20 SETTLEMENT, AGRICULTURE, AND ENVIRONMENT AT AVENTURA, BELIZE: RESULTS OF NEW LIDAR RESEARCH

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In 2009, the first LiDAR (Light Detection and Ranging) was flown over Caracol, Belize, transforming our understanding of Maya settlement, agriculture, and environment, and positioning the country of Belize as a leader in this transformation. Flown a decade later in 2019, this article reports on an 18 square kilometer LiDAR survey at Aventura, northern Belize. The National Center for Airborne Laser Mapping at the University of Houston used an Optech Titan sensor, the world's first multispectral airborne LiDAR sensor, in the Aventura LiDAR survey. With approximately 25 points per square meter, we were able to maximize our detection of smaller features, as documented in ground truthing. LiDAR has two primary uses: (1) locating previously unidentified sites and (2) providing a complex human geography of ancient places that link people and land. This paper highlights how LiDAR facilitates the development of a human geography of ancient places. At Aventura, LiDAR research illustrates a human geography that links people, settlement, agricultural, and environment. Raised field agricultural systems at Aventura along the New River, and systems of bajos and pocket bajos, provide a window into understanding Aventura's environmental positioning, wetland resources, and agrarian roots and insight into a broader New River agricultural-environmental system.

Introduction

LiDAR (Light Detection and Ranging) remote sensing methods provide a macroscopic lens on settlement and society allowing archaeologists to view whole ancient cities, communities, and even regions in ways that were never previously possible. In Maya archaeology LiDAR research has had a particularly transformative effect given that the contemporary tropical forest canopy has long obscured our ability to attain extensive full-coverage surveys. The country of Belize has been a leader in this transformation.

This paper presents the results of the 2019 Aventura LiDAR survey, flown just at the cusp of the global Covid-19 pandemic, that was part of the National Center for Airborne Laser Mapping at the University of Houston's Belize Small Projects Campaign. The Aventura LiDAR survey spanned an 18 square kilometer area around the Maya city of Aventura, Corozal district, northern Belize. The survey allows us to see the extent of the ancient city of Aventura, for the first time, and examine its landscape positioning.

With approximately 25 points per square meter, the Aventura LiDAR was able to maximize our detection of smaller features. LiDAR results were ground truthed based on a 1 square kilometer pedestrian survey at Aventura that was completed between 2015 and 2017 (Fitzgerald 2017; Grauer 2017; Nissen 2016; Robin, Grauer, and Nissen 2015; Robin et. al. 2017; Robin et. al. 2019). LiDAR has two primary uses in Maya archaeology: (1) locating previously unidentified sites and (2) providing a complex human geography of ancient places that link people and land. While locating previously unidentified sites and features is certainly and always a key aspect of LiDAR research, this article highlights how LiDAR research facilitates the development of a human geography of ancient places.

I begin my discussion by briefly situating Belize's historic role in LiDAR research which began at Caracol in 2009 (Chase et al. 2010, 2011a, b, 2012, 2013). I then turn to the Aventura case study, flown a decade later, to illustrate the complex relationships between settlement, agriculture, and environment that LiDAR entails.

Belize's Transformative Roll in LiDAR Research: The 2009 Caracol Flight

You can hardly find an article that doesn't use the term "revolutionize" to describe the roll of LiDAR research in archaeology, and much of that revolution happened in Belize. The first LiDAR campaign across a 200 square kilometer area, was undertaken at Caracol, Belize in 2009, by Arlen and Diane Chase (Chase et al. 2010, 2011a, b, 2012, 2013). The Caracol research established the utility of the LiDAR method for archaeology. It demonstrated that LiDAR could map vaster areas than traditional pedestrian survey could ever cover. It could provide detailed data at the level of archaeological features, and importantly, it could

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Table 1. LiDAR projects in Belize in the first decade of LiDAR research. Table 1 is adapted from Chase and Chase 2017, Figure 22.1, which provides LiDAR coverage information up to 2015.

Location	Year	Area (km2)	Points (m2)
Caracol	2009	200	20
Uxbenka	2011	99	20
El Pilar	2012	20	20
Western Belize	2013	1057	15
Northwestern Belize	2016	257	23.7
Belize Small Projects*	2019	76	15-25
*Aventura, Lamanai, Las Cuevas, Mukelbal Tzul/ Ek Xux Valleys, & Pearce Ruins			

bring detailed environmental and settlement data into unison.

