WHETTING THEIR APPETITE: A SPATIAL ANALYSIS OF SEASONAL FLOODING AND RAISED FIELD AGRICULTURE IN THE LLANOS DE MOJOS, BOLIVIA

by

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ABSTRACT

The Llanos de Mojos, a region of the southwestern Amazon, is a seasonally flooded savannah located in the Beni department of Bolivia. The area sustained a significant pre-Columbian population up to the arrival of Jesuit missionaries in the late 17th century. Local communities constructed agricultural landscape modifications to help cultivate crops such as maize, manioc, and sweet potato. Raised fields contributed to soil nutrient intensification and helped to manage flooding. This study examines the relationship between 40,766 raised agricultural fields which were digitized by the Proyecto SIG Arqueológico del Beni using Google Earth and maps of surface flood coverage. Flood maps from 2012–2016 were analyzed using 14-day aggregates of Moderate Resolution Imaging Spectroradiometer (MODIS) data provided by the Dartmouth Flood Observatory. These datasets were compared using ArcGIS to examine the extent and variability of yearly flooding as well as the number of raised fields which were subject to seasonal inundation on a year-by-year basis. It was found that despite significant portions of the region being covered by seasonal floods, only 5.79% of the fields were exposed to flooding in total. This study concluded that raised fields were more suited to the containment and dispersion of localized precipitation rather than the dispersion of riverine flooding. Several fields that have paleobotanical associations with maize, manioc, and sweet potato cultivation only experience flooding for 1 out of the 5 years analyzed, supporting their practicality for growing water-sensitive crops.
For my mom and dad,
Cindy and Richard Martin
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INTRODUCTION

This thesis is an anthropological analysis of pre-Columbian raised agricultural fields in the Llanos de Mojos (or Mojos) using hydrological, remote sensing data. Mojos is a region of the southwestern Amazon located in the Beni department of Bolivia. Mojos is a 110,000km² seasonally inundated savanna located between the Andes and Brazilian highlands (Figures 1-3) (Walker 2008: 927; Erickson 2000). Mojos experiences seasonal flooding because of heavy regional and interregional rainfall (Hamilton et. al. 2004; Hanagarth 1993). The amount and location of flooding Mojos experiences can be highly variable depending on the year’s climatic conditions (Hamilton et. al. 2004; Hanagarth 1993; Walker 2004). It is based on local rainfall as well as precipitation downriver from Mojos. The landscape is composed of mainly flat terrain and is mostly covered with savannah grasslands (Erickson 2006). Archaeological remains such as earthworks and ceramics along with ethnohistoric reports from Jesuit missionaries in the 17th century, suggests a significant pre-Columbian occupation in this area.

Mojos has many rivers, lakes, and swamps, which drain into the central Mamoré River. These hydrological features can fill and flood from localized rainfall. Rivers in Mojos, especially the Mamoré, overflow their banks because of high water levels downstream as well (Walker 2008:928). Between November and April large portions of the savannah is covered in water. Pre-Columbian people managed seasonal flooding through the construction of earthworks such as forest islands, fish weirs, causeways, and agricultural platforms. Flooding can be managed through the construction of earthworks because floods have a relatively predictable size and timeframe in Mojos. Major floods that occur every 5 to 15 years had the potential to disrupt the lives of the pre-Columbian population (Block 1994; Denevan 1966).
People in Mojos practiced a form of landscape “domestication” in which they managed and controlled the natural landscape using earthworks and specialized cultivation practices (Erickson 2006; Walker 2008). Raised fields are just one category of agricultural modifications located within the larger Mojos that serve as an example of this type of environmental management practice (Figure 4-6). There are fish weirs, occupation mounds and several additional types of agricultural fields located in other sections of Mojos (Garcia-Cosme 2015; Walker 2008). Raised fields were used to grow a variety of crops including maize, sweet potato, and manioc based on paleobotanical remains and ethnohistoric accounts (Block 1994; Denevan 1966; Erickson 1995: 93; Whitney et. al. 2014). Raised fields served as a method of agricultural intensification allowing the pre-Columbian population to utilize the nutrient deficient, clayey soils of Mojos by stacking layers of topsoil (Erickson 2006:251). Raised fields were also constructed to improve the drainage and irrigation of crops (Denevan 2001; Lombardo et. al. 2011) Raised fields have been shown to aid in the dispersion of localized flood waters by increasing the elevation and slope of cultivation platforms (Lombardo et. al. 2011; Walker 2004: 43). Excavations of raised fields revealed erosion has reduced their height by 40 to 50cm since their construction (Denevan 2001; Lombardo et. al. 2011; Walker 2004:43). The increased elevation would have further improved raised fields drainage capabilities. The nutrient and soil content of raised fields has been identified as a reflection of microenvironmental differences throughout Mojos (Rodrigues et. al. 2018). Raised fields in the north and south have exhibited differences based on density and assessment of orientation (Garcia-Cosme 2015; Lee 2017; Walker 2004).
The capacity of raised fields to manage floods has yet to be analyzed on a broad geographic scale (Denevan 1966; 2001; Lombardo et. al. 2001; Rodrigues et. al. 2017; 2018; Walker 2004; 2008; 2012). This thesis examines the relationship between raised fields and flooding over 71,988.09km² of Mojos (Figure 7). Polygons representing individual raised fields provided by the Proyecto SIG Arqueológico del Beni (ProSIGAB), and flooding data provided by the Dartmouth Flood Observatory (DFO) at the University of Colorado served as the foundation of this analysis. Moderate Resolution Imaging Spectroradiometer (MODIS) serves as the underpinning of the DFO’s data by monitoring surface water coverage through the reflectance of light off of the Earth’s surface at a spatial resolution of 250m. MODIS data was aggregated to form the maximum extent of water coverage for 2012–2016. A neighborhood of raised fields sampled by Whitney et. al. 2014 was examined for its spatial relationship to MODIS derived flood coverage in this research. This paper approaches the interpretation of the past from a synthetic approach by combining archaeological associations of earthworks to pre-Columbian people and modern environmental spatial data (Walker 2004). It examines the landscape as a dynamic cultural unit and does not attempt to contextualize Mojos lifestyle or material culture (Anschuetz et. al. 2001). Raised fields are examined from a binary perspective, based on overlap between the two data sets: raised field polygons and MODIS reflectance polygons.

It is hypothesized that:

H1: Raised fields were constructed in areas less exposed to seasonal flooding based on yearly aggregates of surface water coverage.
H2: Raised fields associated with pre-Columbian maize, sweet potato, and manioc cultivation were not exposed to seasonal flooding over the course of several years.

This thesis will attempt to answer the following questions:

1. How many individual fields were exposed to flood waters from 2012 to 2016?
2. Does the flooding of individual raised fields vary from year-to-year?
3. Are there differences in the total number of raised fields that flood in the northern and southern sections of the west-central Mojos?

The analysis showed that only a small number of raised fields (5.79%) were exposed to seasonal flooding based on the DFO flooding data. During the largest instance of flooding in 2014, only a little less than a quarter of raised fields were exposed to flooding (22.39%). This suggests that they have been placed to avoid intense periods of inundation throughout the year. Fields sampled for botanical remains that implied their use for maize, sweet potato, and possibly manioc cultivation, were exposed to flood waters for 1 out of 5 years. The sampled raised fields were exposed to flooding in 2014, considered one of the worst instances of flooding in Mojos in 40 years. The lack of flooding on the sampled fields in 2012, 2013, 2015, and 2016 suggests that they could be cultivated during the wet season without issues from excessive inundation of crops. It was also found that despite more flooding being reported in the southern portion of the Mamoré, raised fields tended to be exposed in greater numbers in the northern section (Hamilton et. al. 2004: 2110; Garcia-Cosme 2015; Lee 2017). This further supports potential regional variations in Mojos earthwork construction (Rodrigues et. al. 2018).
Analyzing the relationship between raised fields and flooding contributes to knowledge about pre-Columbian cultivation techniques and provides a better understanding of the intentionality behind the placement of raised fields. Knowledge about the placement and construction of raised fields can be used to create new methods for mitigating climate change with the recombination of past agricultural techniques (Renard et. al. 2012; Sorribas et. al. 2016). Pre-Columbian agricultural techniques might represent a more effective method of cultivating crops within large, floodplain environments when compared to modern methods (Seghezzo et. al. 2011). Based on the data from 2014, raised field placement in relation to seasonal flooding displayed how populations prepared for extreme instances of flooding (Mayle and Iriarte 2014; Whitney 2014:3). Raised fields may have lessened the impact of excess inundation to crops during these major flood events and evidence of this has been made visible on a large, regional scale. Fields were placed over a significant geographic area and were likely placed in areas that did not experience large amounts of flooding during the average year. Even during the worst years of flooding, most fields would be unflooded and available for cultivation.
BACKGROUND

Archaeological investigations derived from examining the landscape as a unit of culture is defined as landscape archaeology. Landscape archaeology is a type of archaeological analysis based on how past cultures utilized space in connection to local, regional, and global geography (David and Thomas 2008: 25). Landscape archaeology is a holistic study that considers social, historical, and environmental factors for contextualizing cultures. It examines the connection of people and cultures to significant topographic features, environmental characteristics, transportation patterns, and relates sites on a regional and diachronic scale (David and Thomas 2008: 36, 38). Environment is interpreted through synthetic data sources and explores culturally dynamic conceptions and perspectives of people’s surroundings (Anschuetz et. al. 2001). Landscape archaeology can utilize data that is both physical and symbolic. This analysis uses the theoretical foundation provided by landscape archaeology and focuses on the physical characteristics of the pre-Columbian environment. In the case of Mojos, raised fields are observed as a material remnant of the pre-Columbian population. Flooding, as a feature of the environment, is synthesized with raised field data to examine the impact of seasonality on a broad, geographic scale.

