Pre-Columbian forest gardens span 180 km² in Bolivia's Iténez preserve

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The Iténez Forest Preserve in the Bolivian Amazon spans 4,000 km² between two of South America's most significant archaeological landscapes—yet until now it remained unmapped, a blank spot between lowland Bolivia and the Brazilian Amazon. Using satellite imagery from the driest months on record and an AI-assisted detection system, I identified 180 km² of anthropogenic soils and forest gardens across the preserve. These features, connected by dense networks of earthworks that remain to be fully mapped, reveal organized landscape modification on a scale comparable to the region's famous earthwork complexes. The findings demonstrate how ancient peoples transformed rainforest into productive cultural landscapes whose ecological signatures persist today, with local communities continuing to harvest cacao and other useful species from these anthropogenic forests. This work illustrates how AI can support—but not replace—human expertise in archaeological detection at regional scales.

Source: Article Notebook

Introduction

For decades, a 4,000 km² void has persisted in archaeological maps of the Amazon, separating the well-studied earthwork landscapes of Bolivia from the forests of the Brazilian Amazon. The Iténez Forest Preserve occupies this glaring gap along the Bolivia-Brazil border. Located along the Bolivia-Brazil border between the extensively studied earthwork landscapes of the Bolivian lowlands and the forests of the Brazilian Amazon, this 4,000 km² expanse of forest remained largely unmapped by archaeologists. While important studies have documented sites at the preserve's northern and southern margins (Robinson et al. 2021; Prümers, Jaimes Betancourt, and Plaza Martinez 2023; Carson et al. 2016) , the rugged interior—the vast majority of this territory—has remained archaeologically unknown. Dense canopy cover, remoteness, and lack of prior survey work in the interior left it a blank spot on regional maps—a void in our understanding of southwestern Amazonian prehistory. Its position between known centers of pre-Columbian engineering (Peripato et al. 2023; De Souza et al. 2018), however, suggested it might hold similar evidence of ancient landscape modification.

This study fills that gap through systematic remote sensing analysis, revealing extensive anthropogenic landscapes hidden beneath the forest canopy. The work focuses specifically on detecting Amazonian Dark Earth (ADE) and associated forest gardens—patches of modified forest composition that mark ancient settlements and agricultural areas (Schmidt et al. 2014; Palace et al. 2017; Goldberg et al. 2024) . While earthworks are noted where visible, comprehensive mapping of these features beneath the canopy remains for future work. This approach prioritizes the detection of anthropogenic soils and forest composition changes that represent the primary evidence of human landscape transformation in continuously forested regions.

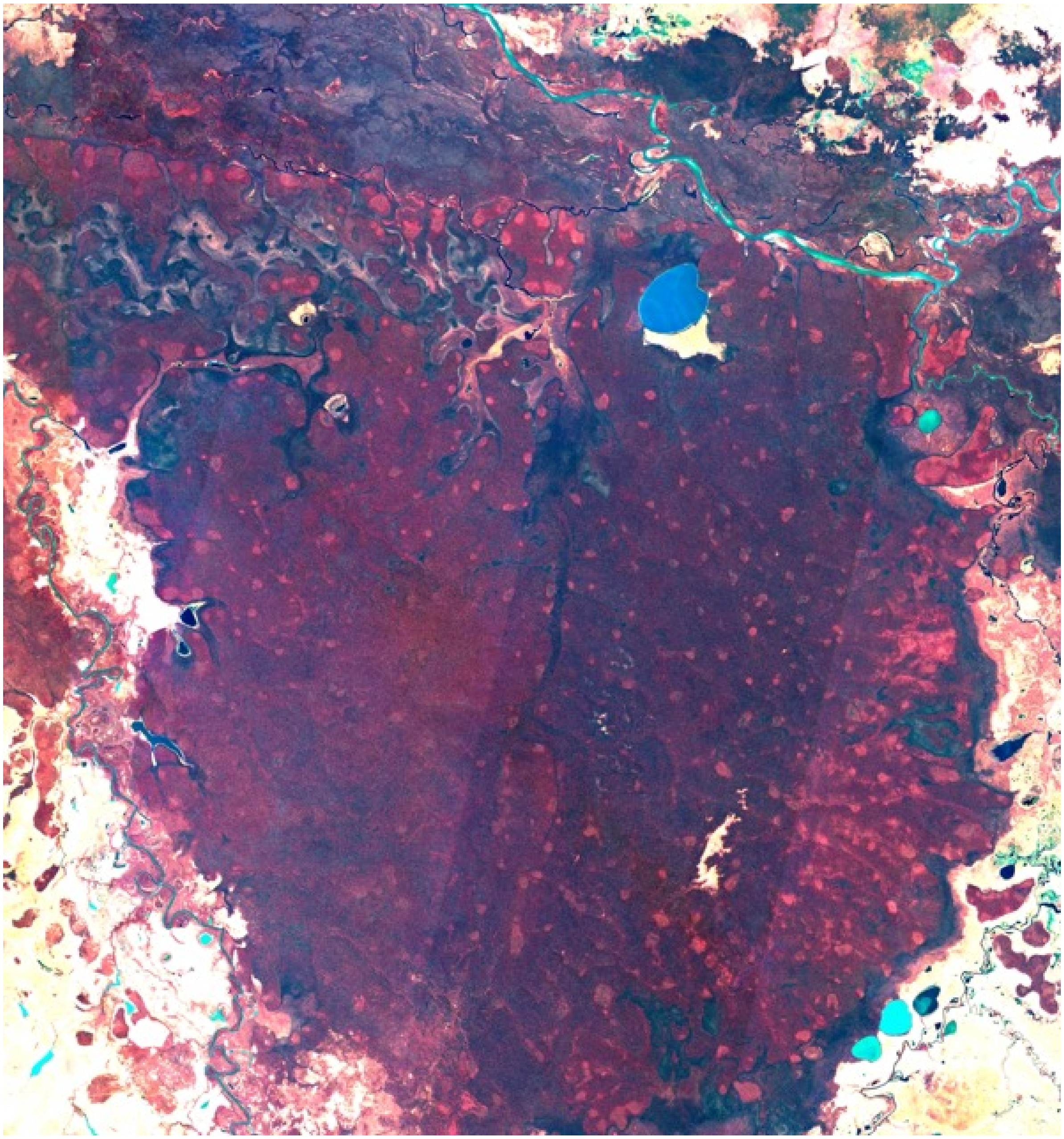


Figure 1: Sentinel-2 false color image composite of Itenez Forest Preserve from summer 2023. Light red spots indicate drier , lowcanopy vegetation associated with anthropogenic forest gardens (palms, cacao, bamboo, and other economically useful plants).