Not only was a robust new areal mapping methodology established through the Caracol research, but persistent questions in Maya archaeology, such as were Maya settlements indeed urban centers, were put to rest once and for all as Caracol's vast settlement was revealed (Chase and Chase 2017). LiDAR is not just a method; it is a means to address persistent archaeological questions.

Extensive systems of agricultural terraces were identified and mapped at Caracol prior to the use of LiDAR, however the LiDAR data revealed an unprecedented view of the scale and extent of terrace agriculture at Caracol and its integration within other aspects of settlement (Chase et. al. 2011a, b; Chase and Weishampel 2016). By bringing together environmental, agricultural, and settlement data, LiDAR at Caracol produced a human geography of a Maya place that illustrated how people and the land were inextricably tied to one another.

In just over a decade that has transpired since the original Caracol LiDAR flight, LiDAR research has expanded in Belize and across the Maya area. Table 1 presents the LiDAR research conducted in Belize between 2009 and 2022. This burgeoning research has resolved a wide range of questions such as: the extent of agricultural production and the physical organization of houselots in the Rio Bravo region (Beach et. al. 2019; Kwoka 2021; Luzzader-Beach, Beach, and Dunning 2021), the nature of anthropogenic landscape modification at Uxbenka (Prufer, Thompson, and Kennett 2015; Thompson 2020), the ditched water management systems at Baking Pot (Ebert, Hoggarth, and Awe 2016), the nature of ancient, historic, and contemporary land use around El Pilar (Ford and Horn 2019), the areal extent of a Preclassic center to the east of and as sizeable as Xuantunich (Brown, Yaeger, and Cap 2016), and the identification of caves used to model ritual landscapes around Las Cuevas (Moyes and Montgomery 2016). LiDAR enhances archaeologists' and heritage managers' abilities to preserve and protect archaeological remains due to the expansive and precise locational knowledge that LiDAR provides.

Aventura LiDAR Research

Aventura is situated in a populated area in the Corozal district between the contemporary communities of San Joaquin, Conception, San Pedro, and Cristo Rey. An 18 square kilometer area was chosen for the Aventura LiDAR survey to provide the most continuous swath of settlement associated with Aventura's central precincts situated between the modern communities to the north, south, and west and the New River to the east (Figure 1).

Issues in LiDAR Research

For all of its value, nobody would say that LiDAR is a deux-ex-machina. Forest cover can affect the quality of LiDAR results. The best LiDAR results are produced in areas of high forest cover, such as found at Caracol. In areas of low and disturbed vegetation, and variable vegetation types, LiDAR results can be more variable. This is of particular concern at

Figure 1. Colorized Digital Elevation Model (DEM) of the Aventura LiDAR survey area.

