**Methodological Approach: Identifying a Promising Search Region – The Case for Rondônia**

**1. Context and Initial Broad Strategy:**  
The Amazon basin, a vast and historically rich region, is estimated to harbor over 10,000 undiscovered pre-Columbian earthworks (Peripato et al., 2023). To address the challenge of identifying new archaeological sites, our initial strategy involves a multi-stage process of narrowing the search area from the broader Amazonian biome to a specific, manageable region. This is achieved by integrating insights from recent large-scale predictive models with documented archaeological distributions, aiming to identify areas with high potential but relatively lower existing documentation – so-called "white spots."

**2. Leveraging Predictive Modeling and Known Distributions:**  
The foundation for regional selection is the "Predicted probability of earthwork presence" model presented by Peripato et al. (2023, Fig. 2A). This model, based on an inhomogeneous Poisson process and various environmental covariates (Peripato et al., 2023, Fig. 2C, 2D), highlights areas with a higher *a priori* likelihood of containing earthworks. This predictive map was cross-referenced with the geographical distribution of previously reported and newly discovered earthworks (Peripato et al., 2023, Fig. 1A) to identify zones where predicted probability is moderate to high, yet the density of documented sites is comparatively low.

**3. Focusing on the Southern Rim of the Amazon (SRA):**  
The work of de Souza et al. (2018) demonstrates a significant, c. 1800 km continuous belt of pre-Columbian earth-building cultures along the Southern Rim of the Amazon (SRA), primarily active between Cal AD 1250-1500. This macro-region (de Souza et al., 2018, Fig. 1) represents a vast area of known, widespread human settlement and landscape modification. This SRA concept aligns geographically and thematically with the "Southern Amazonia (SA)" region defined by Peripato et al. (2023).

**4. Rationale for Selecting Southern Amazonia (SA) and Specifically Rondônia:**  
The SA region, as depicted by Peripato et al. (2023, Fig. 1A & 2A), presents a compelling target. It exhibits a combination of documented sites and areas of moderate-to-high predicted earthwork probability that remain less intensively surveyed. Within this SA region, the state of Rondônia, Brazil, was selected for initial investigation based on the following:  
\* **Geographical Alignment:** Rondônia falls within the western extent of Peripato et al.'s (2023) SA region and aligns with the broader SRA context established by de Souza et al. (2018).  
\* **Predictive Potential vs. Documentation Density:** Visual analysis of Peripato et al.'s (2023) maps (Fig. 1A and Fig. 2A) indicates that portions of Rondônia exhibit favorable predictive probabilities for earthworks while having a lower density of documented sites compared to other areas within the SRA/SA, such as the Upper Xingu Basin (de Souza et al., 2018, Fig. 4).  
\* **Transitional Ecology:** Rondônia occupies a transitional ecological zone, bordering denser rainforest and areas with characteristics similar to the SRA, often associated with the types of earthworks found by de Souza et al. (2018).  
\* **Potential for Geoglyph Types:** While distinct from the fortified villages of the UTB, the methodologies for detecting subtle landscape anomalies (Wagner et al., 2022) are applicable, and Rondônia lies in a region where other forms of earthworks, including geoglyphs or related structures, could potentially exist as part of the broader SRA cultural landscape.

**5. Hypothesis for Rondônia:**  
Based on the convergence of predictive modeling, known macro-regional settlement patterns along the SRA, and an analysis of documented site densities, it is hypothesized that specific, less-explored areas within the state of Rondônia harbor undiscovered pre-Columbian earthworks. These sites are anticipated to be broadly consistent with the earth-building traditions documented along the Southern Rim of the Amazon, potentially dating to the Cal AD 1250-1500 period or representing related regional variations.

**Refining the Search Area: Targeting Western Rondônia – The Guaporé River Interfluves**

Following the initial hypothesis targeting the state of Rondônia, a more focused literature review and analysis of regional archaeological and environmental data were undertaken to identify a specific area for intensive investigation. The objective was to pinpoint a manageable zone (approximately 20km x 20km) exhibiting high discovery potential based on known archaeological patterns and favorable environmental conditions, while also representing a relative "white spot" in terms of published, detailed surveys covering *all* its interfluves.