The detection of these features at regional scale required developing new methodological approaches that combine AI-assisted pattern recognition with expert archaeological interpretation—a partnership where computational tools support but do not replace human expertise in identifying and mapping cultural landscapes.

Methods

Image Selection and Processing

I selected Sentinel-2 imagery (European Union/ESA/Copernicus 2017) from the driest periods in the satellite record (late summer 2023 and 2024), when reduced vegetation moisture and seasonal leaf loss maximize visibility of underlying soil and vegetation patterns. Cloud-free mosaics were processed in Google Earth Engine, combined with a state of the art regional canopy height model (Wagner et al. 2025) to distinguish anthropogenic forest structures from natural variation.

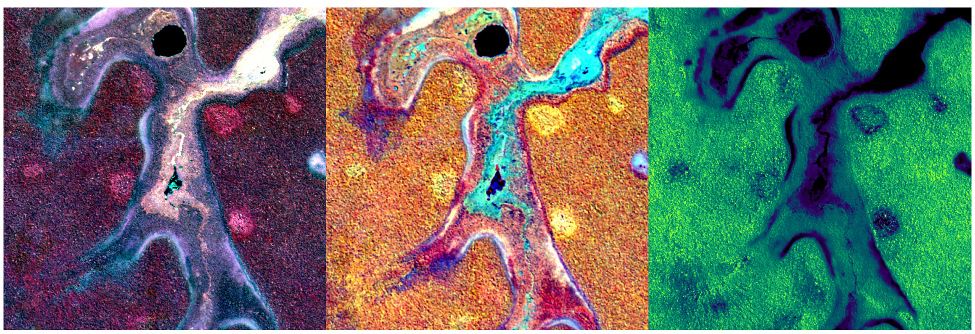


Figure 2: False color Sentinel 2 image chips (left, center) and canopy height estimate (right). Anthropogenic forest patches appears as rounded patches of dry, low-canopy vegetation along terraces. Faint traces of earthworks and ditches can be seen surrounding and connecting the forest patches.

Source: Article Notebook

The imagery was exported as multi-scale tiles (512, 768, and 1024 pixels) with band combinations optimized to highlight spectral signatures of ADE and modified forest. These signatures reflect the distinct ecological characteristics of anthropogenic landscapes: more open canopy structure, seasonal deciduousness, high concentrations of useful plants (palms, bamboos, cacao), and altered soil chemistry from centuries of human occupation and management Robinson et al. (2021).

Figure 3: Detail of transition between natural forest vegetation (left) and anthropogenic forest (right). Not the lighter vegetation, lower canopy, and preponderance of palms and lianas.

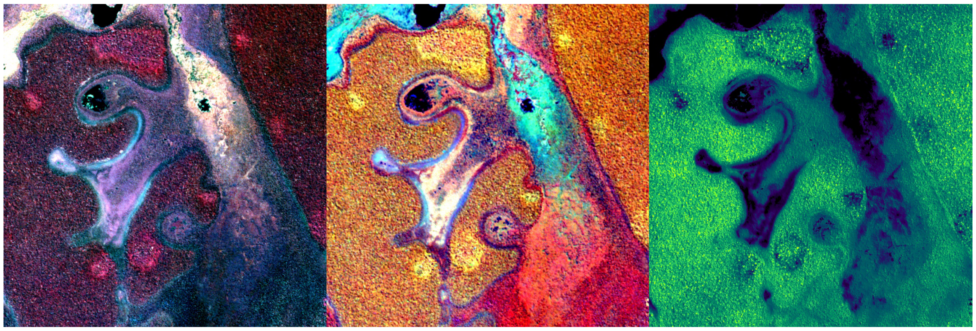
Detection Workflow: Human-AI Partnership

I developed an agentic object detection system using GPT-4.1, and Moondream2 vision-language models to identify anthropogenic features at scale. This system serves as a detection and verification tool, supporting human expertise rather than replacing it. The workflow operates as follows:

1. GPT models review imagery and generate initial hypotheses about feature locations based on spectral patterns and landscape context. They are prompted to view the landscape holistically, looking for patterns across multiple domains, rather than focusing on strict quantitative criteria.
2. The primary models iteratively refine predictions through successive passes using a smaller, specialized vision language models tuned for object detection and grounding. These system lack the domain knowledge of the image contents, so the GPT agent must generate creative, abstract text prompts to detect all features in the scene (e.g. "reddish-pink spots", "purple swirls".
3. The system produces point predictions marking potential anthropogenic sites

4. These points guide large-scale verification and exploration of spatial patterns

Examples:



Source: Article Notebook

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**Scene interpretation (Step 1):**

- **C1:** Shows several compact, lobate, and elliptical reddish-pink/magenta
patches, especially in the lower left, lower center, and upper left. These are
embedded within a mottled forest matrix, not at a forest/nonforest boundary.
Some patches have faint linear connections or ring-like forms.
- **C2:** The same areas show strong yellow/orange signals, supporting the
presence of stressed/drier vegetation typical of ADE patches. The yellow/orange
is compact and matches the C1 anomalies.
- **CHM:** These patches correspond to areas of lower canopy height (darker
blue/purple), sometimes with a ring or edge effect, further supporting the
interpretation as ADE patches.

**Spatial context:** The anomalies are compact, not diffuse, and are located
within continuous forest, not at the edge or in floodplain. Some are clustered
or show faint linear/ring connections, consistent with anthropogenic earthwork
patterns.

**Initial expert estimate:** There are at least 3-4 distinct, compact ADE-like
patches in this scene, possibly up to 5 depending on how the lobate forms are
counted.

**Proceeding to Moondream object detection (Step 2).**

**First tool prompts:**
- "reddish-pink spots"
- "magenta patches"
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Running these in parallel to capture the main compact anomalies.

Synthesis (Step 3):

- Both prompts ("reddish-pink spots", "magenta patches") returned highly overlapping sets of points, confirming the main compact anomalies.
- After removing duplicates, there are 7 unique candidate patches:
  1. (0.0918, 0.2998) - Lower left, compact, strong spectral/structural support.
  2. (0.292, 0.8223) - Lower center, compact, strong support.
  3. (0.4375, 0.7656) - Lower center-right, compact, strong support.
  4. (0.6309, 0.5967) - Center-right, compact, strong support.
  5. (0.7344, 0.1084) - Upper right, compact, strong support.
  6. (0.8486, 0.3789) - Right edge, compact, strong support.
  7. (0.9678, 0.6709) - Far right edge, compact, but needs context check.

