of charcoal into the soil for the dual purpose of improving fertility and sequestering carbon, there is a notable lack of research attempting to quantify the carbon over the scale of a site or region in Amazonia. We undertook this challenge in the Upper Xingu region of southeastern Amazonia in partnership with the local Kuikuro indigenous community who have shared their valuable traditional knowledge on the creation and management of ADE. We used data from over 3500 soil samples from diverse contexts, both ancient and modern, that we collected and analyzed over the past two decades for organic carbon and a range of other chemical and physical properties. Dark earth samples from profiles down to 1 m depth in archaeological sites ranged from 20% to 150% more OC than unmodified forest soil and dark earth profiles in current and historic villages ranged from 20-90% more. We used the results from soil sample transects to estimate the carbon in landuse zones within and surrounding modern, historic, and ancient settlement sites. In continuing work, we are attempting to use satellite remote sensing and artificial intelligence with ground truth data to extrapolate our results across the Upper Xingu region and beyond.

## “Live” Introduction Text

Amazon upland rainforest soils are notorious for their fragile fertility and problems inherent in highly weathered soils of the Tropics. When forests are cleared for agriculture, fertility can quickly drop without intensive management. Dark earth soils stand out for their high fertility, resilience, and high organic carbon content, including abundant charcoal. Organic carbon is recalcitrant and protected in the soil. Dark earths formed at locations of human settlements over the last 2 ½ millennia and are still forming today in some indigenous villages.

Dark earths have taken on new importance as we face a world with atmospheric carbon levels over 30% higher than pre-industrial levels and rising fast. With more carbon than the atmosphere and vegetation combined and a virtually unlimited capacity to sequester and store carbon, soil management for carbon storage will be fundamental to our efforts to take up atmospheric carbon. Research on dark earth has inspired attempts to recreate it and launched the biochar industry that aims to improve soil fertility while sequestering atmospheric carbon.

It has long been known that dark earth soils store significantly more organic carbon than normal background soils but there have been few attempts to quantify it at the site or landscape level. Our results from the Southeastern Amazon show organic carbon levels at archaeological sites and a modern village that are from about 20-220% more than background levels. Landuse, forested versus non-forested, appears to make a large difference in the long-term preservation of carbon in the soil. A forested site that had been cultivated only once, several decades ago, contained more than double the background levels of carbon while a site that has been repeatedly cultivated and burned contained only 20% more than background levels. Dark earth in a modern village contained 59 tonnes/ha of anthropogenic organic carbon and dark earth in a forested archaeological site contained 130 tonnes/ha above background levels. These measurements do not include additional organic carbon in the form of charcoal.

Results of our ethnographic research revealed that indigenous Kuikuro farmers intentionally create dark earth on the periphery of the settlement for cultivating crops. They often spread ash with charcoal and organic waste over the surface to fertilize the soil for later cultivation and they speak with pride about the fertile soil they create.

The refuse disposal and soil management activities carried out in residential areas and on the periphery of the settlement create a pattern of soil modification that is more intense in refuse disposal areas and gradually diminishes with distance outside the settlement. Results of soil analyses show a similar pattern in archaeological settlements suggesting that similar practices were carried out in the past to produce dark earth.

The adoption of sustainable indigenous techniques for managing the soil could increase carbon sequestration and storage. Preservation of the forest on dark earth sites could help to hold the carbon in the ground, while landuse change and cultivation can send it back up to the atmosphere. Climate change will also contribute to carbon loss as soils warm.