Spatial analysis has come to play an increasing role in studying archaeological remains particularly in the form of remote sensing, database management, and geospatial modeling (Howey and Burg 2017; Lock and Pouncett 2017; Walker 2012). Spatial analysis has allowed researchers to digitize and analyze large amounts of data, which can be used to model and simulate human behavior through spatial relationships (Richards-Rissetto 2017). Spatial analysis can be used to visualize complex connections between a variety of factors seen in material
culture and landscape to construct a broader picture of how people and their environment interacted (Whitley 2017).

Spatial analysis is a useful research tool for relating cultural remains that might be too great in size or dispersion to excavate individually. Geographic Information Systems (GIS) is a central feature of archaeological investigations, which allows them to perform spatial analyses with a focus on environmental characteristics (Richards-Rissetto 2017). GIS tools such as ArcGIS offer cheap, easily available programs for analyzing broad spatial questions in archaeology. ArcGIS is a mapping program that allows for the integration of cartographic features with multiple data sets. As technology and mapping resolution improves, the humanistic perspective it provides can grow and shorten “the gap between empirical information and narratives” (Richards-Rissetto 2017: 11).

Public Archaeology and Landscape Analysis

Public archaeology has become a significant component of modern archaeological investigations, especially for capturing large datasets such as the one utilized in this research. Public archaeology is the engagement of people outside of the academic sphere who contribute to archaeological opinion and discussion while also creating content and data for analysis (Merriman 2004). It has been argued that this has caused a decrease in professionalization of the discipline but does not indicate a decrease in the regimentation of the data the public has collected. On the other side of the equation, archaeologists have argued that collected data can be used to solve problems relating to a variety of social and political issues through public
engagement (Altschul et. al. 2018: 21). The synthetic approach in this regard can be used to inform public policy as well as tackle social and cultural problems in the past and present.

There are several organizations which now use public data for archaeological interpretation. For instance, the monitoring of site destruction is a useful conduit that can be done through public spaces and by using spatial data requiring a lower commitment of resources (Altschul et. al. 2018; Xiao et. al. 2018). For example, the Florida Public Archaeology Network has created a website for people to participate in archaeology as Heritage Monitor Scouts\(^1\). The public is given access to a database of cemeteries, which they can use to report damage or vandalism to the sites directly to archaeologists. GlobalXplorer, supported by National Geographic and run by Sarah Parcak out of the University of Alabama Birmingham, uses small portions of satellite imagery that volunteers use to identify potential damage or looting in areas around South America\(^2\) (Gewin 2016). The process has been “gamified” with users being rewarded for their participation with small incentives such as increased access to information about the project. Gamification might be a useful consideration for future digitization efforts in Mojos in which people could identify earthworks in the landscape and have incremental rewards for doing so.

The online availability of archaeological resources means that new questions can be formulated using information readily accessible to both the public and researchers. Data can be transferred across mediums and duplicated to allow multiple individuals to work on the same material. Online spaces also allow for data to be consistently updated and allow for current data

\(^1\) https://fpan.us/projects/HMSflorida.php
\(^2\) https://www.globalxplorer.org/
to be quickly disseminated. Analyses can access information from multiple sources, which can be combined. This presents unique opportunities for other disciplines to inform archaeological perspectives on the environment and past lifeways. The analysis and accompanying data performed in this research using publicly available information will be made immediately available via online archive and made accessible through aggregated internet databases.\(^3\)

_Archaeology of the Amazon_

Amazonian archaeology has long focused on human-environmental interactions as a method of exploring culture, intentionality, and for measuring the size of human impact. A central dispute in Amazonian archaeology was whether the environment allowed for large populations to exist in a sustainable and dispersed fashion (Denevan 1992; Meggers 1971). Professional opinion saw the Amazon as being a “pristine” environment that largely remained unknown to human occupation (Barlow et. al. 2012). Archaeologists argued that the Amazon lacked sufficient resources to support large populations. The lack of available resources would create centralized populations that were often in conflict (Meggers 1971). The lack of animal domestication in the Amazon and relative rarity of game animals was also thought to be a limiting factor of nutrient acquisition for pre-Columbian populations (Gross 1975). It was also thought that the land in between these small bands remained untouched and unmodified by human intervention because of broad environmental constraints on movement and agriculture (Meggers 1954; 1971).

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\(^3\) [http://stars.library.ucf.edu/](http://stars.library.ucf.edu/)
In contrast, Lathrap (1970) suggested Amazonian cultures were complex societies based on the linguistic diversity, dispersion of artifact assemblages, and modification of the local environment. Excavations along the Amazon demonstrated pre-Columbian people likely utilized trade routes that traversed large distances, integrating several cultures and landscapes (Lathrap 1973). Disease became the new explanation for the depopulation of the Amazon rather than pre-Columbian people’s inability to “adapt” to their landscape, as had been suggested previously through cultural ecology (Balée 2013; Denevan 1992; Meggers 1954). This “Pristine Myth” was undone by archaeologists showing that the Amazon was able to support larger populations than purported in earlier literature. It has been the location of several large, centralized, and complex societies who manipulated their environment to better suit their needs (Denevan 1992; Erickson 2000; Heckenberger and Neves 2009).

The abundance of biological diversity in regions of anthropogenic manipulation suggest portions of the current environment is the result of previous human intervention (Levis et. al. 2017). It elucidates the idea that the Amazon is the result of environmental management practices based on the richness and abundance of domesticated species with areas known for their pre-Columbian occupation. Domesticated species are directly associated with modified environments and anthropogenically created soils. It demonstrates that pre-Columbian people could harness and manage natural resources in a fashion that can be contextualized through a modern analysis of the landscape. For example, the Marajoara show ample evidence of Amazonian Dark Earth (ADE) production up to 2 meters deep in some sections (Schaan 2011: 123-126). ADE are soils high in nutrient content created from the long-term deposition of
materials at occupation sites in the Amazon (de Souza et al. 2018; McEwan et al. 2001; Glaser and Woods 2004).

The lack of archaeological material and the inclusion of computational and spatial technologies has made a synthetic approach using collaborative datasets, a useful method for producing research about the social complexities of Amazonian cultures (Anschuetz et al. 2001; Altschul et al. 2018; Walker 2004:11; Walker 2012). In this research, raised fields are compared with the location of modern flood surface coverage. Specific raised fields associated with maize, sweet potato, and manioc cultivation are then spatially associated with floods as well (Whitney et al. 2014; Dickau et al. 2012). This research is defined through analogy, which uses modern data sets and applies them to past patterns. Analogy is useful where there may not be enough archaeological evidence to explain climatic or human behavior (Erickson 2008). Analogy does not always account for the complexities of past lifeways and is not entirely representative of what happened in the past. Instead informed analogy serves as a vehicle through which broad interpretations can be made about the validity of intentionality and regional decision making (Erickson 2006; Walker 2004). Thus, the interactions that people had with Mojos are being defined through the places in which they constructed raised fields and how the modern flooded landscape relates back to seasonal patterns in the past.

*South American Raised Fields*

South American archaeology has developed into an inter-disciplinary examination of past cultures. Research varies broadly because of the continent’s large size, myriad of cultural groups and diverse environments (Silverman and Isbell 2008; Haynes 1948). The coastal Andes and
associated cordillera are rich with culturally specific, accessible material culture and occupation sites for archaeological excavations. On the other hand, research in the Amazon has benefited heavily from remote sensing, giving archaeologists the ability to see environmental modifications on a broader scale (Erickson 2008; Walker 2012). Balée (2013) asserts that it is important for South American archaeology to synthesize current and past ecology. This will help expand experimental paradigms on investigations into how past cultures interacted with their environment.