- All points correspond to compact, lobate, or elliptical reddish/magenta patches in C1, with matching yellow/orange in C2 and low canopy in CHM.
- All are within continuous forest, not at a forest/nonforest boundary.
- The far right edge point (0.9678, 0.6709) is at the image margin but fits the broader spatial pattern.

Summary of synthesis:
- 7 distinct, compact ADE-like patches detected.
- All have dual spectral support, compact form, and context fit.
- No diffuse or nonforest-edge anomalies included.
- Detections are consistent with ancient anthropogenic ADE/earthwork patterns.

DONE.

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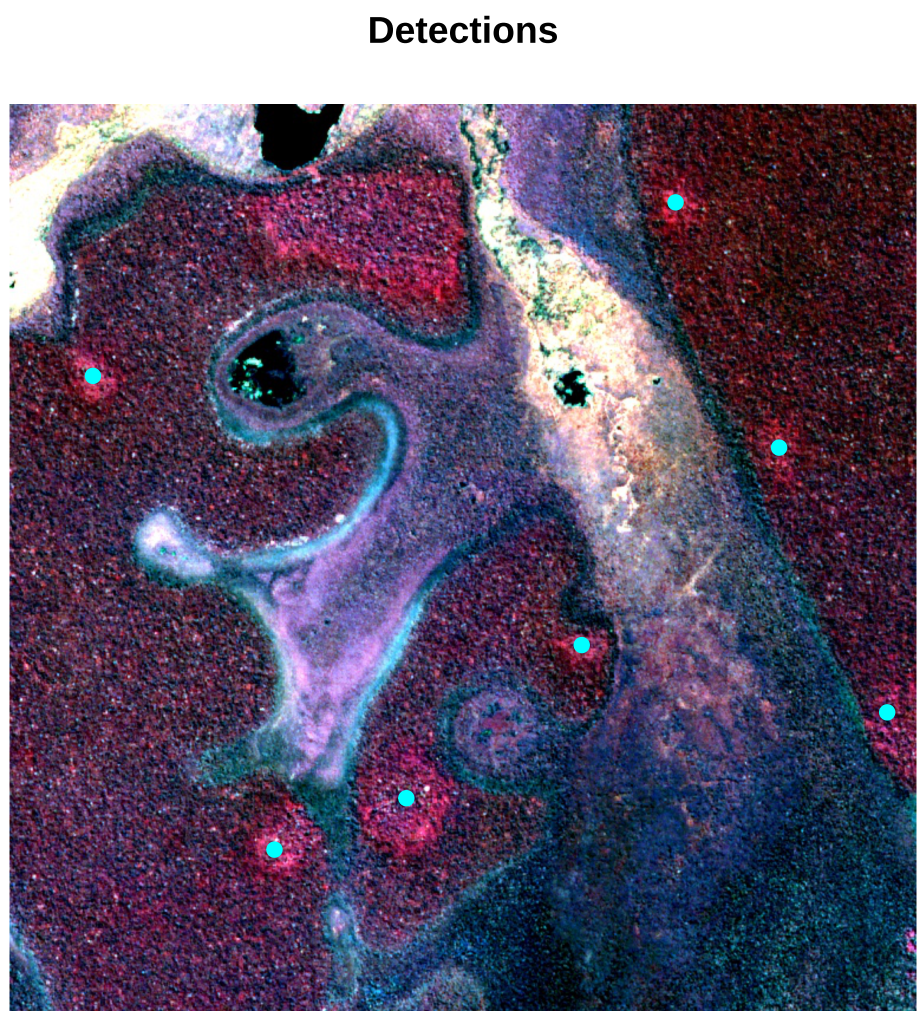

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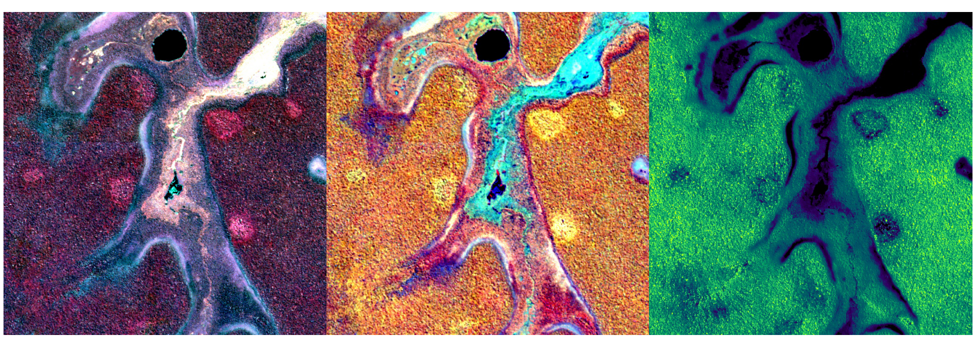

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Scene interpretation (Step 1):

- **C1:** Several compact, lobate reddish-pink/magenta patches are visible, especially to the right of the main drainage, and a few to the left. These are embedded within a mottled forest matrix, not at the forest edge or in open/floodplain areas. The patches are distinct, not diffuse, and have plausible ADE-like form and size (5 ha).
- **C2:** These same areas correspond to bright yellow/orange splotches, supporting the interpretation of stressed/drier vegetation typical of ADE patches.
- **CHM:** The candidate patches show subtle but consistent lower canopy height (darker blue/purple) compared to the surrounding matrix, sometimes with a ringed or compact form.

Context: The anomalies are located on a bluff above a drainage, not on the floodplain, and are not simply forest islands. There are at least 3-5 plausible ADE patch candidates, with some spatial patterning.

Initial expert estimate: 4-5 compact ADE-like patches.

Proceeding to Moondream object detection for precise locations.