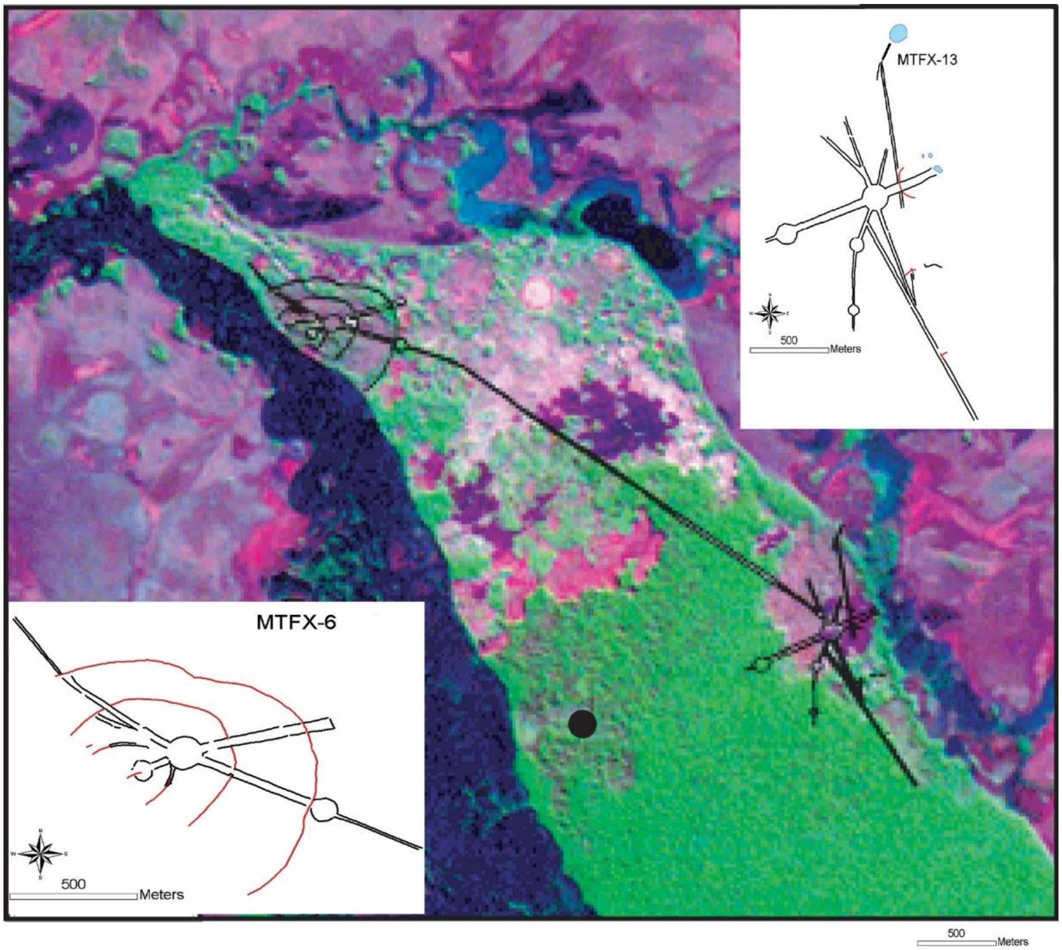
This research highlights the value of traditional knowledge of resource management and research partnerships with indigenous communities for solving today’s pressing problems.