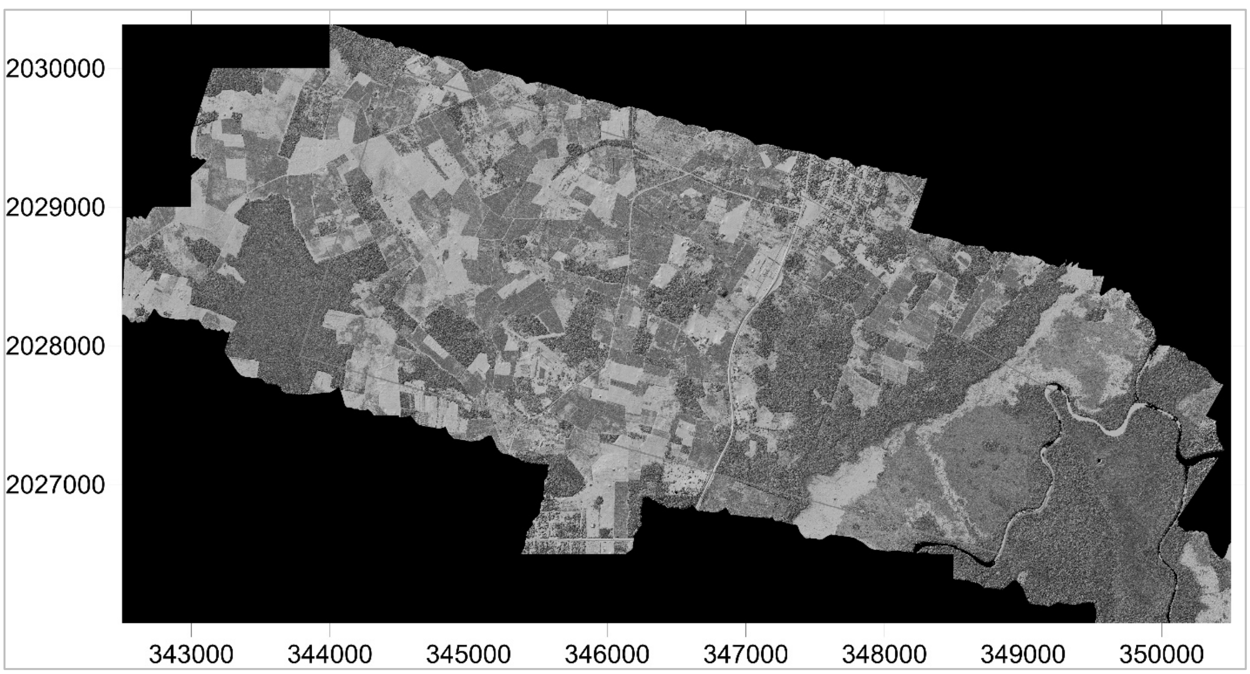

Figure 2. Hillshade Digital Surface Model (DSM) of the Aventura LiDAR survey area.

Aventura as the majority of the Aventura area consists of low, disturbed, and variable vegetation.

Keith Prufer, Amy Thompson, and Douglass Kennett's (2015) evaluation of 2011 LiDAR flight results around Uxbenka in areas of disturbed vegetation found that 90% of small residential structures between 1 and 3 meters high could not be detected in the LiDAR. Their LiDAR survey utilized 20 laser points per square meter, comparable to the Caracol flight. Bernadette Cap, Jason Yaeger, and Kat Brown's (2018) evaluation of the LiDAR survey around Xunantunich that utilized 15 laser points per square meter, identified only 40% of features mapped during pedestrian survey, with small residential structures lower than 2 meters in height being the least detected. Similarly, Scott Hutson, working in in the coastal plains of Yucatan, Mexico and examining LiDAR survey that averaged 15 laser points per square meter, found that 61.6% of archaeological features identified through pedestrian survey that were under 1 meter in height were not detected by LiDAR, however 87.9% of pedestrian-survey-identified features that were 1 meter in height or higher, were visible on LiDAR (Hutson et. al. 2016).

Increasing the average points per square meter, enhancing algorithms and visualization techniques, such as the use of Topographic Position Index, and advances in LiDAR sensor technology are methods that can help address the issues that LiDAR research can have in areas of low, disturbed, and variable vegetation (e.g., Ebert, Hoggarth, and Awe 2016; Huston 2016: Thompson 2020). Timothy Hare, Marilyn Masson, and Bradley Russell (2014) used a high-density LiDAR method, that included a laser point density of 40 laser points per square meter, to map the site of Mayapan, Yucatan, Mexico. This significantly improved the LiDAR detection of small features, however, even this approach still didn't facilitate the visualization of small mounds in settlement areas that are often no more than 10 centimeters in height.

To maximize the detection of small features at Aventura and balance cost considerations, as cost increases with increasing laser point density, I worked with Ramesh Shreatha and Juan Fernandez-Diaz at the National Center for Airborne Laser Mapping at the University of Houston to develop a methodology that would couple their new third generation sensor, the Optech Titan sensor, the world's first multispectral airborne LiDAR sensor, with a laser point density of 25 points per square meter.

Figure 2 shows a Hillshade Digital Surface Model (DSM) of the Aventura LiDAR study area. The Hillshade DSM captures the highest natural (ie., trees, shrub, sugar cane, ground surface) and cultural (ancient and modern buildings, etc.) features on the earth's surface. Visible in the Aventura Hillshade DSM is a patchwork of vegetation types that characterizes the contemporary region. The primary vegetation type in the Aventura region is sugar cane, the primary industry in northern Belize where Aventura is located. Due to the thick, dense nature of sugar cane, pedestrian survey is not possible when sugar cane is present. This resulted in a patchwork style pedestrian survey, which will be discussed further below. Full coverage pedestrian survey would only have been possible at Aventura were the project able to conduct survey year-round and access fields after they had been burned and cut. This pedestrian survey issue provided one of the impetuses for conducting LiDAR research.

