Ancient Footprints, Modern Pathways to Sustainability

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1 Lost Amazonian cities in Upper Xingu

Centuries ago, in the warmth of the Medieval Warm Period, one of the hottest eras humanity has known until today, the Kuikuro and their Indigenous neighbors created a remarkable, green urbanism deep within the southern Amazon. In the heart of the Upper Xingu, they built an intricate network of circular villages, thriving gardens, meandering canals, and protective earthworks, now known as "garden cities." [1]. Some features of this landscape, such as wetland management, and wide roads, hold remarkable relevance for today's sustainability challenges. The Kuikuro's enduring presence in this region reflects how traditional ecological knowledge and cooperative land stewardship allowed them to thrive even during climatic extremes.

However, only in recent decades have scientists begun to fully appreciate this sophisticated Indigenous legacy, in part due to the challenges of terrain, remoteness, and limited interdisciplinary integration across ecological and technological domains. A turning point came in the early 2000s, when Heckenberger uncovered Amazonian Dark Earth (ADE) and large, geometrically organized settlements in the Upper Xingu, connected by roads, reservoirs, and ditches, which had fundamentally shifted the narrative of Amazonia as a pristine wilderness [2][3]. Walker later cataloged 2,000 archaeological sites in the Amazon basin, including 46 in the Upper Xingu. Yet these findings likely represent only a fraction of what remains undiscovered [4]. To date, no study has unified LiDAR terrain models, Sentinel-2 satellite imagery, soil and climate data, and cultural proximity measures in a comprehensive machine learning framework to uncover unknown archaeological sites in the Upper Xingu.

Inspired by the idea of an "**archaeology of hope**" [5], we believe archaeology is not just a tool for understanding what was, but a lens for imagining what could be. By tracing how Indigenous people once responded to environmental shifts with resilience, creativity, and harmony, we seek models for navigating our present crises. Therefore, we ask our questions:

1. *How can modern geospatial and AI techniques help identify ADE and earthwork in the Upper Xingu?*
2. *What can the spatial distribution of ADE and landscape engineering reveal about sustainable land-use strategies in ancient Amazonia?*

To explore these questions, we developed a novel computational approach that integrates multiple modalities—LiDAR terrain models, Sentinel-2 satellite imagery, environmental data, and cultural proximity measures, within a machine learning framework. Our method uniquely incorporates generative AI to hypothesize plausible site locations and interpret model predictions, allowing us to prioritize the most promising areas for future archaeological investigation. This project opens an invitation to recover the ecological wisdom of the Kuikuro ancestors. By uncovering and interpreting these ancient systems, we may gain valuable insights for addressing the ecological and climatic crises of our time.

2 Functional and Environmental Hypotheses for Two Predicted ADE Sites in the Upper Xingu

Our integrated framework identified two high-potential candidate sites for Amazonian Dark Earth (ADE) deposits in the Upper Xingu region: **Site 1** at latitude -11.4869, longitude -55.3030; and **Site 2** at latitude -11.3475, longitude -55.2940.

These sites exhibit outstanding ADE probability scores (0.458 and 0.444), placing them in the top 5% of all GPT-simulated test coordinates in Figure 2. Both are situated within 25 km of major river systems and at mid-elevations (363–369 m), echoing the ecological signatures of known ADE contexts across Amazonia.

Our Random Forest model, trained on $\sim$2,000 labeled archaeological sites, identified **Lidar elevation**, **distance to river**, **topographic elevation**, **precipitation in the coldest quarter (Bio19)**, and **temperature annual range (Bio7)** as the most important predictors for ADE classification (Figure1). Both candidate sites fall within favorable thresholds for these variables—located on *terra firme* uplands with hydrological access and climatic stability, which are key preconditions for long-term anthropogenic soil formation.

Spatially, these locations lie west of the established Xinguano settlement core, within ecologically analogous but understudied zones. Their landscape and environmental profiles suggest they may represent *subsidiary village clusters*, *late pre-Columbian frontier expansions*, or *persistent agroecological zones* (ca. 1000–1500 CE). Ethnoarchaeological literature notes that ADE commonly formed near semi-sedentary village networks, raised-field systems, and forest-edge management strategies. Both predicted sites sit on elevated ridges, avoiding lowland floods while remaining near aquatic routes for transportation and subsistence—settlement traits characteristic of the Xingu-Issanaré cluster to the east.

Climatically, the candidates fall within the optimal range for both Bio19 and Bio7, indicating seasonal predictability and potential for slash-and-burn cycles and post-harvest enrichment—known contributors to ADE formation. Their soil and vegetation characteristics, extracted via Google Earth Engine, further align with patterns observed at confirmed ADE sites.