## BACKGROUND

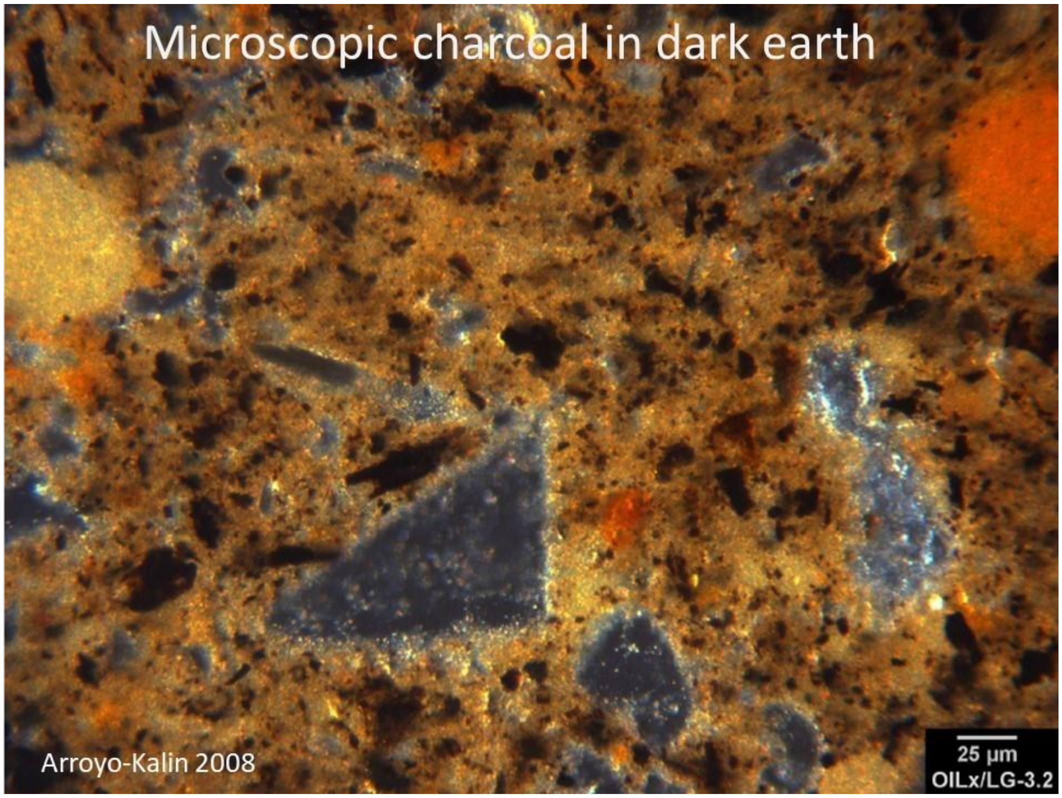
Anthrosols - human-modified soils


Dark earth soils are characterized by dark color, high organic matter, high fertility, elevated levels of soil nutrients, and the presence of charcoal, artifacts and ecofacts.


In the Amazon Basin they formed in areas of ancient settlements.




Map showing two archaeological sites in the Upper Xingu (Heckenberger et al. 2003).



Soil organic carbon (SOC) is elevated above background levels and includes quantities of recalcatrant pyrogenic carbon. SOC is protected in soil aggregates and organo-mineral complexes.

Big Questions about Dark Earth

- How much stored carbon?
- How fertile?
- How widespread?
- How was it formed?
- Was it intentional?

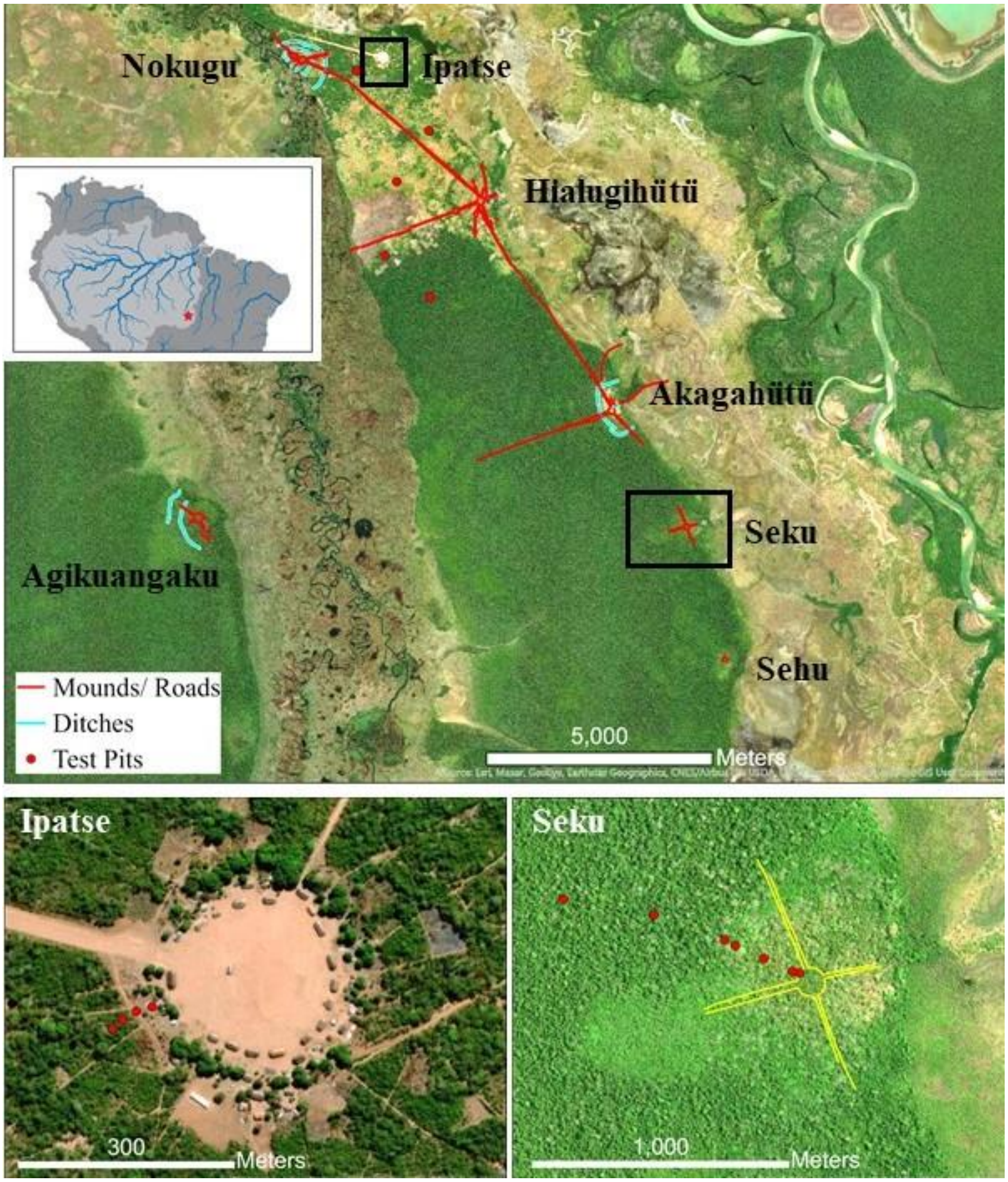
We found that carbon and nutrient levels are substantially higher than background levels and gradually decrease with distance on the periphery of settlements. Ethnographic data indicates that much dark earth is intentionally formed through soil and waste management practices.