Recent uses of spatial analysis have helped integrate several kinds of archaeological investigation. Several examples of archaeological analyses in South America seek to connect broad data sets by examining regional spatial patterns. These spatial data sets can be combined to promote multi-scalar approaches to interpretations about the past, which examine lifeways through pattern identification. For example, Menendez (2016) uses dental caries and isotopic exchanges based on agricultural expectations to relate populations spatially in the Andes. Osorio et. al. (2017) combined “lithic technology, faunal remains, radiocarbon dates, and other archaeological materials related to different social activities” to track the peopling of South America by analyzing mobility. Wernke (2013) observes spatial patterns in the Colca Valley based on the age and location of terraced fields in relation to local Inka political organization. He argues that the cultural identity of villages under Inka rule is evident from how they modified and constructed their fields. Cultural divisions could be partitioned from the technological, temporal, and locational nature of their associated agricultural features, specifically terracing and canals.
On a continental scale, agricultural modifications are found throughout many regions of South America and represent a variety of cultures and populations (Denevan 2001; Wernke 2010). These earthworks highlight the complexity of pre-Columbian cultures in adapting to their environment (Denevan 2001; Erickson 2006; Mayle and Iriarte 2014). Nordenskiöld [2009 (1916)] was one of the first researchers to take note of the different kinds of agricultural modifications found in South America. While working in Mojos, he postulated that there would be similar earthworks found in other parts of the Amazon. He initially remarked that these mounds were constructed primarily to remove pre-Columbian people from the surrounding flood waters. He argued that the size and geographic distribution of these earthworks also shows that there are similar environmental considerations regarding their method of construction and morphology.

The Llanos de Orinoco of Venezuela is a seasonally inundated savannah like Mojos with agricultural earthworks found throughout it (Denevan 2001; Hamilton 2004). The two savannas are predominately covered in dry savannah grasses and drain into a centralized river system. The Orinoco River feeds directly into the Atlantic from the Andean downslope while the Mamoré ultimately connects to the Amazon. The mounds located here have similar properties to those in Mojos indicating the existence of complex communities and chiefdoms with a distinct sense of centralization (Erickson 2000: 2). Ridged fields in the Orinoco serve as another example of patterned, agricultural intensification that served the purpose of removing crops from the seasonal inundation that occurs in the region (Denevan and Zucchi 1978). It would also be a useful source of nutrient refreshment for crops. There have been some previous comparisons of
the region to Mojos based on the clayey geology and discussions of field morphology (Denevan 2001).

There have been reports published on mound fields in French Guiana, which suggest that their construction was as a method of hydrological control (Denevan 2001; McKey et. al. 2010; Rostain 2008). They are patterned in parallel neighborhoods with individual fields numbering in the thousands. These mounded fields were likely capable of supporting a large and centralized pre-Columbian population (McKey et. al. 2010: 7825). The fields on the French Guiana coast are also located in a floodplain prone to consistent inundation from deeply embedded swamplands (Iriarte et. al. 2010). Seasonal floods occur here from the overflow of these freshwater swamps. Fields were built as a method of retaining and dispersing this water. They were also useful for accumulating organic soils to improve the availability and intensification of nutrients for cultivation.

Additional instances of raised fields found in the Lake Titicaca Basin heavily utilized access to groundwater resources rather than through surficial exposure (Denevan 2001; Janusek and Kolata 2004). Their construction was also used to create arable soil and exploit nutrients from encroaching wetlands. They were an important agricultural mechanism during the Middle to Late Formative Periods and heavily used throughout the Tiawanaku Period in the Andes (Bruno 2014; Stanish 1994). The pampa, where raised fields were constructed, is low-lying, flat terrain susceptible to seasonality in the form of flooding during the wet season from October to March (Denevan 2001: 266). The resulting circulation of water in surrounding canals improved the nutrient content of the soils and served as a supply of water throughout the year as it infiltrated through the soil. This could have prolonged the growing season by up to 2 months.
Crops grown on the fields were changed based on seasonal variables and included root crops, quinoa, and maize. These raised fields were key to local subsistence and suggested management practices did not require direct intervention by an “elite” system (Stanish 1994). It is argued that drought reduced the efficiency of the raised fields to a point that they were abruptly abandoned because of salinization and their inability to properly irrigate crops (Janusek and Kolata 2004; see also Erickson 1999).

The Marajoara of Marajó Island who lived at the mouth of the Amazon were a similar mound building culture and used their earthworks predominately for settlement (Denevan 1964; Roosevelt 1991; Schaan 2011). The island is a large floodplain, suggesting earthworks were constructed to remove inhabitants from localized inundation. Occupation mounds varied in height from 3 to 20 meters tall and could extend for several hectares of land (Roosevelt 1991: 30). The region experiences seasonality much like Mojos in which water is scarce from August to December but floods during the wet season from the enormous amounts of water that flow out of the Amazon. Communities in this region have also constructed fish weirs and ponds like those seen in Mojos (Erickson 2006; McKey et. al. 2016; Schaan 2011). Elevated fields in this region were used to control water through the creation of adjacent canals, which would direct seasonal flooding away from crops. In the rainy season, these canals would be wide enough and deep enough to allow for canoe travel. Continuous management of these fields suggested their capacity to maintain fertility for the long-term cultivation of manioc and sweet potato (Schaan 2011: 17, 74-75).

The Salta in Argentina had hundreds of thousands of large mounds used for manioc and sweet potato cultivation (Denevan 2001:25). Salta planting beds were useful for mitigating
winds, but a hydrological analysis has not been completed on these fields (Denevan 1980). The Argentinian Salta has seen significant modern day agricultural modification coupled with sweeping deforestation (Seghezzo et. al. 2011). Modern features have replaced ancestral ones using methods not suitable for sustainable cultivation.

Raised fields thrived in wetland environments and integrated well with seasonally inundated regions. They served as a useful tool for intensifying soil nutrient content and for removing crops from excess inundation. Assessing the impacts of replacing local farming practices on hydrology are useful for modelling the continuing effects of population growth and climate change. It exemplifies the usefulness of pre-Columbian environmental mitigation practices as a method managing seasonal climate patterns regarding agriculture. It also demonstrates that earthworks can be combined with local ecosystems to the benefit of the indigenous or local communities.
ENVIRONMENT AND PEOPLE OF THE LLANOS DE MOJOS

Mojos Raised Fields

Denevan defines raised fields as any land that has been artificially elevated for crop cultivation and agriculture (2001:220). Fields in Mojos were constructed by excavating soil from the sides to create platforms where crops could be cultivated. The parallel ditches created through this process have been noted for their ability to retain water (Denevan 2001). They have an average width of 5 to 20 meters and can be between 140 to 1000m long (Denevan 2001: 242; Lee 2017). Their height varies between 8 and 60cm with the average field being about 20cm high (Denevan 1966: 85-86; Lombardo et. al. 2011; Walker 2004: 33). Estimates of erosion from excavations and soil sampling suggest raised fields have lost 40cm to 50cm of topsoil since their original construction and would have been more effective at remaining above flood waters in the past (Lombardo et. al. 2011: 507; McKey et. al. 2010; Walker 2004; Whitney et. al. 2014). The creation of raised fields had several benefits including the reduction of pests, increase in nitrification, and aeration of the soil (Denevan 2001:220). Although raised fields are currently nutrient poor because of leaching over time, the initial construction of raised fields would have intensified the nutrient content of the soil for cultivation purposes (Lee 2017; Lombardo et. al. 2011; Whitney et. al. 2014). Raised fields are primarily located within the open savannah. They are visible in satellite imagery because of erosion that causes their surface to become rigid and whitish in color (Walker 2004: 33; Whitney et. al. 2014). The parallel ditches from their construction also contribute to their visibility in satellite imagery.
Many raised fields in Mojos are still able to remain above seasonal flooding (Denevan 2001). Raised fields were placed in parallel or oblique neighborhoods with 3 to 6m of space in between each field (Denevan 2001; Lee 2017). Neighborhoods of raised fields can be located several hundred meters from each other. A centralized authority would not be necessary to complete their construction but coordination between farmers would have ensured sufficient space was made between plots (Walker 2011a).

Based on an analysis by Boothby (2012), raised fields were mostly built near waterways. They were also noted to be oriented around hydrological features in the environment (Boothby 2012: 63). Garcia-Cosme (2015) noted different densities between raised fields in the northern and southern portions of the west-central Mojos. Northern raised fields are more clustered than southern fields. Lee (2017) analyzed the orientation of fields. It was discovered that fields in the north are patterned along a north-south, east-west axis. Fields in the southern portion are titled off this axis by several degrees.

Geography and Environment

Several rivers run through Mojos including the central Mamoré River and its tributaries: the Iruyañez, Omi, Yacuma and Rapulo Rivers. The tributaries flow west to east towards the Mamoré on a slight downslope from the eastern Andes (Boixadera et. al. 2003). The Mamoré eventually flows into the Amazon River. The slow downstream flow of river waters is another contributing factor to flooding in the region (Walker 2008). High water levels downstream cause the Mamoré and its tributaries to “backup” and overflow onto the landscape during the wet
season depositing 1 to 3 meters of water across the surrounding savannah (Figure 8) (Denevan 1966, 2001; Lombardo et. al. 2011; Walker 2008).

There are several perennial lakes (baijos) and swamps within Mojos as well. During the dry season, water is sparse with large extents of aridity, but water is still present in these lakes and swamps (Denevan 1966: 11). Lakes and swamps have the potential to overflow from local precipitation as a single year can see between 1500 and 1800mm of rainfall (Denevan 1966). Up to 30cm of rainwater can collect on the savannah landscape as well because of local precipitation (Boixadera et. al. 2003; Walker 2008: 929).