These spatial-environmental signatures suggest they may mark **western frontier expansions** of known ADE clusters, extending the boundaries of pre-Columbian occupation. Notably, these locations remain unregistered in archaeological databases and deforestation alerts (e.g., TerraBrasilis), enhancing their novelty.

Functionally, the two sites may have supported **satellite agroecological hamlets** embedded in polynucleated settlement systems, consistent with the **forest urbanism** paradigm—where Indigenous communities transformed landscapes without large-scale clearing. Discovering ADE here would provide compelling evidence for decentralized, resilient, and ecologically attuned land-use strategies by ancestral Xinguano societies.

Taken together, these factors support high confidence in the archaeological potential of these two sites and underscore their value as priorities for future collaborative field validation.

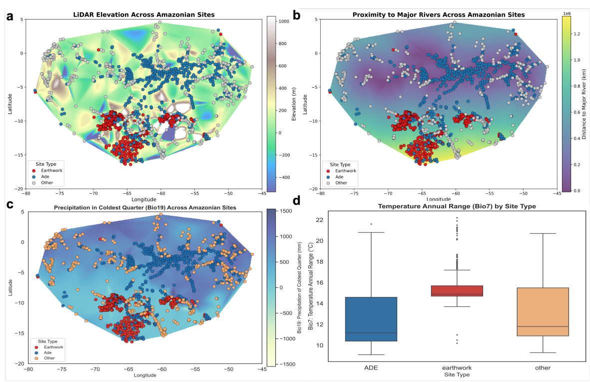

Figure 1: Top predictors distinguishing three archaeological sites.

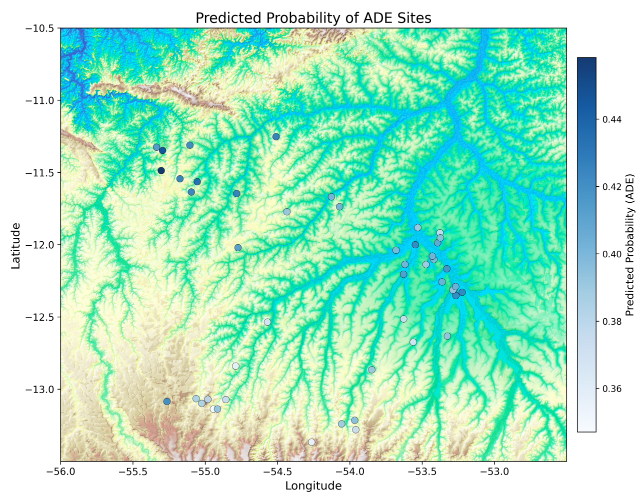

Figure 2: Predicted ADE probabilities across candidate sites.

3 Proposed survey effort with local partners

To validate our model predictions and deepen our understanding of past human–environment relationships, we propose a collaborative survey effort grounded in community-based archaeology. In partnership with the Kuikuro and other Xinguano communities, this initiative will integrate low-impact field techniques—including drone-based LiDAR mapping, surface vegetation surveys, shallow soil geochemistry (e.g., phosphorus and charcoal analysis), and shovel test pits, with oral histories and Indigenous ecological knowledge.

Beyond detecting traces of Amazonian Dark Earth or ancient earthworks, our goal is to illuminate how ancestral populations lived not against the forest but *with* it—modifying soils, managing water, and shaping vegetation through sustainable, decentralized, and enduring strategies. These field efforts are not solely about verifying predictions; they are about co-producing knowledge that places Indigenous stewardship at the heart of ecological resilience.

A shared digital dashboard will support transparent collaboration, enabling real-time updates, integration of community insight, and participatory decision-making. In doing so, we aim to establish not merely a validation pipeline, but a replicable, decolonial model for archaeological science, one that elevates ancestral ingenuity as a guide for facing today's challenges: from climate change to biodiversity loss to sustainable land use.

This journey is more than a search for sites-it is a dialogue across time. The deep soils of the Upper Xingu may preserve not only the imprint of habitation, but the memory of aspiration: of people who lived in reciprocity with rivers, ridges, and rain. By fusing AI-driven discovery with Indigenous-led interpretation, we seek not just to reveal data, but to recover wisdom—encoded in landscapes, embedded in story.

Our project is a small gesture within a larger movement: an archaeology not of collapse, but of continuity; not of conquest, but of care. As we uncover ancient blueprints for living well with the land, we are reminded that the past is not behind us, it lies beneath us, ready to teach. In the footprints of the forest, we glimpse pathways toward a more resilient, more just future.

References

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