# APPROACH

Focus on the Upper Xingu region

Kuikuro (Ipatse) village in the Upper Xingu.

The research was a collaboration with the indigenous Kuikuro community as partners and sponsors of the research.



Upper Xingu Study Area with insets of the Kuikuro village (Ipatse) and Seku archaeological site.

## FIELD DATA COLLECTION

We analyzed depth-resolved soil samples along transects in ancient and modern settlements, measuring organic carbon, pH, nutrient concentrations, and physical properties.
Results are shown in diagrams for two transects. The Ipatse transect begins in the backyard trash midden area (on left in diagram) and proceeds for 60 m outside the village into an adjacent manioc garden. The Seku transect begins at the plaza edge and proceeds for 970 m outside the settlement.

## MAPPING

We carried out mapping with hand-held and precision GPS incorporated into an online GIS.

Features including plazas, roads, ditches and middens were mapped with GPS.

## SAMPLE COLLECTION

Samples were collected from archaeological trenches, test pits and cores along transects at a contemporary Kuikuro village (Ipatse), two historical villages, five archaeological sites, and off-site locations.

## LABORATORY ANALYSIS

We measured 18 soil properties including pH, organic carbon, Al, P, Ca, K, Mg, Cu, Fe, Mn, Zn, magnetic susceptibility, and electrical conductivity.

## ETHNOGRAPHIC RESEARCH

We performed ethnographic study of modern indigenous soil management beliefs and practices.

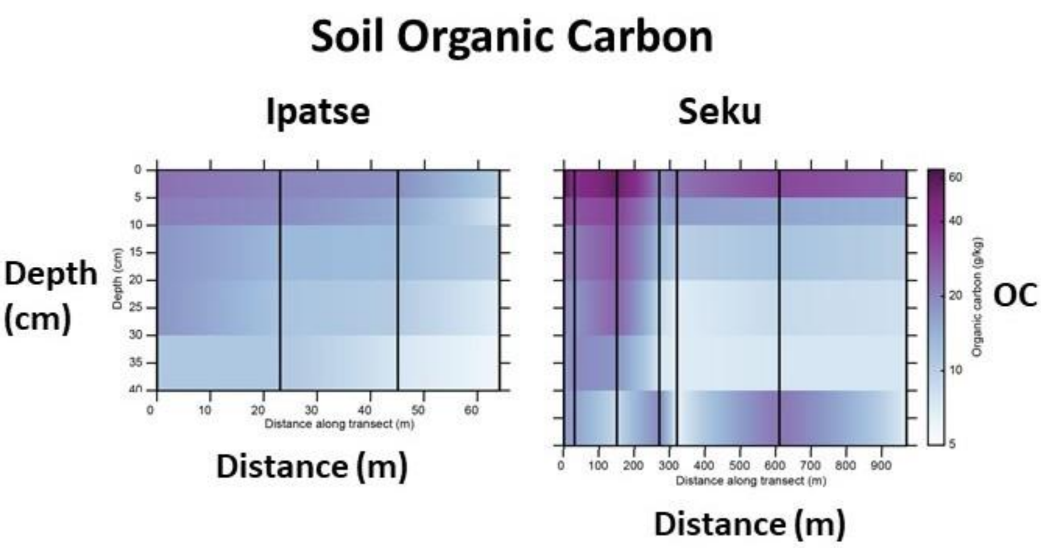
Interviews were carried out with elders in the native Kuikuro language.