A large, permanent swamp is located to the northwest of the modern-day town of Santa Ana del Yacuma between the Omi and Yacuma Rivers known locally as the Kinato Wetland (Walker 2008; 2011b). The swamp is a paleoriver created from the avulsion of one of the nearby rivers (Dickau et. al. 2012; Lombardo 2016; Walker 2011b). Avulsions occur from sedimentation that causes a river to suddenly shift from its original course. Smaller fluvial changes in Mojos create oxbow lakes along the more active channels in the region, particularly along the Mamoré (Hanagarth 1993; Lombardo 2011). There are several large lakes located towards the northern extent of the location of the raised fields which are distinct hydrological features. They include Laguna La Porfia, Laguna La Encerada, and Laguna Guachuna, Lago Rogaguado, and Lago Ginebra.

Seasonal floods are a dynamic hydrological feature of Mojos. Fluvial deposits on the fields suggest that flooding may have been more severe and widespread in the past than it is today; However, climatic patterns in the region have been consistent since about 3,000kya.
(Hoffman et. al. 2003; Lombardo et. al. 2011). Seasonal floods are relatively consistent in size by year allowing for the construction of earthworks and management systems, but large and damaging floods occur about every decade. 1773, 1800-01, 1853, 1886, 1895, 1928–29, 1930, 1947, 1959, 2007, 2008, and 2014 were all years with higher than average levels of flooding which disrupted the lives of contemporary populations in Mojos (Block 1994; Denevan 1966; Ovando et. al. 2016). Jesuit missionaries remarked on a community in Mojos that split up after the original riverside settlement was destroyed by seasonal flooding (Block 1994: 26). One group rebuilt along the river while the rest settled a new village in the savanna. This shows how seasonality may have had a continuous, direct impact on the livelihood of the pre-Columbian population. On a more modern timescale, 2014 was one of the worst instances of flooding in Mojos in 40 years (Ovando et. al. 2016). The floods caused 64 deaths, stranded the local population, and caused millions of dollars in economic damage.

The reason flooding is largely surficial in Mojos is because of the high clay content of the soil. It prevents penetration from flood waters and encourages its collection on the landscape (Boixadera et. al. 2003; Rodrigues et. al. 2018). Hardpacked quaternary stones and clay exist under the topsoil of Mojos which impedes the creation of groundwater (Clapperton 1993; Lombardo et. al. 2011; Whitney et. al. 2014). The clay content, which varies between 8% and 90%, combined with low levels of organic soils would have made agriculture difficult to intensify nutritionally (Lombardo et al. 2011: 508). The organic soils that are found in Mojos are partially the result of fluvial deposits from seasonal floods (Walker 2008: 929).

Tree cover has taken advantage of small changes in elevation to escape flood waters (Denevan 1966; Walker 2004). Gallery forest grows on the silt-deposited berms next to the rivers.
or within stream-valleys cut by flowing water (Plotkin 2011). Oftentimes, forest and shrubs take advantage of the elevated platforms that the earthworks in the region provide. For example, forests have colonized the occupation mounds that can be found throughout the area. (Denevan 1966; Erickson 2000; Erickson and Balée 2006). These island-like hills known as forest islands served as the location of pre-Columbian settlements. Forest islands were accreted through “successive constructions, elevation, and modification of platforms” over generations providing enough change in elevation to prevent exposure to seasonal flooding (Dickau et. al. 2012: 3). The larger forest islands are useful for modern ranchers to place their homes and for agriculture (Walker 2011b: 4).

Rain water and runoff are the primary reason that raised fields might experience seasonal inundation. The morphology of raised fields may reflect this influence and be the result of a multi-causal relationship to water exposure. A terrestrial LiDAR based assessment of the slope of raised fields suggests their construction in the north-eastern and central Mojos was purposefully designed for water to collect in the parallel ditches while also moving water away from the bulk of the crops (Lombardo et. al. 2011). Additional research by Rodrigues et. al. 2017 shows that the morphology of raised fields was designed to create enough change in elevation to promote proper drainage. Flood water is then allowed to collect in pools that can be accessed for a portion of the dry season. It has been noted that the ditches created during the construction of a raised field will maintain the presence of rain water for several months into the dry season (Erickson 1995). Slight increases in elevation as shallow as 20cm, allow for the removal of flood waters from raised fields.
Social Organization and Communities

According to the Jesuit missionaries who settled in the region in the late-17th century, villages in the Llanos de Mojos were autonomous and centralized on forest islands (Block 1994; Denevan 1966). Ceramic assemblages, stone tools, and modifications to the islands themselves revealed several layers of stratigraphy indicating long periods of continuous occupation (Erickson 2000; Erickson and Balée 2006). Causeways between some forest islands suggest groups had interconnected communities (Walker 2004: 27). They facilitated easier movement through the savannah to support trade and communication networks (Denevan 1992; Trombold 1991). A leader or headman would be elected who controlled daily activities such as hunting, the location of the village, and cultivation practices associated with drinking (Denevan 1966: 46). A centralized authority would have been useful for the planning and construction of Mojos earthworks. Small numbers of individuals, between 30 to 100, were required to construct groups of raised fields within a “distinct spatial unit” (Walker 2008:934). The organization of this undertaking may have been the result of construction enacted under a “head-man” from each occupational cluster (Denevan 1966; Walker 2008: 933, 934). Ethnohistoric reports indicate that one chief from the region may have ruled between 5 to 7 individual islands (Walker 2004: 119).

There are six linguistic groups that have been identified in the Llanos de Mojos associated with the pre-Columbian occupation of Mojos: The Movima, Mojo, Baure, Canichana, Cayuvava, and Itonama (Denevan 1966; Metraux 1948: 408-430; Hornborg 2005). The Mojo and Baure are Arawak languages, which is a highly dispersed language group located in South America (Walker and Ribeiro 2011). It is a language primarily associated with mound builders and agriculturalists who modify the landscape for cultivation and settlement (Erickson and Balée
The Movima, Baure, Canichana, Cayuvava, and Itonama are linguistically isolated from the Arawak and may have arrived much later to Mojos (Denevan 1966:40-43). Despite ethnic and linguistic distinctions, all of these groups modified their environment to better suit their needs (Denevan 1966; Epps 2009). This indicates the regional need for cultures in Mojos to “domesticate” their environment to manage shifting seasonal conditions (Erickson and Balée 2006: 249). The raised agricultural fields for this analysis have been primarily associated with the Cayuvava indigenous group based on their geographic location in the west-central Mojos (Denevan 1966; 2001; Garcia-Cosme 2015). This area is located to the south of the region’s major lakes and stretches several kilometers south of the Omi river. Research suggests they were responsible for the initial development of raised field creation (Garcia-Cosme 2015). In the 17th century, the Cayuvava had broken up into 7 distinct villages which were ruled by a single headman (Metraux 1948). Eguiliz and Torres reported that one of them had a population of 2,000 individuals while the other 6 had 1,800 each. Later reports by Agustin Zapata, described five villages of the Cayuvava that had 4–5,000 people in total. (Walker 2004:25).

Overall, reports from Jesuit Missionaries in the late-17th century remain an important piece of the puzzle regarding interpretations of pre-Columbian landscape modification and agricultural intensification (Block 1994; Walker 2008). Their accounts show that seasonal flooding has long been an issue that both past and modern populations had to overcome regarding settlement and food acquisition (Block 1994; Denevan 1966). Missions were often moved because of their construction in areas which experienced seasonal floods (Block 1994). Wetland and savannah ecosystems are the driving force behind pre-Columbian people’s success in intensifying agriculture in the Amazon, but this was not true for arriving missionaries (Block
Missionaries who arrived in the region relied on slash and burn agriculture which took advantage of forest islands to cultivate staple and cash crops (Denevan 1966:32; Block 1994:156). Settlers cultivated Old World crops such as tamarind, cotton, and citrus to supplement plantains, sugar cane, and manioc without utilizing the pre-Columbian earthwork systems.

The current population is predominately ranchers who utilize the accreted forest islands to remove their homesteads and cattle from the seasonal floods (Walker 2011b). They describe the inundation as “water from below” and “water from above” ascribing a type of duality to the yearly hydrological cycle (Walker 2004: 21). “Water from below” comes from the overflow of local rivers. “Water from above” is the result of localized precipitation. The source of water varies between years and is reflected in the microclimates of Mojos (Rodrigues 2018:366). Modern modifications to the landscape come in the form of man-made lakes, dikes, roads, and cattle trails which crisscross the savannah (Figure 9).