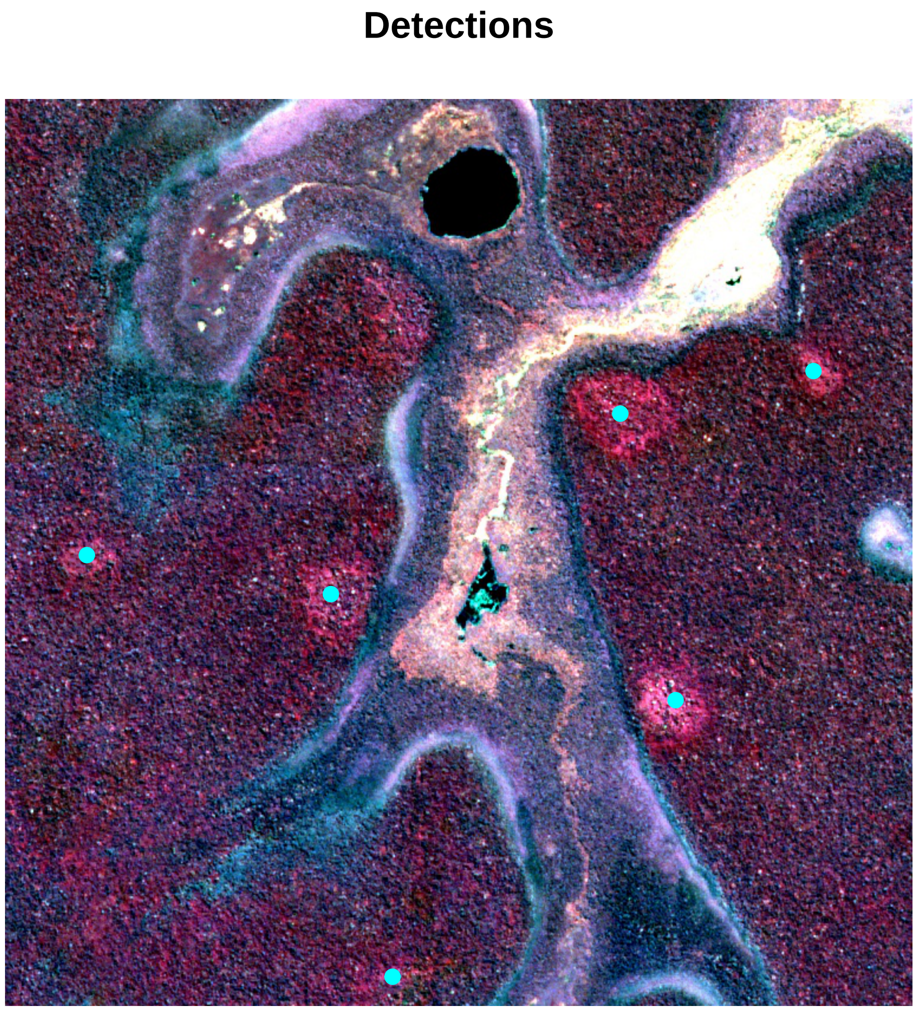
Synthesis of Moondream points (Step 3):

- All three prompts ("reddish-pink spots", "magenta patches", "lobate red blobs") returned highly consistent sets of points, with only minor coordinate variation.
- After removing duplicates and checking against the imagery:
  - 5 compact, plausible ADE patch candidates are confirmed. These are all within the continuous forest matrix, have strong dual spectral support (C1/C2), and show subtle but consistent CHM anomalies (lower canopy).
  - Two additional points (lower left and lower right edge) are at/near the image edge but are consistent with the broader spatial pattern and context.
  - All detected patches are 5 ha and have compact, lobate/elliptical form.

Summary: 5-6 distinct ADE-like patches, all with strong spectral-structural support and appropriate context. Will finalize and deduplicate for the final result.

DONE.

Source: Article Notebook



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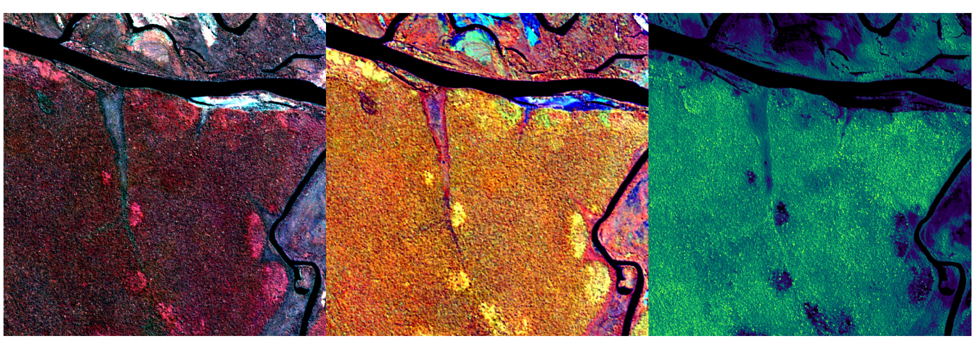

Source: Article Notebook

Scene interpretation (Step 1):

- **C1:** Several compact, lobate, reddish-pink/magenta patches are visible, especially in the central and lower portions of the image. These patches are distinct from the surrounding forest matrix, which is more mottled and darker. The patches are not diffuse, and some appear loosely clustered or aligned along subtle linear features.
- **C2:** The same areas show strong yellow/orange splotches, confirming low transpiration and supporting the presence of stressed/dry vegetation typical of ADE patches.
- **CHM:** These patches correspond to areas of slightly lower canopy height (darker blue/purple), sometimes with a ring or core structure, further supporting the interpretation as ADE forest patches.

Context: The anomalies are within a continuous forest matrix, not at the forest edge or in floodplain, and are compact, not diffuse. Some are loosely aligned along subtle drainage or earthwork traces.

Initial expert estimate: There are approximately 7-9 valid ADE patch candidates in this scene.

Proceeding to Moondream object detection for precise point locations.

Synthesis of Moondream results (Step 3):

- Both prompts ("reddish-pink spots", "large magenta patches") returned overlapping sets of points, with strong clustering in the central, lower, and right-central portions of the image.
- After removing redundant/overlapping points and excluding those that are too small, at the image edge, or lack compactness/context, I identify 8 distinct, compact ADE patch candidates:
  - Central vertical cluster (3): (0.4102, 0.6172), (0.4102, 0.8301), (0.5, 0.9248)
  - Lower right cluster (3): (0.7783, 0.71), (0.834, 0.834), (0.832, 0.6006)
  - Right-central (1): (0.8564, 0.335)
  - Central left (1): (0.3193, 0.5068)
- All selected points have strong dual spectral support (C1/C2), compact form, and context fit (within continuous forest, not at edge or in floodplain).
- Some additional points (e.g., at extreme top/left edges) are excluded due to insufficient context or size.

Summary: 8 distinct ADE patch candidates identified, all with strong

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spectral, structural, and contextual support.