Observations and mapping of daily activities were carried out.

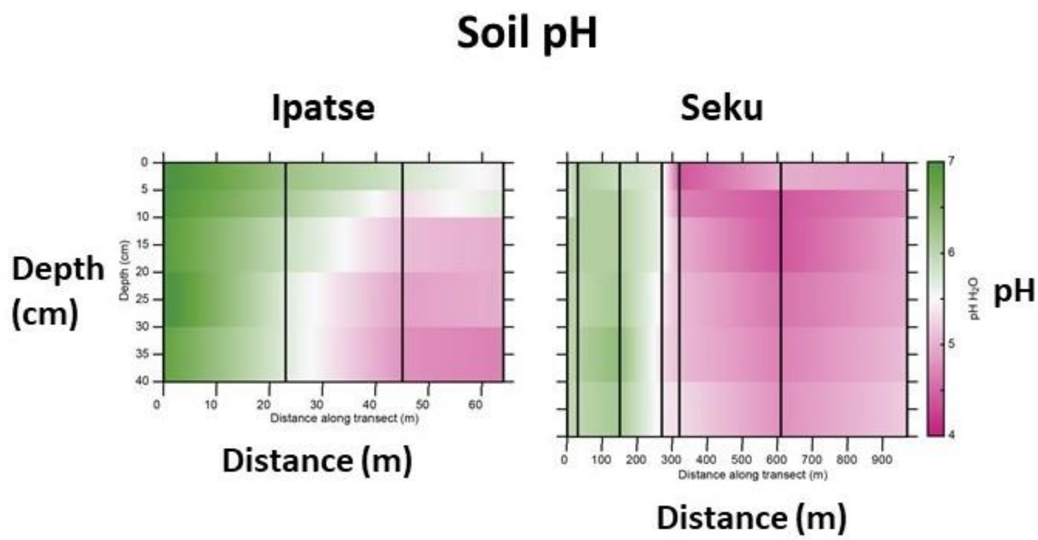

Field visits were carried out.

# SOIL RESULTS

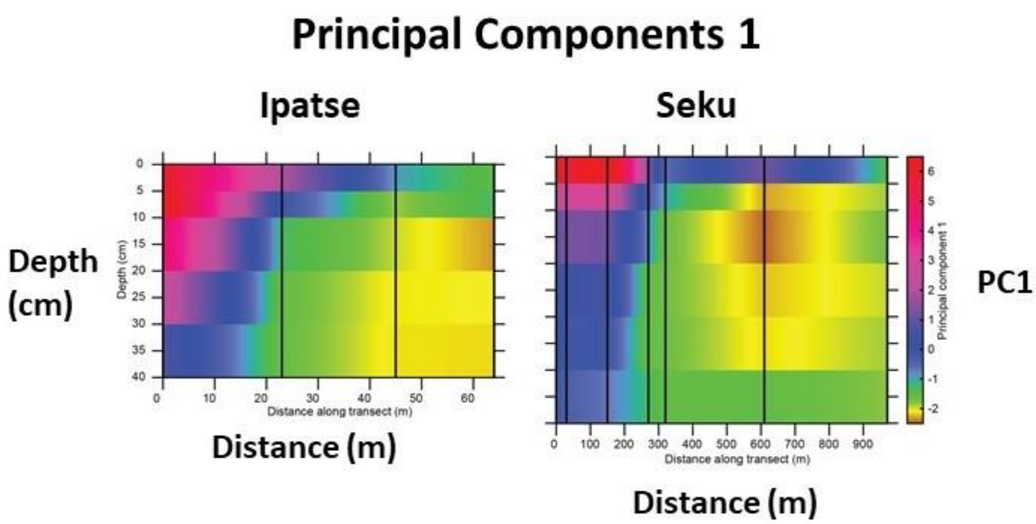
Results from transects leading out of a modern Kuikuro village (Ipatse) and an archaeological settlement (Seku) show similar patterns in soil properties that are modified through human activities.