For this analysis, man-made lakes were identified using Shuttle Radar Topography Mission Water Body Data (SRTMWBD) which identified permanent bodies of water on the Earth’s surface. SRTM data is combined with the DFO’s MODIS derived data for a more complete picture of Mojos water surface coverage and to better correlate the origins of regional flooding. Dikes have been constructed and maintained by two of the local towns: Santa Ana and Trinidad (Denevan 1966). Roads have been created to cross the savannah both by on horseback, car, and motorcycle. Roads have been raised to avoid issues with flood waters. Cattle trails can be traced from the ranches along the savannahs usually leading to salt licks or pasture. Although the current population is prepared for the seasonal floods that occur, there has been significant
disruption caused by floods that far exceed their normal levels. Most modern-day agriculture is swidden or slash-and-burn with plots showing up as squares within the gallery forests in satellite imagery. Runways for planes have also been placed onto strips of high ground so that resources can be brought into isolated ranches. Raised fields have not been used for agriculture by the modern population although experiments to create and cultivate crops on them has been attempted (Erickson 2005; Saavedra 2009).

*Food Acquisition and Agriculture*

Many types of earthworks have been built in Mojos which required a coordinated effort to construct and maintain (Erickson 2000; Heckenberger et. al. 2008; Walker 2008). Agricultural earthworks in similar areas of Mojos include ditched and platform fields. Other example of non-agricultural modifications includes causeways, fish weirs, and forest islands which are scattered across the savannah. These modifications to the environment contribute to the idea of Mojos as a “domesticated landscape” which can be exploited based on the significant seasonal flooding events that happen each year (Erickson 2006). The continued existence of these modifications to the environment demonstrates that earthworks were intended to have long-lasting benefits to the populations that lived there.

The pre-Columbian population had constructed raised fields since as early as 500AD until European contact in Mojos (Erickson 2006; Walker 2004). They created them as a means of managing the possible environmental limitations of their agricultural practices. Raised fields are effective material remains for comparing environmental conditions and human constructions because of their continued visibility in satellite imagery. Despite the shifting size of the
population in Mojos, the remains of pre-Columbian agricultural systems suggest that the
cultivation practices of this region were intensive (Walker 2004:19). The amount and regional
distribution of fields suggests that they sustained a large and mobile population who practiced a
variety of cultivation techniques (Denevan 2001). The number and dispersion of fields would
allow for fallow periods and ensure that some fields remained unflooded (Denevan 1966).
Archaeological remains have helped to identify the types of crops that were being cultivated
based on palynological, methodological, and analogous occurrences (Figure 10) (Dickau et. al.
2012; Erikson 2000; Mayle and Iriarte 2014; Walker 2008; Whitney et. al. 2014).

Fire was just as important part of the cultivation process in the Llanos de Mojos as water.
It may have been used to preserve the savanna landscape and prevent the encroachment of
nearby gallery forest (Whitney et. al. 2014). It may also have been used as a method of
refreshment that clears away debris from cultivation practices, microflora and fauna, and place a
layer of “nutrient-rich ash” on the burned top soil (Denevan 2001:39). Modern ranchers who live
in the region continue to burn areas of savannah to refresh the nutritional content of the grassland
for cattle grazing (Plotkin 2011).

The pre-Columbian population used a mix of different crops to exploit variations in
regional morphology and to utilize space within ditches and on the mounds themselves (Denevan
1964; Lombardo et. al. 2011; Rodrigues et. al. 2018). A neighborhood of fields was sampled by
Whitney et. al. 2014 located near the Iruyañez river and a large forest island, El Cerro. It
primarily included pollen associated with the cultivation of Zea mays (maize) on raised fields.
The authors also discovered the presence of I. batatas (sweet potato) pollen suggesting an
increase in its cultivation beginning around 1280AD. Samples procured from ceramics found at
occupation sites in Mojos suggests that large raised fields were used to cultivate manioc as well (Dickau et. al. 2012). Beans and squash were also likely supplements to Mojos diet, but evidence of their cultivation has not been discovered in Mojos (Dickau et. al. 2012; Denevan 1992; McKey et. al. 2010; Whitney et. al. 2014).

Maize is one of the most significant crops of the New World with a relatively high starch content and relatively short period of cultivation. In archaeological contexts, it has been a primary mover behind increasing complexity and of environmental domestication (Roosevelt 1980; Denevan 1966). Mojos may have been no different. Savannah forests and flora was removed for the cultivation of maize based on the lack of associated botanical remains (Whitney et. al. 2014). Maize could be produced on these fields at an estimated rate of “4000 kg yr\(^{-1}\) per hectare of raised field surface” which is considered a high yield of the crop (Lombardo et. al. 2011:504). Maize would have required significant nutrient intensification and refreshment to be cultivated properly in Mojos. Modern varieties of maize are susceptible to drought and respond poorly to arid environments\(^4\). They need between 500 and 800mm of water throughout their growing period to survive. Mojos receives twice the amount of required rain water for the cultivation of maize during the wet season. When combined with “floods from below” the exposure to excess water from flooding may be detrimental to maize crops as well. Maize in sitting water can experience increased acidity which affects their ability to photosynthesize and properly remove waste oxygen, resulting in a less healthy plant overall (Yordanova and Popova 2007).

\(^4\) http://www.fao.org/docrep/u3160e/u3160e04.htm#TopOfPage
Root crops are much more suited to the tropical climate, nutrient poor soil, and potential exposure to flooding in Mojos than maize (Lombardo et al. 2011; Whitney et. al. 2014). As previously mentioned, maize cultivation was replaced with an increase in the production of sweet potato. This shift also coincided with a decline in the local population and an increase in savannah forests. Evidence of sweet potato production is seen in many cultures throughout the Amazon (Denevan 1966; Roosevelt 1980). Overall, sweet potato is slightly more calorically productive than maize (de Vries 1967; Jones 1959:25; Roosevelt 1980). Sweet potato can be grown in poorly drained areas but suffers when directly exposed to flooding (Ghuman and Lal 1983; Roosevelt 1980). During the dry season, exposure to direct water sources becomes much less important if the sweet potatoes can access water through their root systems (Rostain 2008).

The presence of manioc, besides being a staple of nearby cultures and regions, was also discovered in the macrobotanical remains of several sites in Mojos, taken from the interior of ceramics (Denevan 1966; Dickau et. al. 2012). Fraser et. al. 2012 noted that there was a significant amount of genetic diversity among manioc. The cultivation of manioc was less impacted by the presence of water and more impacted by the type of soil that it was grown in. That being said, manioc is still not resistant to long periods of direct exposure to water (Roosevelt 1980). Many of the same qualities of sweet potato can be said about manioc. Manioc is twice as calorically productive as sweet potato because of their carbohydrate dense nature (Jones 1959:25).

This analysis is using a synthetic approach to modeling potential crop viability and flooding. The interpretations of the data consider modern varieties of crops which may not be representative of pre-Columbian species that were used. Previous plant species may have been
better adapted to the environment and could be cultivated within the constraints of unstable levels of seasonality. By combining data about modern cultivars with raised field data, it compares their enduring construction and demonstrates their ability to navigate potential shifts in agricultural use (McKey et. al. 2010).
DATA SOURCES

The Proyecto Sistemas de Información Geográfica Arqueológico del Beni (ProSIGAB) is an ongoing research project that includes the use of open source mapping software such as Google Earth and ArcGIS Earth to digitize artificially modified features in Mojos. Students meet weekly to discuss findings, morphology, and anomalies in the imagery as well as aggregate their collected data. Google Earth provides access to satellite photos of features including raised fields, mound fields, causeways, fish weirs, and forest islands. Currently, the project has digitized 40,766 raised fields in the west-central region of Mojos (Figure 11). In addition, over 600 forest islands, several thousand mound fields, dozens of potential causeways, and several fish weirs have been identified in the imagery.

Researchers manually digitize features by creating polygons after they are identified in the satellite imagery. The majority of those involved in this project are students who have designed protocols revolving around feature identification and methodology. It is still important to note that each person may have a different interpretation of their extents. Satellite imagery is released periodically in this region, which has received progressively better resolution. In some instances, this reveals new environmental modifications as differentiation in the color of the soil is easier to distinguish. Polygons for the raised fields were created to cover the relative shape based on what was visible in the satellite imagery. For example, as of April 2018 several thousand mound fields have become more visible in the satellite imagery allowing for their digitization.
Raised fields are the primary focus of this project which are collected polygons from several years of digitization by students. The polygons were created using SPOT imagery within Google Earth, which was taken between 1986 and 2016. Since support for Google Earth has been discontinued new imagery is beginning to be accessed using ArcGIS Earth which uses Digital Globe imagery taken throughout 2017 and beyond. This project uses a combined version of raised fields that were mapped between 2011 and 2015 as polygons created by undergraduate and graduate students at the University of Central Florida. Raised fields were combined in GIS and instances of overlap were accounted for by Lee (2017). It combines and removes discrepancies in how polygons were positioned over satellite imagery.

*Dartmouth Flood Observatory*

The Dartmouth Flood Observatory at the University of Colorado uses spatial technologies to monitor flooding around the world in real time, including Moderate Resolution Imaging Spectroradiometer (MODIS) provided by NASA (Brakenridge et. al. 2018). It is an open source organization that publishes their data through an online database with maps showing the spatial extents of surface water coverage. Data is processed as new flood events occur around the Earth using remote sensing data. These maps are released as vectors or shapefiles which have been classified between present flood waters and null values. Polygons in the maps indicate the presence of surface water coverage. Data for each region is tabulated daily and made accessible for public use. The yearly classified floodplain calculations are only available for download directly on the site as a single aggregated geoTIFF which cannot be reclassified by year. In this
case, the DFO was contacted directly and the data was provided as compressed ArcGIS compatible (.shp) files.