The patchwork of vegetation types that make up the Aventura LiDAR survey area also include cattle pastures, manicured grass lawns, highly disturbed areas of grass and shrub, and forest canopy. Cattle pastures are present in limited numbers. Manicured grass lawns are found across the modern communities that adjoin Aventura and on the former Fruta Bomba factory property that is currently the site of the Aventura Construction Supplies & Block factory. Highly disturbed areas of grass and shrub are located in former sugar cane fields that are no longer in use and have not been converted to another use, as sugar cane production today in northern Belize is decreased from its production peak in the 1960s and 1970s. Forest canopy still shrouds Aventura's central precincts and large buildings where plowing, and agriculture is not feasible due to structure height and stone density. Given its patchwork, low, and disturbed vegetation types the Aventura area is suboptimal for LiDAR data acquisition, requiring extra attention to methodological considerations.

Small Feature Recovery with the Optech Titan Sensor and a 25 Points/m^2 Laser Point Density

From 2015 to 2017, the Aventura Archaeology Project, completed a pedestrian survey of a central 1 square kilometer are around Aventura's site core (Fitzgerald 2017; Grauer 2017; Nissen 2016; Robin, Grauer, and Nissen 2015; Robin et. al. 2017; Robin et. al. 2019). The pedestrian surveys were directed by Kacey Grauer, Zachary Nissen, and Kat Fitzgerald. The shape of the pedestrian survey area was a patchwork, as we had to survey around active sugar cane fields. There were parts of the Aventura region that were always inaccessible to pedestrian survey during the summer months of our research and would only have been accessible had we been able to conduct a year-long survey.

The Aventura pedestrian survey drew upon Global Positioning System (GPS), Total Station, and Geographical Information System (GIS) technology, to develop 2D and 3D georeferenced digital imagery of cultural and natural features. Systematic field walking enabled full-coverage pedestrian survey in an area outside of active sugar cane production. We collected information on natural features (land formations, vegetation, environment), cultural features (architecture, agricultural fields, other human constructions), and chronology (relative dating of archaeological features through surface ceramic analysis). The pedestrian survey combined three survey techniques to achieve its goals: (1) topographic mapping, (2) archaeological reconnaissance, and (3) surface ceramic analysis. The survey team walked the cut cane fields, forests, and other vegetation types of the Aventura area. All cultural and natural features and topography encountered on survey were recorded using a combination of a Topcon GTS-605 Total Station and a Trimble Juno GPS to produce an accurate and georeferenced map in a GIS.

The Aventura pedestrian survey work provided a baseline data set to ground truth the LiDAR data. Figure 3 shows the LiDAR survey results visualized as a Digital Elevation Model (DEM) with the pedestrian survey area superimposed. Comparing the mounds identified in pedestrian survey and the LiDAR DEM documents that all mounds greater than 40 centimeters in height that were identified in the pedestrian survey were identified in the LiDAR DEM. The LiDAR DEM also visualized 40% of mounds between 29 and 39 centimeters in height. No mounds under 29 centimeters in height were visualized. Ground truthing LiDAR results is important to determine the extent of settlement loss, for proposing population estimates, assessing social organization, and especially in understanding the humblest commoner Maya houses. The Aventura LiDAR research methods that combined the Optech Titan sensor and a 25 points/m^2 laser point density produced improved visualization of small features. However, we were still unable to visualize 7% of our smallest mounds, or 19% of mounds under 1 meter, which will affect what we can say about commoner settlement at Aventura based on LiDAR data. Given that our ground truthing occurred within the central 1 square kilometer of the city center of Aventura, additional ground truthing further in Aventura’s hinterlands is needed before we can provide reliable population estimates based on the LiDAR data, as the percentage of small mounds in hinterland areas is likely to be greater than in the central area.

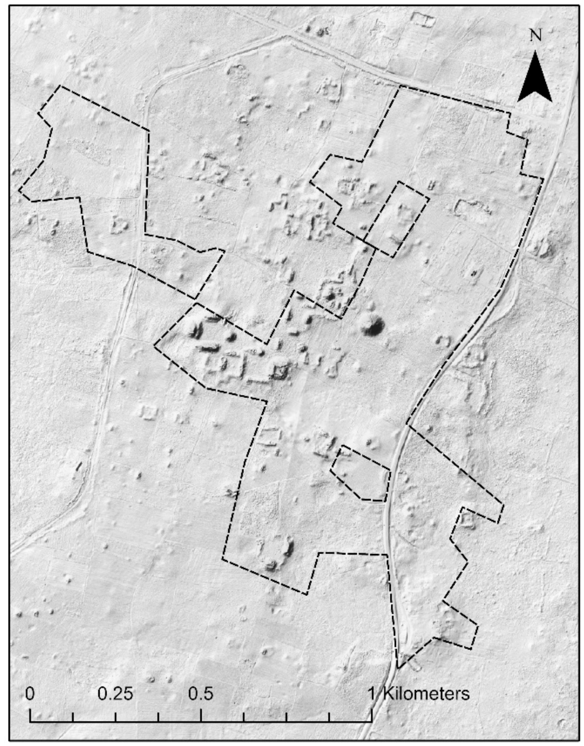

Figure 3. Aventura pedestrian survey area superimposed on the LiDAR Digital Elevation Model (DEM). The pedestrian survey area is shown with dashed lines.