The patterns show that anthopically modified soils have a higher degree of alteration at greater depths closer to the center of the settlement (left) and that both degree and depth of alteration decrease gradually with distance from the center.



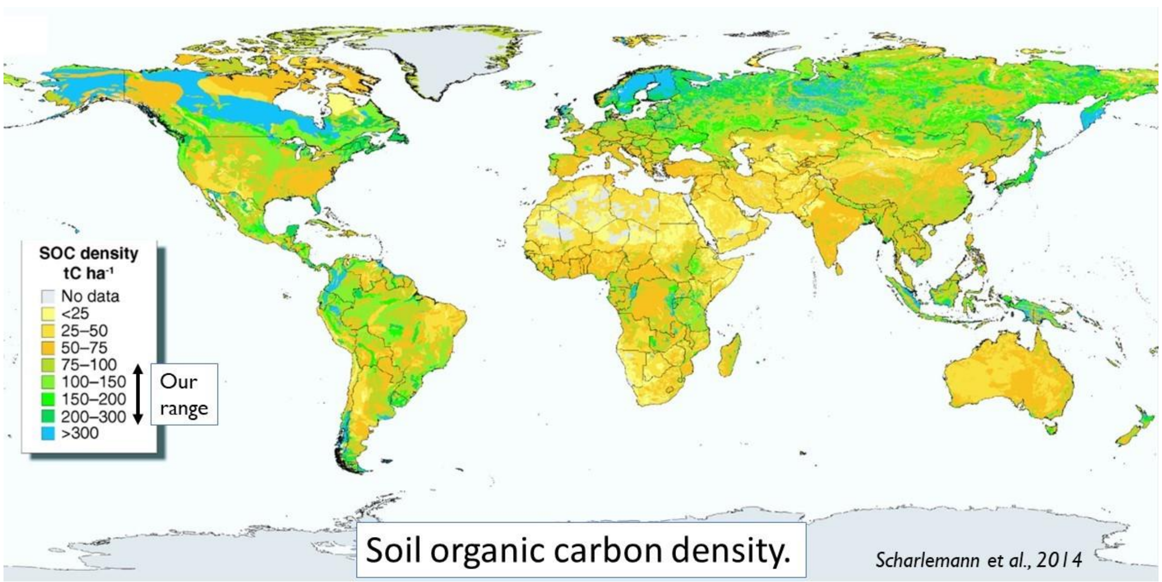

Other human-modified properties include P, K, Ca, Mg, Cu, Fe, Mn, Zn, magnetic susceptibility, electrical conductivity, and cation exchange capacity.