*Data Sources*

MODIS is an instrument used to collect environmental remote sensing data onboard two satellites, Terra and Aqua, which have been in operation since 2000. The first satellite they placed into orbit for MODIS, Terra or EOS-AM1, examines “connections between Earth’s atmosphere, land, snow and ice, ocean and energy balance to understand Earth’s climate and climate change”\(^6\). It is useful for examining data that includes the composition of natural geography. Aqua, or EOS-PM1, was launched in 2002 with several additional tools for data collection. It examines precipitation rather than geology of the Earth’s surface. This includes monitoring for water vapor, snow, ice, and even soil moisture by examining the reflectivity and radiative energy fluxes from different types of material\(^7\). MODIS is the primary tool used by the DFO to generate their maps of floods. The data is processed at a spatial resolution of 250m. The availability of MODIS data after 2012 is the result of the process being automated with the data placed into a simplified Graphic User Interface on the DFO website.

Discussions about daily levels of river discharge were measured using a separate sensor and satellite. It was calculated using microwave radiometry starting as far back as 1998 (2002 for rivers at high elevations). This data is also provided by the DFO as charts that measure the average flow rate of several rivers within the region. The flow regimes from all the rivers from

\(^5\) [http://csdms.colorado.edu/pub/flood_observatory/MODISlance/070w010s/](http://csdms.colorado.edu/pub/flood_observatory/MODISlance/070w010s/)

\(^6\) [https://terra.nasa.gov/](https://terra.nasa.gov/)

\(^7\) [https://aqua.nasa.gov](https://aqua.nasa.gov)
within a designated sheet can sometimes be used to predict flooded areas as flow rate and floods can be positively correlated. Multiple calculations are made at specific monitoring spots along designated water ways, compared based on intervals of 1.5, 5, 10, and 25 years, and measured against the threshold of their lowest calculated flow.\(^8\).

\(^8\)https://floodobservatory.colorado.edu/DischargeAccess.html
MATERIALS AND METHODS

Regional Review

The hydrology of Mojos is an important consideration for the construction of raised fields in the region. The geographical range and large number of raised fields suggests that water would have been a primary concern for their cultivation (Lombardo 2011; Denevan 2001). It is important to note that this data has been collected over several years’ worth of digitization efforts by ProSIGAB. In this time, the imagery provided by Digital Globe has improved in resolution significantly which may have revealed raised fields which are not included in the imagery. The Kinato Wetland was digitized again to better account for it as an area of permanent inundation during the wet and dry season. Permanent water bodies were digitized by an earlier master’s thesis in the form of lines to represent the contemporary route of the tributaries to the Mamoré as well as the Mamoré itself (Boothby 2012).

The study area is in the west-central Llanos de Mojos and represents 71,988.09km² of the region (Table 1). It was designated as a rectangle that captures most of the flooding recorded through the MODIS derived data in Mojos. The analyzed area encapsulates the entire extent of mapped raised agricultural fields, the length of all four tributaries to the Mamoré (The Yacuma, Omi, Iruyañez, Rapulo, and the Kinato Wetland), a portion of the Baure, and a section of the Mamoré.

Data Management

Spatial analysis for this project was completed using ArcGIS 10.4.1. Access to the program was provided by the University of Central Florida and was used on several computers
with powerful processors capable of working with large data sets. The data provided by the DFO is useful for savannah environments where there is not much tree cover to impact the reflectivity measurements from MODIS. The MODIS derived data detects water when there are at least several centimeters of surface coverage (Vantrepotte et. al. 2013). It is also important to note that the MODIS derived data forms a maximum pattern for the inundation that occurred in Mojos. The data is aggregated from the maximum extent of polygons recorded over the course of 365 days. Cloud cover is accounted for by accruing 14-day averages of measured reflectance. Soil that is highly saturated but does not have visible water will not be recorded by the MODIS reflectance data. All data was projected into South American Datum 1969, UTM 20 to remain consistent with the raised field polygons. Permanent water sources, especially the lakes and non-seasonal swamps, identified by the SRTMWBD were considered a part of the flooding in this analysis. Permanent water bodies accounts for 2,032.19km² of the study area. The portion of the Mamore River included in this assessment represents 183.35km². The sinuous length of the river represented is 1,241km (Table 2).

**Mapping Methodologies**

Data was downloaded from the DFO at the University of Colorado which processes several bands of MODIS data that is available using their publicly accessible online databases. Previously digitized materials were provided by volunteers and researchers who worked as a part of ProSIGAB. A shapefile of 40,766 edited and delineated raised fields was downloaded from the ProSIGAB Google Drive. Raised fields were analyzed as polygons, which had attributes that identified their area and ID number. The DFO data for 2012–2016 took the form of 5 sets of geoTIFFs. Data from 2012 was corrupt and had to be retrieved from the DFO’s web map which
could be parsed from the world map using additional cartographic layers provided by ESRI. The web map is a simplified aggregate of worldwide floods similar to Google Earth. The data was limited to 2012–2016 as previously recorded data had not been back-processed and were not put through a similar automated identification process as the assessed materials. The DFO was also directly contacted for questions regarding the resolution and accuracy of the data specifically when dealing with savanna environments. SRTMWBD data was downloaded from NASA’s EarthExplorer database as polygons at a 90m resolution\(^9\) (NASA JPL 2013). SRTMWBD data needed to be added to the DFO data because of incomplete registration for permanent water bodies. The *Reclassify* tool in ArcGIS was used to parse null space surrounding the flooding in the geoTIFFs provided by the DFO. Afterwards they were converted into polygons using the *Raster to Polygon* tool. Data reclassified as null space could then be deleted by using the *Select by Attribute* utility and deleted in the *Editor* mode.

Permanent water features were added in as polygons from SRTMWBD (NASA JPL 2013). The limits of the SRTMWBD data served as the maximum extents of the study area as each section of data was larger than Mojos itself. Polygons that extended beyond this area were cropped using the *Minimum Bounding Geometry* (MBG) and *Intersect* tool. MBG was run as an envelope to contain of the SRTM data provided in a single, large rectangular polygon. Polygons could then be intersected with this polygon, shrinking their size significantly. All additional polygons included in this analysis were clipped and classified based on this layer. Lines created by Boothby (2010) were used as the baseline for the location and identification of rivers in

\(^9\) [https://earthexplorer.usgs.gov/](https://earthexplorer.usgs.gov/)
Mojos. The SRTMWBD polygons and lines representing permanent water were merged into a single layer. The SRTMWBD and yearly extent of flood waters for 2012-2016 were then merged individually and aggregated to form the foundational polygon layer for the analysis.

Raised fields were then processed using the *Intersect* tool with individual years of flooding to calculate fields that are overlapping. Splitting partially flooded fields from completely flooded fields was done by running the *Select by Attribute* tool. The raised fields were chosen as the target layer and the source layer was the individual flooding years. The spatial selection method was then chosen to be features that “completely contain the source layer feature”. The selected features were then exported as an independent layer. The size of raised fields was measured using a combination of MBG and the *Calculate Area* which identified the size of individual fields. The Mamore River line provided by Boothby was used to *Clip* the river system out of the SRTM polygon. The polygon was measured by area and then reconverted into a line. The length of the line could then be measured through the *Calculate Geometry* tool from within the Attributes pane. The *Near* tool was used to calculate the distances between environmental features such as floods, raised fields, and permanent water sources. Excel spreadsheets served as the predominate method for cataloging and recording information gathered from ArcGIS. The analysis tools in Excel were used to tabulate the averages, sums, and percentages, and to create reference tables.

To highlight the raised fields sampled in Whitney et. al. (2014) a copy of the raised field map was taken directly from the article and georeferenced to the digitized ProSIGAB material (Figure 12, 13). The fields were selected and then manually removed as an individual layer, so they could be independently manipulated from the rest of the raised fields polygons. The *Near*
tool was run from a centroid of the field group to the nearest flooding polygons by year to calculate the distance between them.