Aventura LiDAR Results

One of the most notable aspects of the LiDAR data at Aventura is the abundance of its raised agricultural fields along the New River (Figure 4). The raised fields are found along the first elevated area along the river course – just west and above a wide marshy area that

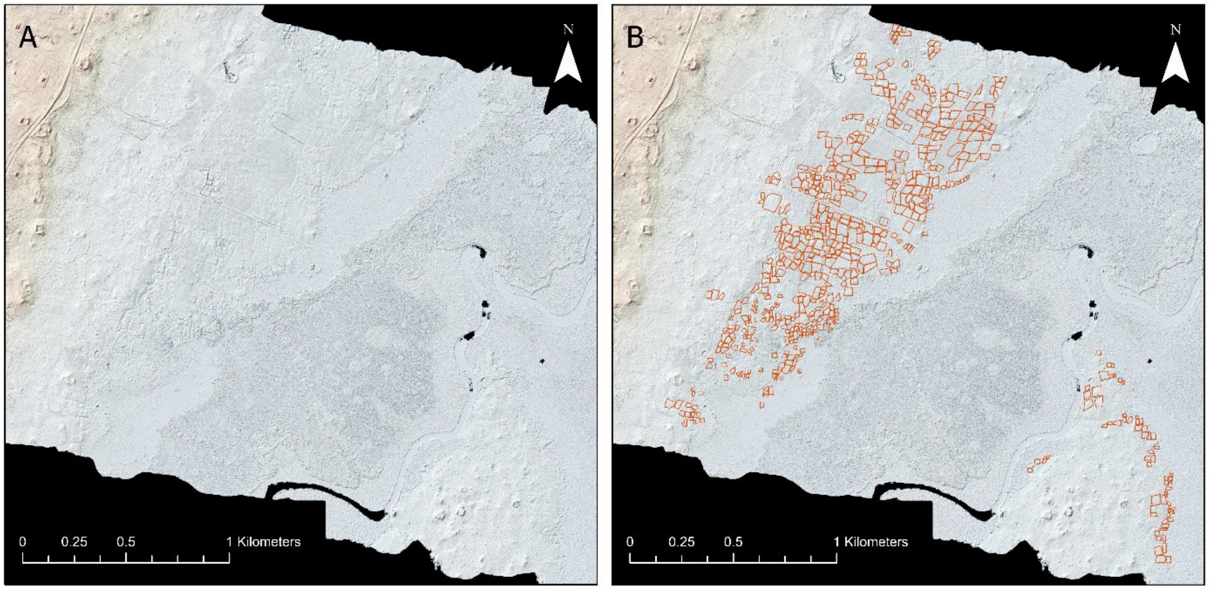

Figure 4. Raised fields adjacent to Aventura. (a) LiDAR model of raised fields. (b) GIS line drawing of raised fields superimposed on the LiDAR model.