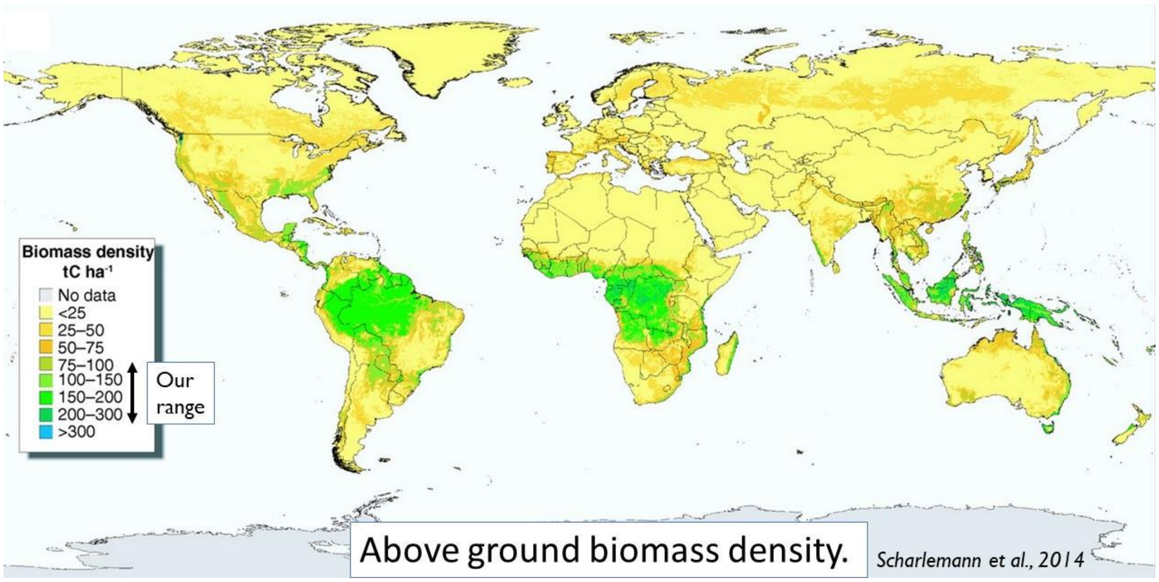

Principal components analysis incorporates these variables to show the general pattern. Concentrations not generally increased by human activities but are abundant in background soils, such as Al and Fe, show inverse relationships.

| | | Organic carbon abundance (tonnes/ha) | Area (ha) | Inventory (tonnes) |
|---|---|---|---|---|
| | Forested background | 111 | - | - |
| | Unforested background | 81 | - | - |
| *Forested sites* | Seku dark earth | 241 | 38 | 9000 |
| | Akagahütü dark earth | 129 | | |
| *Unforested sites* | Nokugu dark earth | 97 | 61 | 5900 |
| | Modern village | - | 6.8 | 650 |
| | *- Domestic* | *76* | *1.8* | *130* |
| | *- Midden* | *140* | *2.1* | *300* |
| | *- Plaza* | *75* | *2.9* | *220* |

Soil organic carbon abundance and inventory in different contexts. Results show an elevated abundance of SOC in archaeological sites and in middens in the modern village.




Dark earth is among the most carbon-rich soils on earth.



Dark earth contains as much carbon in the top 1 m of soil as all above ground biomass.

## ETHNOGRAPHIC RESULTS

Kuikuro farmers intentionally create dark earth by spreading ash, charcoal, and organic waste.

The economy is based on fishing and manioc agriculture, creating large quantities of nutrient-rich organic waste.

Residents exploit the refuse disposal area for planting diverse crops.

The most fertile modified soil forms in trash middens mounded up to 60+ cm above the original ground surface. Trails cut through the area of middens surrounding the village.

Manioc processing waste is often spread over the ground for fertilizing the soil.

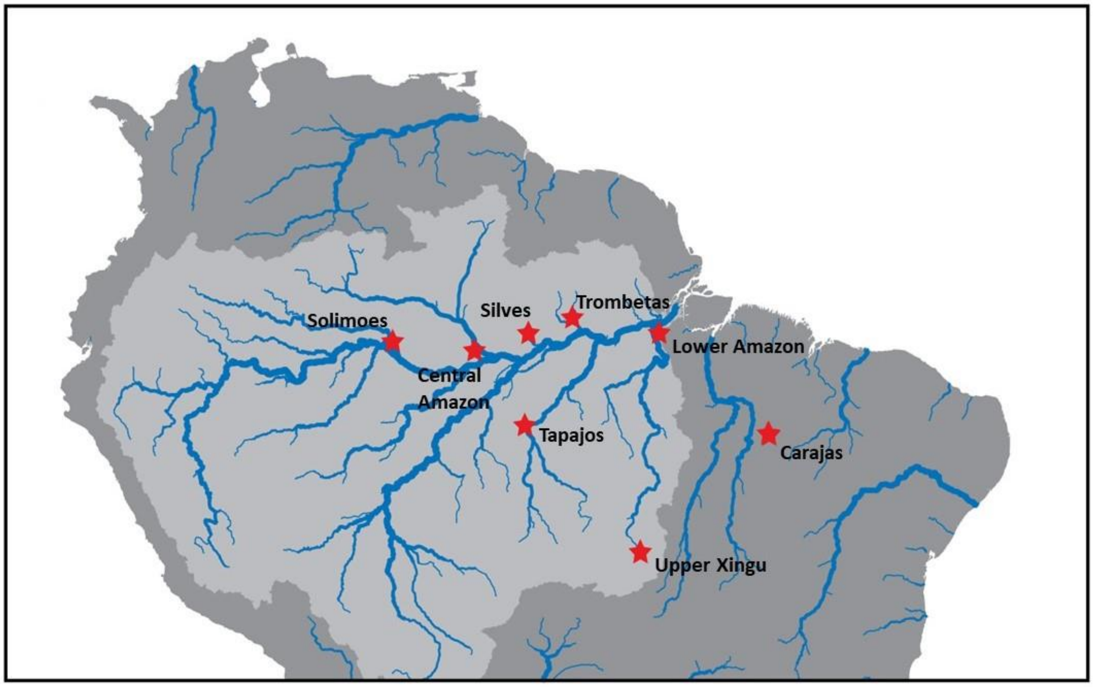
Burning is used for diverse purposes, making a large contribution to dark earth formation.