DONE.
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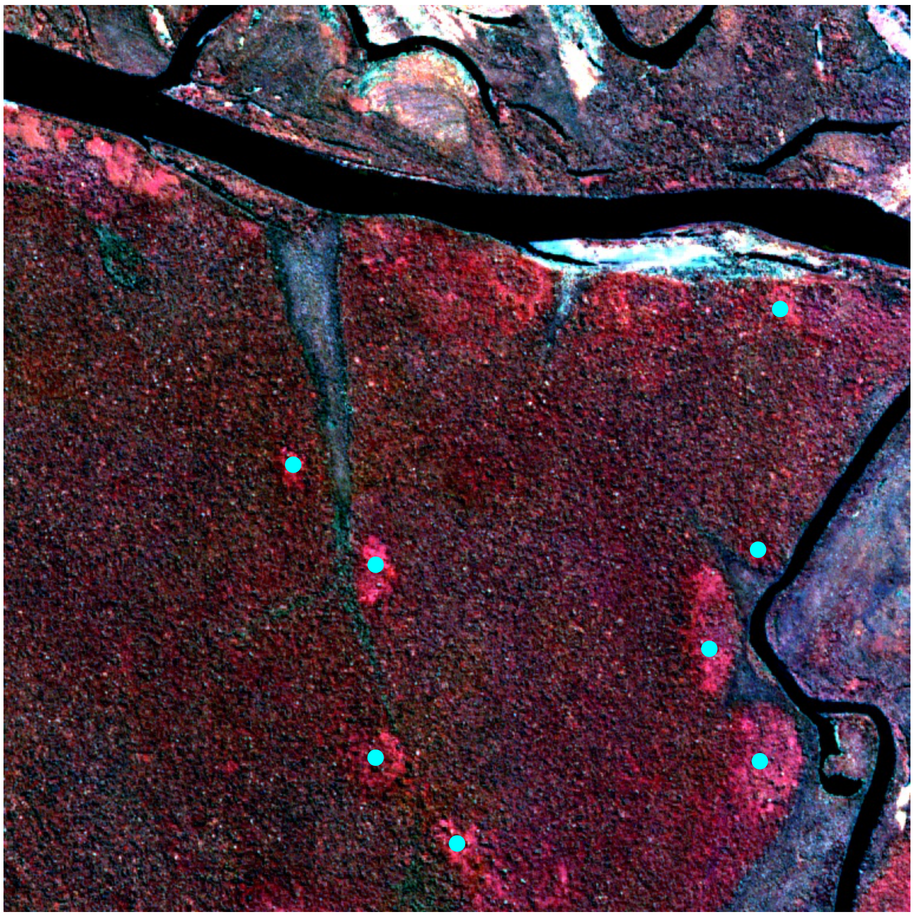
Source: Article Notebook



Source: Article Notebook

Critically, this AI component operated in parallel with detailed manual mapping. I meticulously reviewed and labeled hundreds of polygon boundaries over anthropogenic forest patches through careful imagery analysis, with the AI and manual mapping developing iteratively and informing each other. Earthworks—canals, ditches, and geometric earthworks—were recorded where visible through the canopy, though comprehensive mapping of these linear features remains a priority for future work with higher-resolution imagery. This approach allowed me to iteratively calibrate and validate the models' ability to detect known archaeological features in zero-shot and few-shot learning contexts. The models were not fine-tuned but leveraged pre-trained capabilities to recognize visual patterns consistent with archaeological features. This approach exemplifies how AI can extend human capacity for regional-scale analysis without replacing the expertise necessary for accurate feature identification and interpretation.

Results

The analysis **identified approximately 180 km² of anthropogenic soils and forest gardens within the Iténez Forest Preserve, representing 5% of its total area—comparable to the footprint of many modern world cities**, though distributed as a network of patches rather than a contiguous area. I mapped over 350 individual fields ranging from 5 to 700 hectares, with clear spatial clustering along bluffs, drainages, and floodplain margins in upland *terra firme* forest—confirming hypotheses about bluff-edge settlement systems previously proposed for this region (Denevan 1996).

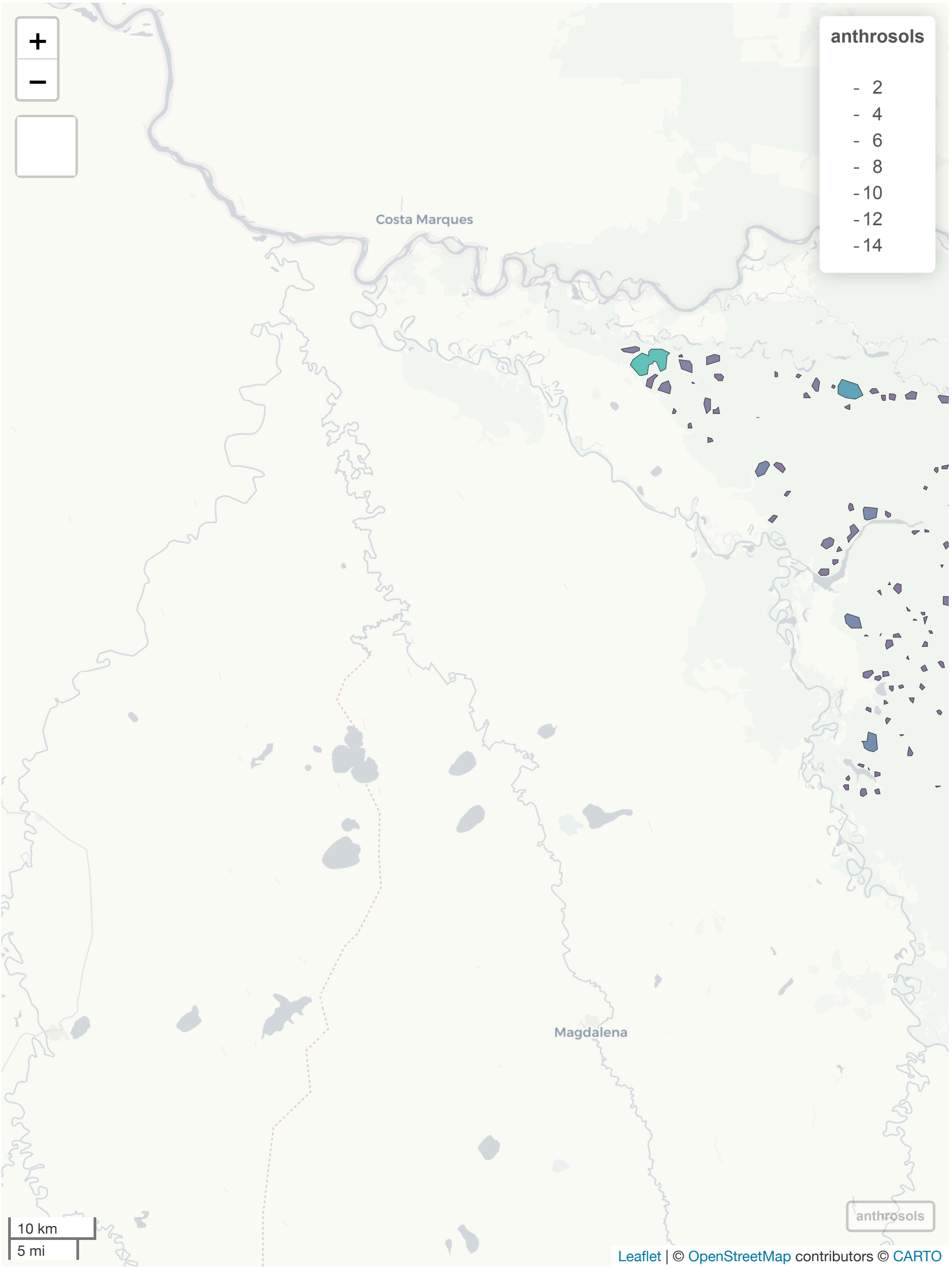


Figure 4: Anthropogenic forest patches.