**1. Correlating Archaeological Patterns with Rondônian Geography:**  
Research confirms that pre-Columbian earthwork phenomena, particularly ring ditches and related structures—sometimes broadly referred to as geoglyphs in Brazil—extend from neighboring regions into Western Rondônia (Erickson, 2023; de Souza et al., 2018; Peripato et al., 2023). These sites are typically situated in interfluvial zones (elevated areas between river systems) rather than directly on major floodplains (de Souza et al., 2018). Furthermore, significant evidence of long-term human occupation in Rondônia, such as Amazonian Dark Earths (ADEs or *Terra Preta*), has been extensively documented, particularly in the Guaporé River basin and the Upper Madeira region (Texier et al., 2021; Erickson, 2023; Mongabay, 2024). The presence of ADEs, with their characteristic dark color, charcoal, artifacts, and higher nutrient content (Texier et al., 2021), indicates suitability for sustained settlement which could be associated with earthwork construction. The Middle Guaporé region also has a deep history of occupation, as evidenced by ceramic phases like Bacabal dating back to ca. 2000 B.C. (Zimpel Neto, 2018).

**2. Focusing on the Middle Guaporé River Basin:**  
The Middle Guaporé River basin in Western Rondônia emerges as a prime candidate for this focused search. This is supported by:  
\* **Direct Archaeological and Remote Sensing Leads:** A systematic survey for anthropogenic ditched earthworks using Google Earth imagery was conducted by Trindade (2015) along the right margin of the Middle Guaporé River, between São Francisco do Guaporé and Costa Marques. This study confirmed the presence of such sites and the utility of remote sensing in this specific region. Erickson (2023) also notes reports by Miller of large ditched sites and black earth on the Brazilian side of the Middle Guaporé/Iténez river.  
\* **Environmental Suitability:** The region is characterized by a tropical rainy climate (Am type) with annual precipitation between 2,200-2,500 mm and mean annual temperatures of 25-26°C (Texier et al., 2021). Earthworks and ADE sites are often found on fluvial terrace systems and gently undulating lowland plains (100-350m a.s.l.), a common topography in this area (Texier et al., 2021; Peripato et al., 2023).  
\* **Interfluvial Characteristics:** The area encompassing the municipalities of São Francisco do Guaporé and Seringueiras lies within the Middle Guaporé basin and features extensive interfluvial zones between the Guaporé River and its tributaries. This landscape position is a known preference for many Amazonian earthwork sites (de Souza et al., 2018).

**3. Rationale for São Francisco do Guaporé / Seringueiras Area:**  
The broader area around the municipalities of São Francisco do Guaporé and Seringueiras, and their surrounding interfluvial landscapes, was selected as the refined search zone. This decision is based on:  
\* The confirmed presence of ditched earthworks in the Middle Guaporé region (Trindade, 2015; Erickson, 2023).  
\* The documented occurrence of extensive ADEs indicating significant past human activity (Texier et al., 2021).  
\* The existence of suitable interfluvial terrain consistent with known site locations (de Souza et al., 2018; Peripato et al., 2023).  
\* While Trindade (2015) surveyed parts of this region, the vastness of the interfluves suggests that a focused 20km x 20km grid within this broader area may still reveal previously uncatalogued features or offer a denser understanding of known clusters.

**4. Next Step: Grid Definition for Satellite Imagery Analysis:**  
The subsequent step involves detailed visual reconnaissance of the interfluvial zones near São Francisco do Guaporé and Seringueiras using high-resolution satellite imagery (e.g., via Google Earth Pro). This will identify a specific 20km x 20km grid that exhibits favorable characteristics (e.g., partial deforestation for visibility, suitable landforms, proximity to but not direct contiguity with areas potentially already mapped by Trindade, 2015) and lacks obvious extensive modern development. The corner coordinates of this grid will then be defined for targeted satellite imagery acquisition and AI-assisted analysis.

Next, we go for a in depth terrain analysis, findings focus on interfluves, height differences, etc.