Limitations

Hydrology can be a difficult environmental factor to model and interpret in the archaeological record as environmental shifts and sedimentation can change the course of water regimes. Only five years of fully processed flood coverage data are available from the DFO. Long-term trends are much more difficult to interpret and predict because of this lack of data. The MODIS derived data is also an aggregate of areas that have flooded and does not discern patterning of floods temporally. The MODIS derived data utilized in this analysis can capture the extents of flooding but is not able to differentiate between the sources of the flooding. Significant differences exist in the resolution that this data covers. MODIS derived data is represented by polygons at a resolution of 250m. Reflectance data is also not able to penetrate tall grasses and trees. Flooding is likely much larger than what is represented in the MODIS derived data if it is not significant enough to be picked up by the sensor. Fields that have not been directly flooded might be calculated within the much larger flood polygons or have experienced a very brief bout of inundation through the year. Fields that are calculated to be partially exposed in this analysis have the potential to be entirely inundated or many meters from surficial water. SRTMWBD has a spatial resolution of 90m, meaning permanent water bodies are accounted for in much more specific terms spatially than DFO’s flooding.
ANALYSIS

The focus of this analysis is the raised fields and their relationship with the polygonal representation of yearly seasonal flooding extents. Excess water would have had detrimental effects on the types of plants they cultivated and could make on-foot traversal to distant fields more difficult. The distribution of raised fields regarding their distance and potential exposure to water was observed over 5 years of MODIS reflectance data to primarily observe overlap. The study area covers a rectangular area of 71,988.09km$^2$. Permanent water bodies account for 2,032.19km$^2$ (2.82%) of the study area based on the SRTMWBD imagery. The Mamoré River accounts for 183.35km$^2$ (0.25%) of the permanent water bodies from this region. In sinusoidal terms, the length of the river included in this analysis is 1,233.13km in total. Permanent lakes make up 1,848.84km$^2$ (2.57%) of the study area.

Within the study area, there are 40,766 digitized raised fields. As noted in the work of Garcia-Cosme (2015), there are more raised fields in the northern portion than the southern portion which are much more densely packed, when divided at the Omi River. Measurements were taken from the raised fields through the intersections of multiple polygons based on their pre-determined area values. Raised fields have a minimum length of 18m and a maximum of 3,140m with the average being 332m. Raised fields vary in area from 16m$^2$ to 44,695m$^2$.

Previous estimates on the mean area of flooding was around 30,000km$^2$ with a median of about 25,000km$^2$ (Hamilton et. al. 2004:2115). There was 1905.20km$^2$ (2.65%) of flooded area recorded by the DFO MODIS data in 2012. When included with the SRTMWBD data, the area of standing water in the landscape increases to 3,927.39km$^2$. 2013 reached an extent of
1,324.89km² (1.84%) of flooding. Standing water in total for 2013 was recorded at 3,357km² (4.66%). Flooding in this period reached a maximum extent of 17,060.91km² (23.70%) based on the DFO MODIS data alone. The complete SRTMWBD data increases the total for 2014 to 19,093.10km² (26.52%) of water in Mojos. 2015 had 957.39km² (1.33%) of flood waters with a total of 2989.58km² (4.15%) being attributed to water surface coverage. Finally, 2016 had 923.73km² (1.28%) of flooding and a total final coverage of 7982.08km² (4.11%). Overall, the average amount of flooding based on the DFO MODIS derived data covers 4,434.42km² with the outlier year of 2014 included (Table 3). With the permanent water bodies, 6566.61km² of Mojos is covered in water throughout the year with 2014 included (Figures 14-18).

In 2012, 39,913 (97.88%) raised fields were not exposed to flood water throughout the year based on the intersections between the raised field and yearly MODIS polygons. 425 (1.04%) were partially flooded and 428 (1.05%) were completely inundated. In total, 853 (2.09%) of the raised fields were exposed to flooding during the year. 2013 had similar numbers to 2012 with 39,930 (97.95%) raised fields not being exposed to seasonal flooding. 279 (0.68%) were partially exposed to flooding and 557 (1.37%) were exposed entirely. The sum of the raised fields exposed in 2013 is 836 (2.05%). 2014 stands as a unique year out of the five recorded years with the greatest amount of flooding and the most fields inundated by flood waters. During this year, 31,637 (77.61%) fields remained completely unflooded. 1,490 (3.66%) were partially flooded and 7,639 (18.74%) were completely flooded. When combined, 9,129 (22.39%) raised fields were exposed in 2014. 2015 marked a significant shift in the opposite direction of the number of flooded fields and turned out to be the year with the lowest number of fields exposed to seasonal flooding. 40,483 (99.31%) of fields were unflooded throughout the year of 2015.
(0.20%) were partially flooded and 200 (0.49%) were completely flooded. In total, a relatively small 283 (0.69%) fields were exposed to flood water. Finally, 2016 had 40,062 (98.27%) raised fields which remained unexposed to flood water throughout the year. 327 (0.80%) were partially exposed and 377 (0.92%) were completely inundated. 2016 had 704 (1.73%) raised fields exposed to flooding (Figures 19-23).

On average 38,405 (94.21%) of the raised fields remained unflooded throughout all five years. 520.8 (1.28%) are partially flooded throughout the recorded years. 1,840.2 (5.51%) are completely flooded on average. Only 2,361 (5.79%) are exposed to flood water when included with one of the most extreme instances of flooding historically recoded in Mojos. Over the course of all five years there were 2 (0.005%) raised fields that were constantly and completely flooded each year. Similar combinations of years, such as the removal of 2014, produce similarly insignificant results regarding the number of consistently exposed raised fields. They usually add an additional 2 completely flooded raised fields to the direct north (Figures 24-29)(Tables 4-6).

The raised fields sampled in Whitney et. al. 2014, remained mostly unflooded during the five sample years. In 2012, the fields were located 0.6km from the nearest MODIS recorded instance of flooding. In 2013, the distance increases significantly to 3.3km from flooding. 2014 is the only year in which the fields experience inundation which covered all the sampled fields. 2015 was the closest the fields came to MODIS flooding and were 0.41km from the nearest polygon. Finally, in 2016, the raised fields were 1.18km from flooding. This places the sampled raised fields an average of 1.09km away from flooding during the analyzed years (Figures 30-35).
Patterning and Interpretations

The largest concentration of consistently inundated raised fields occurs in the northern section of the west-central Mojos, in areas that are closely associated with rivers and their tributaries. Fields which have been exposed to water all five years are on average 304.65m from the nearest recorded river. The closest flooded field is less than a meter from a river located in the northwestern Mojos and the furthest is located 2.4km from a permanent water source. This shows the relationship between raised fields to flowing water sources and provides a better idea for how “water from below” traverses the landscape. Based on the conclusions made by Garcia-Cosme (2015) which found more raised fields outside a 1km distance from rivers, it supports the idea that more raised fields would be built away from flooded rivers to avoid seasonal inundation (2017: 62). This demonstrates that raised fields were not necessarily a flood mitigation technique in their design and construction.

The DFO also records river flow using microwave radiometry to track the movement of water. This data showed that 2012 had the lowest river flow rate in the Mamoré of all 5 years; However, the low recorded flow rate did not correlate to a reduced amount of flooding in Mojos. 2012 represents the second greatest amount of flooding out of the 5 years processed. This year in turn also had the second largest number of raised fields exposed to flood waters all together. It had the most partially flooded fields aside from 2014 but is second to 2013 for largest number of completely flooded fields. The spatial distribution of the raised fields exposed to flood waters is relatively evenly distributed with slightly more fields flooded in the northern section of the west-central Mojos. The inundated fields are centralized but push marginally more westward.
2013 is the third most flooded year surveyed. It had only 17 less fields exposed to flood water than the previous year, 2012. This year had the largest number of completely inundated fields aside from 2014 but has the third most partially flooded fields. The spatial distribution of the flooded raised fields is heavily tilted towards the northern fields. There is a smattering of inundated fields located in the far southern portion of the study area. Like 2012, the fields are centralized in Mojos but lean westward.

2014 is an outlier year with an extreme amount of flooding that disrupted the lives of the current population of Mojos. Almost a quarter of the fields were flooded this year which is far greater than any of the other years. The majority of these were instances in which the entire field was inundated. Flooded fields are split in clusters in the north and south. The patterning of the flooded fields suggests that most of the flooding would be sourced from the overflowing banks of the Mamoré River rather than through direct precipitation.

2015 had the least amount of inundated raised fields with only 283 having been exposed to water. This is a drastic difference from the previous season which also had greater variance in the percentage of completely and partially inundated fields. In 2015, Raised fields were only flooded in the northern area of Mojos. There are two clusters of flooding in this section, one in the east closer to the Mamore and one in the west south of Laguna Guachuna. The final year, 2016, is much more in line with the flooding seen in 2012 and 2013. It has the 4th most flooded fields but is a significant increase from the previous year. 2016 has a north and south cluster like those seen in 2013 and 2014. There is, again, a western lean to the inundated raised fields.
The low amount of flood water that raised fields are exposed to supports the idea that their placement by the pre-Columbian population was based on associations with the movement and collection of water on the landscape. The clustering of inundated raised fields suggests that it is the result of associations with nearby permanent water sources such as rivers or lakes that experience differential amounts of flooding based on the year. Previous studies point to raised fields having benefits on a small scale regarding water management but this thesis suggests that their placement decision can be mapped and observed on a regional scale (Lombardo 2011). The variability in the coverage of fields by flood water suggests that the regional spread and number of raised fields may have been a way to overcome the bouts of seasonal inundation that occur in Mojos. The observed separation in the locational values of flooded raised fields is related previous studies which have suggested divisions based on linguistic divisions and differences in the orientations of the raised fields (Garcia-Cosme 2015; Lee 2017). Areas in which flooding occurred, may have altered pre-Columbian decisions on field morphology and placement that considered the presence and timeframe of surface water coverage throughout the course of several years.