"Charcoal and ash we sweep, gather it up and then throw it where we will plant, to turn into beautiful *eegepe* [dark earth]. 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, and then it turns into beautiful eegepe."

Interview with Kanu Kuikuro, June 2018
Translation by Yamalui Kuikuro

# CONCLUSIONS

- We observe similar spatial patterns of enrichment in ancient and modern dark earth.
- Much ancient dark earth was created intentionally and is still begin created today.
- Indigenous people have valuable traditional knowledge about sustainable management of the soil in the Amazon rainforest.
- Dark earth in Amazonian archaeological sites stores a substantial amount of carbon.
- Some of this carbon could be lost as soils warm from climate change and with shifting landuse (Nottingham et al. 2020).
- We expect that our model generally applies in diverse regions of the Amazon Basin.




Locations with similar patterns of soil modification based on archaeological and soil research.

# REFERENCES

Arroyo-Kalin, M., 2008. Steps towards and Ecology of Landscape: a Geoarchaeological Approach to the Study of Anthropogenic Dark Earths in the Central Amazon Region, Brazil. Doctoral dissertation. Department of Archaeology, University of Cambridge, Cambridge.

Heckenberger, M.J., Kuikuro, A., Kuikuro, U.T., Russell, J.C., Schmidt, M., Fausto, C., Franchetto, B., 2003. Amazonia 1492: pristine forest or cultural parkland? Science 301:1710-1714.

Nottingham, A., P Meir, E Velasquez, BL Turner, 2020. Soil carbon loss by experimental warming in a tropical forest. Nature 584:234-237.

Scharleman, J.P.W., Tanner, E., Hiederer, R., Kapos, V. 2014. Global soil carbon: understanding and managing the largest terrestrial carbon pool. Carbon Management v. 5, num. 1:81-91.

Schmidt, M.J., 2010. Reconstructing tropical nature: prehistoric and modern anthrosols (terra preta) in the Amazon rainforest, upper Xingu River, Brazil. Doctoral dissertation. Geography Department, University of Florida, Gainesville.

SCHMIDT, M.J.; PY-DANIEL, A.R.; MORAES, C.P.; VALLE, R.B.M.; CAROMANO, C.F.; TEXEIRA, W.G.; BARBOSA, C.A.P.; FONSECA, J.A.; MAGALHÃES, M.P.; SANTOS, D.S.C.; SILVA, R.S.; GUAPINDAIA, V.L.; MORAES, B.; LIMA, H.P.; NEVES; E.G.; HECKENBERGER, M.J. Dark Earths and the human built landscape in Amazonia: a widespread pattern of Anthrosol formation. Journal of Archaeological Science, v. 42, p.152-165, 2014.

Woods, W.I., Texeira, W.M., Lehmann, J., Steiner, C., WinklerPrins, A.M.G.A., Rebellato, L. (Eds.), 2009. Amazonian Dark Earths: Wim Sombroek's Vision, Springer, New York.

# ACKNOWLEDGEMENTS

We thank the Kuikruo Indigenous Association of the Upper Xingu and community for making research possible. Research was partially funded by grants from the National Science Foundation, Abdul Latif Jameel Water and Food Systems Lab, Wenner-Gren Foundation, and William T. Hillman Foundation.

J-WAFS

The Wenner-Gren Foundation
For Anthropological Research, Inc.

NSF

EAPS
Earth, Atmospheric and Planetary Sciences