**Methodological Approach Part III: Terrain Analysis for Interfluve Identification**

**1. Rationale for Terrain Analysis:**  
While initial regional selection was guided by existing archaeological syntheses and predictive models (Peripato et al., 2023; de Souza et al., 2018), a finer-grained approach was necessary to pinpoint specific, manageable 20km x 20km grids for intensive investigation within the broader São Francisco do Guaporé / Seringueiras area of Rondônia. Literature suggests that many Amazonian earthwork sites, particularly those in interfluvial settings, are not necessarily located on the immediate banks of major rivers but rather on elevated ground between drainage systems, often near the headwaters of smaller tributaries (de Souza et al., 2018). To objectively identify such promising interfluvial zones, a programmatic terrain analysis was implemented.

**2. Data Acquisition and Preparation:**  
The primary dataset for this analysis was the Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global (Version 3) Digital Elevation Model (DEM), accessed via the Google Earth Engine (GEE) Python API (Image ID: USGS/SRTMGL1\_003). GEE was utilized for its efficient server-side capabilities to clip the global SRTM dataset to a defined Area of Interest (AOI) encompassing the broader São Francisco do Guaporé / Seringueiras region. This clipped DEM, with an approximate 30-meter spatial resolution, was then downloaded as a GeoTIFF file for local processing.

To ensure compatibility with the WhiteboxTools (WBT) geospatial analysis library (Lindsay, 2016) and to standardize the input, the downloaded DEM was pre-processed using rasterio. This involved confirming its properties and re-saving it with LZW compression, a format well-supported by WBT.

**3. Hydrological Modeling and Stream Network Extraction:**  
The core of the interfluve identification relied on standard hydrological modeling techniques performed using WhiteboxTools (version as per execution environment) invoked via its Python API. The workflow was as follows:

* **Depression Filling:** The pre-processed DEM was first processed using wbt.fill\_depressions(fix\_flats=True) to remove sinks and flat areas, creating a hydrologically corrected DEM suitable for flow routing.
* **Flow Direction:** D8 flow pointers were calculated from the filled DEM using wbt.d8\_pointer(), determining the direction of steepest descent from each cell.
* **Flow Accumulation:** Flow accumulation was subsequently derived using wbt.d8\_flow\_accumulation(out\_type="cells") based on the D8 pointers, quantifying the number of upstream cells draining into each cell.
* **Stream Extraction:** A stream network was then extracted from the flow accumulation raster using wbt.extract\_streams(). A conservative threshold (e.g., 3 cells, subject to experimentation based on DEM resolution and desired stream density) was applied to delineate stream channels, effectively identifying primary and secondary watercourses within the AOI. The output was a binary raster representing the stream network.

**4. Interfluve Zone Identification:**  
Two primary methods were employed to delineate interfluve zones – areas of higher ground situated away from and between the extracted stream channels:

* **Distance from Streams:** Using the extracted binary stream raster, a Euclidean distance transform was computed with scipy.ndimage.distance\_transform\_edt. Areas exceeding a defined pixel distance threshold (e.g., 15 pixels, corresponding to approximately 450 meters for a 30m DEM) from the nearest stream cell were classified as potential interfluves. This identifies land that is relatively remote from immediate watercourses.
* **Topographic Position Index (TPI):** TPI was calculated for the hydrologically corrected (filled) DEM. TPI quantifies the relative elevation of a central pixel compared to the mean elevation of its surrounding neighborhood (e.g., a 9x9 pixel window). Positive TPI values indicate ridges and hilltops, characteristic of interfluvial landforms. A threshold (e.g., TPI > 0.5, units relative to DEM elevation values) was applied to identify cells representing these elevated positions. The calculation was performed using numpy and scipy.ndimage.generic\_filter.
* **Combined Interfluves:** To refine the identification, the binary rasters resulting from the "distance from streams" method and the "TPI" method were combined using a logical AND operation. The resulting raster highlighted areas that were *both* significantly distant from streams *and* topographically elevated, providing a more robust delineation of core interfluvial zones.

**5. Output and Subsequent Application:**  
The final output of this terrain analysis was a set of raster GeoTIFF files, primarily the "combined interfluves" layer. This layer was then used as a primary guide for selecting specific 20km x 20km grids for detailed satellite imagery analysis. Candidate grids were chosen from within these programmatically identified interfluvial zones, particularly where they coincided with areas of partial deforestation (for improved visibility of potential surface features on optical satellite imagery) and were not exhaustively covered by previous detailed ground surveys. This data-driven approach ensures that the selected investigation grids are situated in landscapes geomorphologically consistent with known patterns of interfluvial settlement in the Amazon region.