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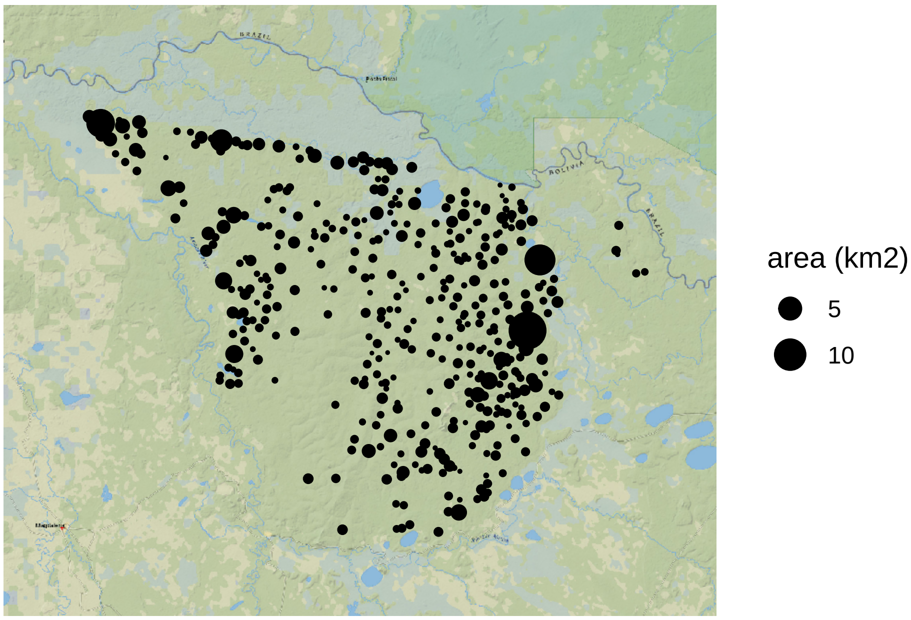

Figure 5: Anthropogenic forest patches.

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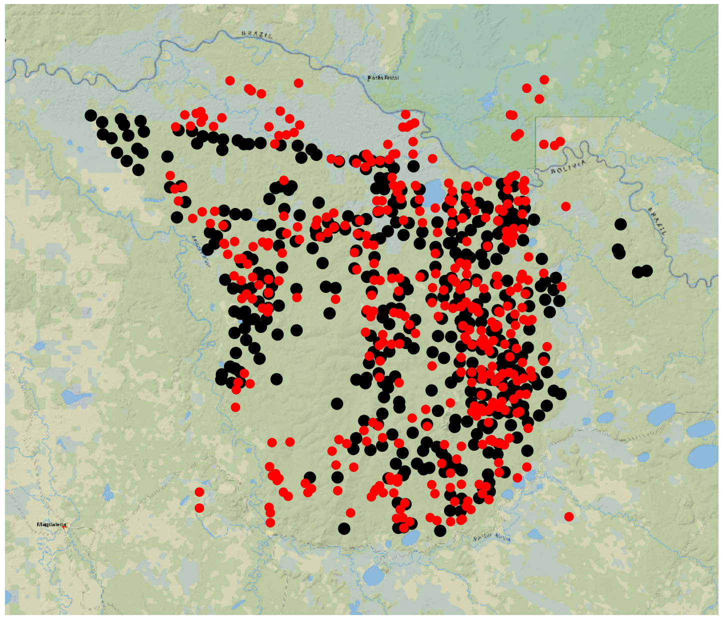
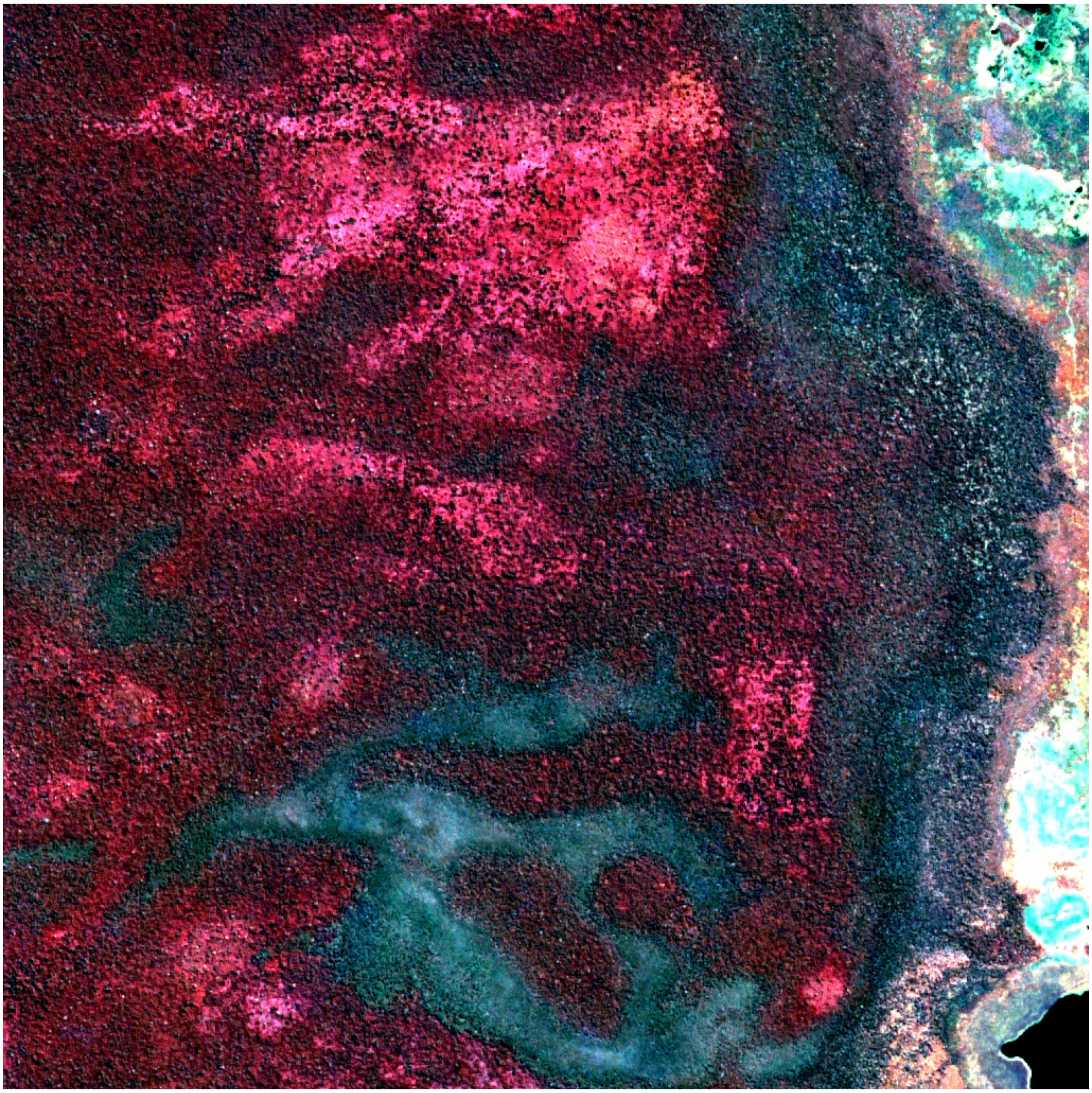