Whitney et. al. 2014 argues that the botanical evidence taken from raised fields in the northern west-central Mojos suggests that the pre-Columbian population cultivated maize. Maize is sensitive to exposure to moisture making it important for the raised field system to improve the properties of local drainage. The data shown here suggests that the sampled fields rarely flood except during exceptionally large instances which took place during 2014 in the analyzed years. Besides 2014, the sampled fields and flooding are on average one kilometer away from each other. Maize would be suitable for cultivation in this location if it had continued access to
irrigation. In this case, raised field’s ability to contain water within their ditches would be an important attribute of maize cultivation rather than the dispersion of water.

Root crops would need access to groundwater during years that floodwaters were distant. Manioc and sweet potato thrive when not directly exposed to inundation but can easily reach water through their root systems (Jones 1959). With Mojos soil being difficult for water to penetrate through, these fields may have had a more difficult time being irrigated during dry years or seasons. Root crops may have been best utilized during the wet season when access to water would be improved on these fields.
CONCLUSION

This hydrological analysis merges two open source data sets to solve questions within an archaeological context. Digitized data from ProSIGAB and MODIS derived data provided by the DFO were combined to examine the spatial relationship between raised fields and seasonal flooding in the Llanos de Mojos. This analysis hopes to contribute to discussions about the cultivation and construction of the modified environment by the pre-Columbian people of Mojos.

It was hypothesized that raised fields were placed in locations that less seasonal flooding occurred across several years. It was shown that fields experience very little seasonal inundation based on the MODIS derived data. It was also hypothesized that fields that were directly associated with the cultivation of maize, sweet potato, and manioc would not be exposed to seasonal floods. These fields only experienced flooding in 1 out of the 5 years analyzed, with the flood year being one of the worst periods of inundation in recent history.

On average, 2,361 (5.79%) of the raised fields out of 40,766 are inundated by water over the course of the five years analyzed. This includes 2014, one of the worst instances of seasonal flooding in 40 years. Since so few raised fields are exposed to flooding, it demonstrates how their placement impacted their ability to remain dry through most of the year to protect crops for excessive flooding. The place fields were constructed may have been chosen over time based on where flooding had occurred previously. Fields were placed to avoid riverine flooding while the morphology was designed to mitigate and capture localized precipitation. Local environmental factors may have played a larger role in raised field construction based on this data. Crops such as maize would benefit from less direct exposure to flood water but on the other hand irrigation
during the dry season may have been a primary characteristic of the raised field system. The flooding in 2014, which extended out from the Mamoré, shows that the larger river systems in the region can have a massive impact on the places in which fields flood. In conjunction with smaller scale interpretations, raised fields may have been useful constructions for a variety of crops based on their relationship with water on an inter-regional scale.

Understanding the spatial characteristics of where fields flood and which do not is important to understanding potential differences among the construction and utilization of raised fields regionally. The location of raised fields can be indicative of planning structures which may have helped pre-Columbian people mitigate the effects of seasonal flooding on their agricultural practices while improving soil nutrient content and maintaining access to captured water for irrigation during the dry season. The analysis revealed that several clusters of inundated raised fields existed through the five years analyzed. Differences in spatial distribution and density of the clusters are visible between the northern and southern portions of Mojos. Only two fields of 40,766 were flooded consistently among all five years suggesting that the area experiences a high level of variability in the position of water throughout years and seasons. This indicates that pre-Columbian populations were prepared for potentially unpredictable locations of seasonal flooding. Populations in Mojos may have been encouraged to create fields over a large geographic and temporal space to best manage yearly variability in surface water coverage.

The raised fields presented in Whitney et. al. 2014 are not exposed to seasonal flooding in 4 out of the 5 years sampled. The data supports the idea that raised fields would have been useful as a method of soil intensification and water containment regarding the planting of maize, manioc, and sweet potato rather than as a tool to protect water-sensitive crops. Manioc and sweet
potato would not have suffered root rot but may not have had access to the ground water resources necessary to survive or thrive (Ghuman and Lal 1983). Raised fields’ occasional exposure to large seasonal floods was offset by their ability to provide a productive harvest. These large floods may also have provided the savanna an opportunity for nutrient refreshment to improve their productivity in future years (Walker 2008).

**Future Research**

Geomorphological processes and sedimentation over time may have had a significant impact on the current landscape of Mojos. Creating a full predictive model for the movement of silts and the deposition of sediments would be a first step towards creating an accurate representation of how the hydrological systems of Mojos operated. Measuring the length of time that raised fields remain saturated after exposure to rain and flood waters would help focus future research on how cultivation practices might be affected during the wet season. The penetration of water into the clayey soils and how that might affect the root systems of crops and viability of specific plant species is another route that future research might take. Accessing data from the previously recorded large floods in 2008-2009 would be useful in reassessing the validity of how raised fields handle periods of increased stress such as seen in 2014. Raw MODIS data is available online in the Land Processes Distributed Active Archive Center (LPDAAC). Methods like those used by the DFO could be used to generate additional flood layers for prior years leading up to 2012.

Using the daily .shp files instead of the yearly .shp files would also be an useful method of analyzing the patterning and variability of floods experienced in Mojos in greater depth.
Applying statistical analyses to the locations of flooded raised fields would help to solidify the differences between the northern and southern fields. Assessing the variance between the disproportional number of raised fields in the northern west-central Mojos versus the southern west-central Mojos would further contribute to examining the regional attributes of flooding and agriculture. Flooding data could be used to help determine the overall navigability of Mojos based on networks that consider both terrestrial movement and via canoe. MODIS is only one type of instrument that could be used to examine surface flood coverage in Mojos. Radar, infrared, and vegetation patterns would be other useful spatial methods for tracking the occurrence of surface flooding.
APPENDIX A: FIGURES
Figure 1: Map of South America including the Amazon River, the Andes, and Llanos de Mojos. (Google Earth)
Figure 2: Map of Bolivia (Google Earth)
Figure 3: Image of the Beni region of Bolivia with highlighted borders. This encapsulates the majority of the Llanos de Mojos. (Google Earth)
Figure 4: Aerial photo of raised fields with signs of burning. (photo by John H. Walker)
Figure 5: Spatial extent of large raised fields in the Llanos de Mojos, mapped by ProSIGAB as of 2017.
Figure 6: Satellite map of raised fields along the Iruyañez River, showing how they contrast with the surrounding landscape.
Figure 7: The extent of the study area with visible lakes and rivers.
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Figure 10: Map of the raised fields and forest islands sampled in Whitney et. al. 2014.
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Figure 19: Map of raised fields and their association with regional flooding in 2012.
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Figure 21: Map of raised fields and their association with regional flooding in 2014.
Figure 22: Map of raised fields and their association with regional flooding in 2015.
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Figure 24: Fields exposed to flood waters in 2012.
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Figure 26: Fields exposed to flood waters in 2014.
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Figure 31: Map of sampled raised fields and their spatial relationship to flooding in 2013. Flooding occurred relatively far away as compared to other years analyzed.
Figure 32: Map of sampled raised fields and their spatial relationship to flooding in 2014. This is the only year that the fields were directly exposed to flood water according to the MODIS data.
Figure 33: Map of sampled raised fields and their spatial relationship to flooding in 2015. There was another small basin less than a kilometer away to the west of the sampled fields.
Figure 34: Map of sampled raised fields and their spatial relationship to flooding in 2016. Flooding occurred mostly to the north of the raised fields.
Figure 35: A combined photo of the sampled raised fields and flooding in the years analyzed. This demonstrates the large amount of variability in the location of flooding throughout different seasons.
Table 1: Spatial extent of the study area utilized in this analysis.

<table>
<thead>
<tr>
<th>Spatial Extent of Study Area</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Top</td>
<td>8562623.102571 m</td>
</tr>
<tr>
<td>Left</td>
<td>66337.397728 m</td>
</tr>
<tr>
<td>Right</td>
<td>392299.346221 m</td>
</tr>
<tr>
<td>Bottom</td>
<td>8338931.118059 m</td>
</tr>
</tbody>
</table>

Table 2: Amount of permanent water coverage in Mojos identified by the SRTMWBD.

<table>
<thead>
<tr>
<th>Permanent Water Coverage of Study Area</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mamore:</td>
<td>183.35km² 0.25%</td>
</tr>
<tr>
<td>Lakes and Tributaries:</td>
<td>1,848.84km² 2.57%</td>
</tr>
<tr>
<td>In Total:</td>
<td>2,032.19km² 2.82%</td>
</tr>
</tbody>
</table>

Table 3: Yearly totals of flooding identified by the DFO within the study area of Mojos.

![Yearly Flooding Totals](chart.png)
Table 4: Total number of fields which remain unflooded in each year analyzed.

![Unflooded Fields by Year](image)

Table 5: Totals for partially and completely flooded raised fields.

![Partially and Completely Flooded Raised Fields](image)
Table 6: Total number of raised fields that experience flooding throughout the analyzed years.
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