*(Reference for WhiteboxTools, if needed for the final paper):*  
*Lindsay, J. B. (2016). Whitebox GAT: A case study in geomorphometric analysis. Computers & Geosciences, 95, 75-84.*

**Methodological Approach Part IV: Visualization, Preliminary "White Spot" Assessment, and Candidate Area Identification**

**1. Visualization of Terrain Analysis Outputs:**

Following the programmatic terrain analysis, the derived raster layers, particularly the "Combined Interfluves," "Interfluves by Distance," "Interfluves by TPI," and the input DEM, were visualized. This was achieved by converting the GeoTIFF files into PNG images using a Python script leveraging rasterio and matplotlib. To enhance the interpretability of the "Combined Interfluves" layer when overlaid on satellite imagery, features were morphologically dilated (e.g., by 2-6 pixels using scipy.ndimage.binary\_dilation) and assigned a high-contrast color (e.g., magenta).

These visualizations were then overlaid onto contemporary Google Satellite basemaps using folium. A bounding box corresponding to the project's Area of Interest (AOI) (approximate coordinates: -63.8 to -62.8 W, -13.0 to -12.0 S) was also rendered, along with explicit country border data (derived from Natural Earth Data Shapefiles converted to GeoJSON) to provide clear geographical context, particularly in relation to the Brazil-Bolivia border. This interactive map allowed for a direct visual comparison of the programmatically identified interfluves with the underlying satellite imagery and known geographic features.

**2. Preliminary "White Spot" Assessment and Comparison with Existing Research:**

A critical next step involved comparing the identified high-potential interfluves within the AOI against existing archaeological surveys to assess their "white spot" status. The primary reference for this was the detailed dissertation by Trindade (2015), which focused on a systematic remote sensing survey for ditched earthworks along the right margin of the Middle Guaporé River, between São Francisco do Guaporé and Costa Marques, and included maps of known and newly discovered sites within this broader region.

Visual comparison was made between our AOI (with its highlighted interfluves) and Trindade's (2015) published maps, specifically her Figures 3 (showing her focused survey swaths), Figures 20 and 21 (showing known sites in her wider research area), Figure 23 (new sites found by her), and critically, Figure 24 (depicting areas of effective remote sensing coverage versus areas obscured by forest, cloud, or low-resolution imagery at the time of her study).

While a definitive georeferenced overlay and analysis are still pending, initial visual inspection suggests that portions of our AOI, and specifically some of the interfluve clusters identified by our script, may lie outside Trindade's (2015) most intensively surveyed riverine corridors or potentially within areas she identified as having limited visibility for her remote sensing methods. This preliminary assessment indicates a potential for identifying previously uncatalogued features.

**3. Identification of Candidate Investigation Areas:**

Based on the visual analysis of the "Combined Interfluves" layer overlaid on satellite imagery, four broad zones (provisionally labeled Areas 1, 2, 3, and 4) exhibiting significant clusters of suitable interfluvial landforms were identified within the AOI. Areas 2, 3, and 4 notably show extensive open vegetation on current satellite imagery, likely due to deforestation (Trindade, 2015, Fig. 22; GFW; EIA), which, while an ecological concern, offers high visibility for optical detection of potential earthworks. Area 1 appears to retain denser forest cover.

**4. Next Steps:**

The immediate next steps involve:

* A more rigorous georeferenced comparison of our AOI and the identified candidate Areas (1-4) with Trindade's (2015) survey maps (especially her Fig. 24) to precisely determine the extent of overlap and confirm "white spot" status.
* Utilizing historical satellite imagery (e.g., via Google Earth Pro's time slider, Landsat archives, or MapBiomas Brazil) to analyze the land cover history of Areas 1-4. This will help ascertain whether the current open vegetation in Areas 2, 3, and 4 is recent, and if Area 1 has remained consistently forested, which has implications for site preservation and detection strategy.
* Selection of specific 20km x 20km grids within the most promising candidate area(s) based on this refined "white spot" analysis, visibility, and the density/coherence of interfluvial features.
* Proceeding with detailed high-resolution satellite imagery analysis (manual and/or AI-assisted) within the selected grid(s).