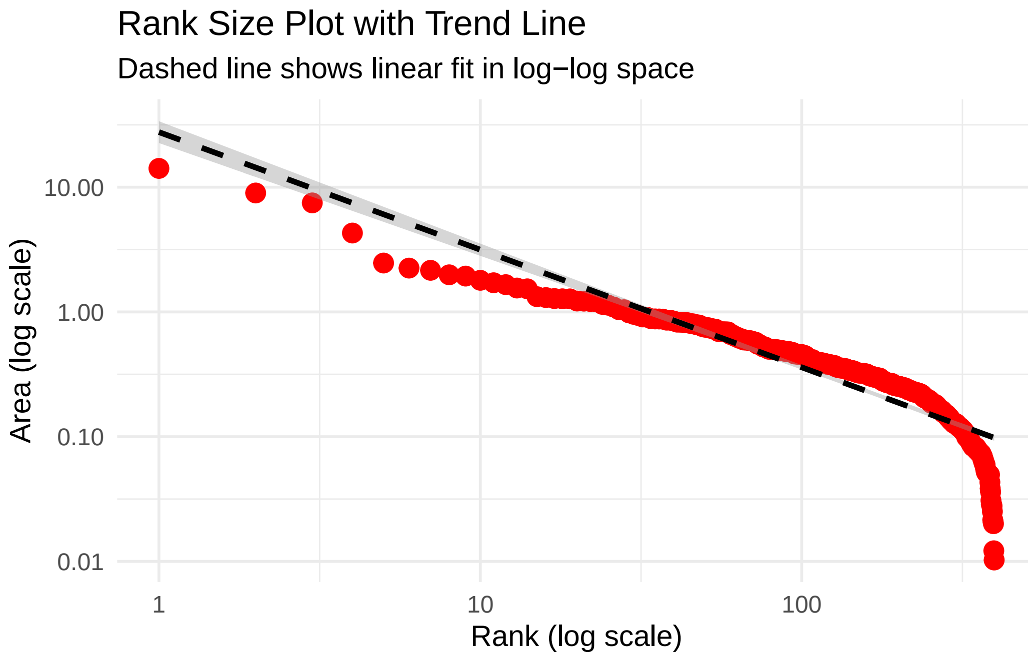
Figure 6: Manually labeled site locations (black) compared to automatically detected locations (red).

Source: Article Notebook

The most striking discovery is a major complex spanning more than 4 kilometers, where large-scale fields connect through networks of earthworks. Across the mapped area, an exceptionally dense system of linear features links settlements into an integrated landscape. While full mapping of these earthworks awaits future work with canopy-penetrating sensors, their visible portions already demonstrate a level of landscape integration comparable to the most complex sites in neighboring regions.



Rank-size analysis reveals a clear hierarchical structure in field sizes and site distribution, with the size distribution following a power law with an exponent close to 1 on log-log plots. This pattern, consistent with organized settlement systems, matches the scale and complexity documented in the Llanos de Mojos and Baures (Prümers et al. 2022; Erickson 2000). The largest sites anchor networks of settlement and agroforestry patches, suggesting centralized planning and resource management across the landscape.



Source: Article Notebook

These anthropogenic landscapes remain ecologically distinct today. Forest composition in mapped areas shows high concentrations of economically useful species, particularly cacao, making the region a modern hotspot for wild cacao cultivation—a direct legacy of ancient land use practices (Carson et al. 2016) . Local and Indigenous communities continue to harvest these resources, underscoring that these are not merely archaeological sites but living landscapes where ancient management practices continue to shape both forest ecology and human livelihoods.

Discussion

These findings transform our understanding of the Iténez region from archaeological blank spot to critical piece in the Amazonian puzzle. The extent and organization of anthropogenic landscapes documented here match or exceed those in better-studied areas, confirming that large-scale landscape engineering extended continuously across the southwestern Amazon. This fills the last major gap in the regional archaeological map between the Llanos de Mojos and Baures, revealing that the Iténez was not a periphery but an integral part of pre-Columbian regional systems.

The hierarchical site structure and extensive earthwork networks point to complex social organization capable of coordinating landscape modification across thousands of square kilometers. Rather than isolated communities practicing small-scale agriculture, the evidence suggests integrated regional systems linking settlements through engineered infrastructure and shared land management practices. The concentration of sites along bluff edges and floodplain margins confirms earlier hypotheses about settlement preferences in *terra firme* forests, while the scale revealed here exceeds previous expectations.

The ecological legacy of these ancient landscapes extends beyond their archaeological significance. Forest composition in mapped areas reflects centuries of human selection for useful species, creating patches of anthropogenic forest that blur the line between nature and culture. The continued harvesting of cacao and other products from these forests by contemporary communities represents an unbroken tradition of forest management extending from pre-Columbian times to the present. This continuity challenges us to recognize that the "pristine" forests we seek to conserve are themselves products of Indigenous innovation and management.

The successful detection of these features through combined AI and expert analysis demonstrates new possibilities for archaeological survey in forested regions. The human-AI partnership developed here—where computational tools assist in pattern detection while human expertise guides interpretation and mapping—offers a model for scaling archaeological survey across Amazonia's vast forests. This approach proved particularly effective for identifying the subtle spectral signatures of anthropogenic soils and forest gardens that would be impossible to map at this scale through ground survey alone.

Implications and Future Directions

This work contributes to the mounting evidence that the Amazon was extensively shaped by its pre-Columbian inhabitants, adding a major piece to our understanding of regional cultural landscapes. The Iténez landscapes join the growing inventory documented by recent synthetic works, while demonstrating that significant discoveries remain to be made even in the 21st century. The findings reinforce emerging models of pre-Columbian Amazonia as a mosaic of engineered landscapes rather than pristine wilderness punctuated by occasional cultural sites.

Future research should pursue several directions. First, LiDAR or high-resolution radar imagery could reveal the full extent of earthwork networks currently hidden beneath the canopy, allowing comprehensive mapping of the linear features only partially visible in optical imagery. Second, systematic field verification and dating would establish the chronology and cultural affiliations of these landscapes, potentially revealing connections to known archaeological cultures of the Llanos de Mojos and Baures. Third, detailed ecological studies of forest composition and soil properties would deepen our understanding of how ancient management practices created the anthropogenic forests that communities value today. The methodological approach developed here—combining AI-assisted detection with expert archaeological interpretation—offers broader applications for Amazonian archaeology. As we refine these tools, maintaining the balance between computational efficiency and human expertise will be critical. AI can help us see patterns across vast scales, but understanding what those patterns mean for human history requires archaeological knowledge that no algorithm can replace.

These findings also have immediate relevance for conservation planning. Protecting these forests means protecting both biodiversity and living Indigenous heritage—recognizing that the ecological richness we value today emerged from millennia of human management.

Conclusion

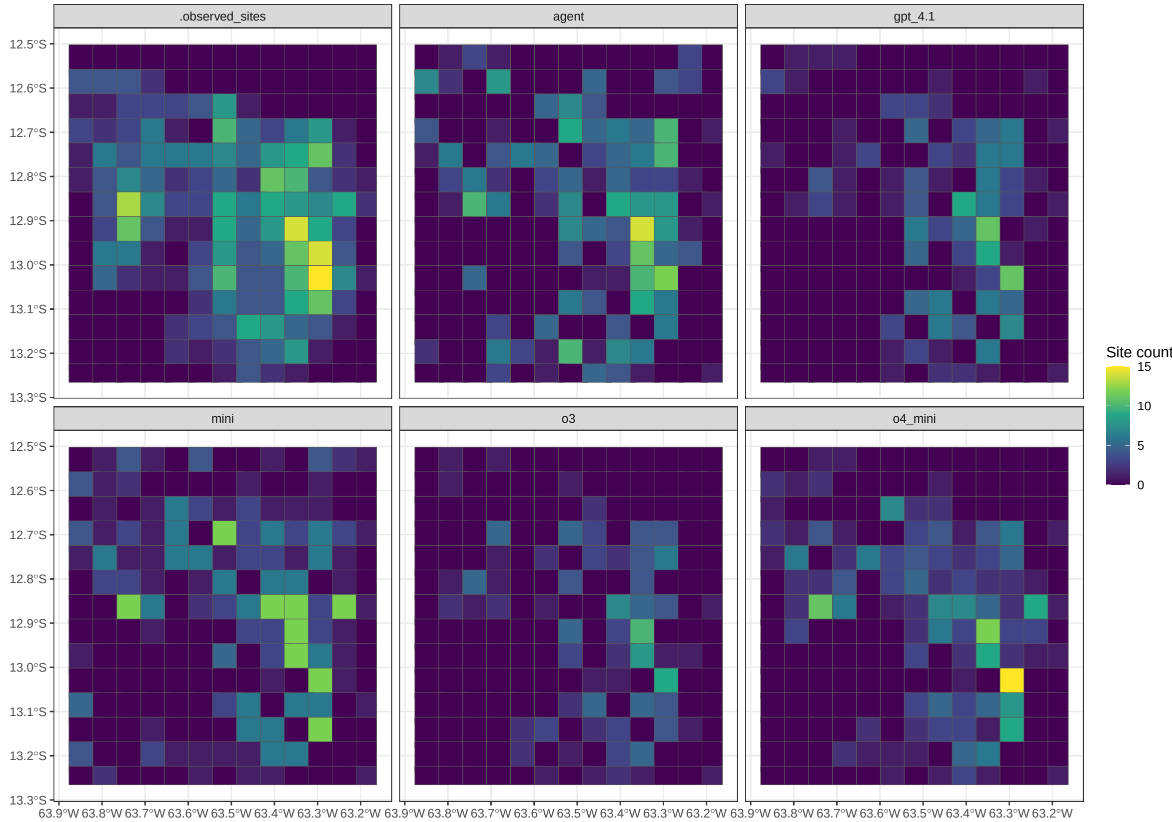
The Iténez Forest Preserve emerges from this analysis not as pristine wilderness but as a cultural landscape shaped by centuries of Indigenous management. The 180 km^2 of mapped anthropogenic soils and forest gardens, connected by dense earthwork networks and organized in hierarchical patterns, demonstrate that pre-Columbian peoples transformed this region as extensively as anywhere in Amazonia. This work fills the last major blank spot in the archaeological map of the southwestern Amazon, revealing continuous cultural landscapes between previously studied regions.

These findings illustrate both the potential and limits of new technological approaches to archaeology. While AI-assisted detection enabled mapping at unprecedented scales, the interpretation and validation of these features required human expertise at every step. This partnership between computational tools and archaeological knowledge offers a path forward for understanding Amazonia's human past across its vast forested expanses.

As we continue to reveal the Amazon's deep human history, we gain essential perspective on its present and future. The forest gardens where communities harvest cacao today are living monuments to Indigenous landscape management, reminding us that the biodiversity we value emerged from millennia of human-forest interaction. Understanding this legacy is crucial not only for archaeology but for contemporary efforts to conserve and sustainably manage these cultural landscapes.

Appendix

Comparison of tile-level site counts from observed data and zero-shot results from a variety of GPT models with and without agentic capability.



Source: Article Notebook

Performance metrics for zero-shot site detection:

model	accuracy	sens	spec	f_meas
o4_mini	0.742	0.672	0.873	0.773
nano	0.681	0.950	0.175	0.796
agent	0.670	0.613	0.778	0.709
mini	0.654	0.664	0.635	0.715
gpt_4.1	0.637	0.513	0.873	0.649
o3	0.615	0.454	0.921	0.607

Performance metrics for automated zero-shot site detection.

Source: Article Notebook

Performance metrics for zero-shot site counting:

model	rmse	mae	rsq
agent	2.910	1.852	0.460
o4_mini	3.063	1.901	0.486
mini	3.097	2.143	0.413
gpt_4.1	3.331	2.170	0.458
o3	3.637	2.379	0.404
nano	3.813	2.703	0.072

Performance metrics for automated zero-shot site counting.

Source: Article Notebook

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