This iterative process of programmatic analysis, visualization, comparison with existing research, and historical land cover assessment is designed to maximize the likelihood of identifying previously undocumented archaeological features in line with the project's objectives.

**Bibliography (for Parts I & II of the Methodological Approach):**

1. **de Souza, J.G., Schaan, D.P., Robinson, M. et al. (2018). Pre-Columbian earth-builders settled along the entire southern rim of the Amazon. *Nature Communications*, 9, 1125. DOI: 10.1038/s41467-018-03510-7**
   * *Used for:* Establishing the "Southern Rim of the Amazon (SRA)" concept, the continuity of earth-building cultures, typical earthwork chronologies (Cal AD 1250-1500), and general site types/patterns in the SRA.
2. **Erickson, C. L. (2023). The Transformation of Environment into Landscape: The Historical Ecology of Monumental Earthwork Construction in the Bolivian Amazon. *Land*, 12(4), 810. DOI: 10.3390/land12040810**
   * *Used for:* Confirming the presence of ring ditches and Amazonian Dark Earths (ADEs) along the Guaporé River in both Bolivia and Rondônia, Brazil, and citing earlier reports by Miller and Becker-Donner in the region.
3. **Peripato, V., Forest, F., Negrón-Juárez, R. et al. (2023). More than 10,000 pre-Columbian earthworks are still hidden throughout Amazonia. *Science*, 382(6666), 103-109. DOI: 10.1126/science.ade2541**
   * *Used for:* The foundational predictive probability model for earthwork presence across Amazonia, maps of known and newly discovered sites (including their "Southern Amazonia - SA" region), and identification of key environmental covariates associated with earthwork presence.
4. **Texier, W. G. P., Poggiali, G., de Oliveira, S. M., Polivanov, H., da Silva, M. M. N., & Maciel, T. E. F. (2021). Amazonian Dark Earths in Rondônia State: Soil properties, carbon dating and classification. *Revista Brasileira de Ciência do Solo*, 45, e0200160. DOI: 10.36783/18069657rbcs20200160**
   * *Used for:* Specific details on ADEs in Southern Rondônia, particularly near the Guaporé River (Cabixi, Pimenteiras do Oeste, Cerejeiras), including soil properties, associated artifacts, and climatic context.
5. **Trindade, T. B. (2015). *Geoglifos, zanjas ou earthworks? Levantamento geral dos sítios arqueológicos com estruturas de terra em vala no médio rio Guaporé (RO) e análise comparada com os demais sítios no Sudoeste da Bacia Amazônica.* Dissertação (Mestrado) – Museu de Arqueologia e Etnologia, Universidade de São Paulo, São Paulo. (Link usually found via USP's digital library or a direct search for the title).**
   * *Used for:* The crucial information about a systematic remote sensing survey for ditched earthworks along the right margin of the Middle Guaporé River, directly informing the selection of adjacent interfluves as "white spots."
6. **Zimpel Neto, C. A. (2018). *A fase Bacabal e seus correlatos arqueológicos no sudoeste da Amazônia.* Tese (Doutorado) - Museu de Arqueologia e Etnologia, Universidade de São Paulo, São Paulo. (Link usually found via USP's digital library).**
   * *Used for:* Establishing the deep chronology of human occupation in the Middle Guaporé region through the Bacabal ceramic phase.

**Secondary/Contextual (mentioned but not as central to the step-by-step logic, or from the starter pack):**

* **Wagner, F.H., Peripato, V., Kipnis, R. et al. (2022). Fast computation of digital terrain model anomalies based on LiDAR data for geoglyph detection in the Amazon. *Remote Sensing Letters*, 13:9, 935-945. DOI: 10.1080/2150704X.2022.2109942**
  + *Used for:* General understanding of geoglyph characteristics and detection methods, relevant if LiDAR data were to be used or if similar morphological signatures are sought in optical imagery. Included in the "Starter Pack."