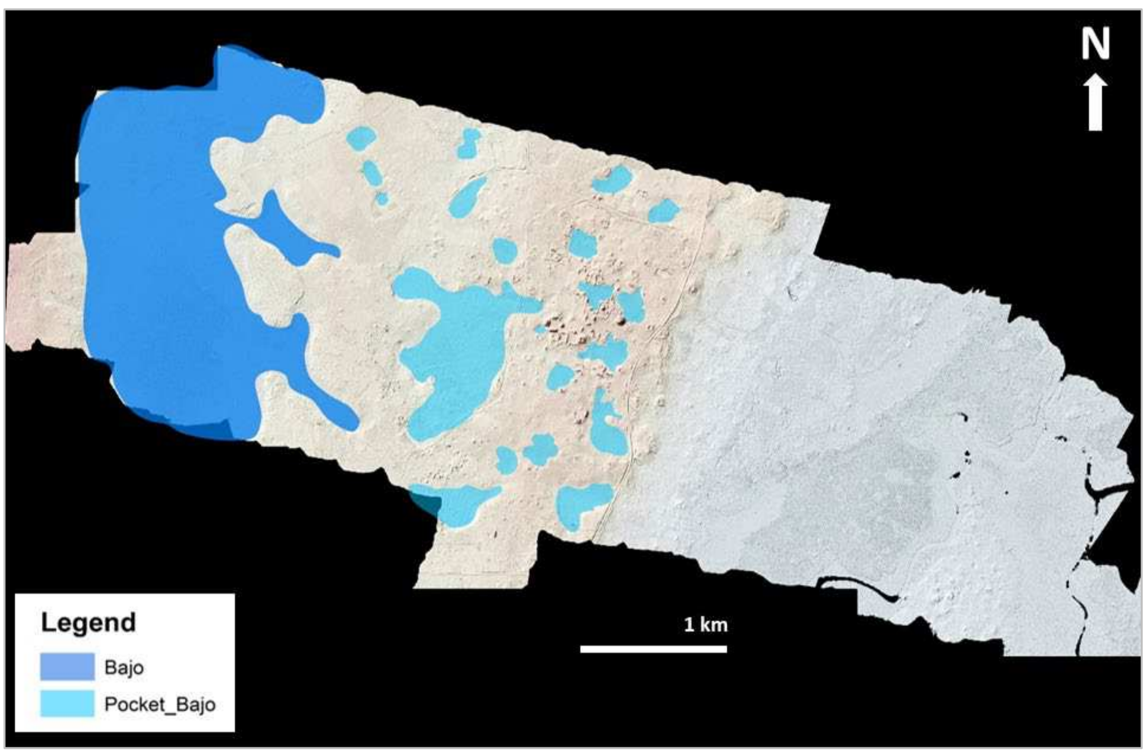

Figure 5. *Bajos* and Pocket *Bajos* at Aventura.

immediately surrounds the river. Additional raised fields are located along the edges of an elevated island delta to the east where the New River splits and then rejoins. There is also a small settlement cluster on the island delta as well.

Raised fields at Aventura were visualized for the first time through LiDAR research and their identification is transformative to our understanding of Aventura as well as the human geography of the New River region of Northern

Belize. Since the work of Raymond Sidrys (1984) in the 1970's Aventura has been identified as the probable production center for the Buyuk Striated Double Mouth Jars. Geographically, Aventura has been described as located between the New River and Rio Hondo, which certainly is the case. The LiDAR data resituates our attention to Aventura being a city located along the New River, situated on the second elevated area along the river course, an area of sufficient elevation to support habitation. The broad first area of elevation, between the settlement and the marshy area immediately along the river, which had as larger or larger of a footprint as the city itself, supported a vast extent of raised field agriculture.

This evidence situates Aventra as a breadbasket for food production. Raised fields were not just significant areas of agricultural production, but they could have been used for aquaculture and hunting as well. Scholars such as Vernon Scarborough (1986), and Billie Lee Turner and Peter Harrison (1983) have postulated about the existence of raised fields all long the New River. In the 1980s Vern Scarborough (1986) attempted to use SLAR, side-looking airborne readout, to identify raised fields along the New River and Fresh Water Creek region between Aventura and Cerro Maya, however the technology at the time was not sufficient, and he was unable to gather evidence to document their existence.

The Aventura LiDAR results demonstrate the existence of a previously only posited, lower New River raised field system, that supports the idea of Northern Belize being a breadbasket region for food production. Furthermore, it greatly expands our understanding of settlement and agricultural organization in the Maya area as a whole. In contrast to the central Peten area of Guatemala with its sizeable and more centralized urban centers, in Northern Belize we see a greater abundance of smaller sized sites, like Aventura, each associated with fertile agricultural zones, indicating a different, and perhaps less hierarchical social order. The real significance of LiDAR research is not just its identification of new ancient features, such as the raised fields at Aventura, but the interpretive potential that LiDAR's broad understanding of human-land relations reveals.

Expanding beyond the New River and the Aventura LiDAR research area, recent LiDAR research along the Rio Bravo which joins with the Rio Hondo on Belize's northwestern boarder, by Tim Beach, Sheryl Luzzadder-Beach, Tom Guderjan, Fred Valdez and colleagues documents raised field agriculture along the Rio Bravo (Beach et. al. 2019; Luzzader-Beach, Beach, and Dunning 2021). The new LiDAR documentation of raised fields in Northern Belize along the Rio Bravo and at Aventura complements and expands Billie Lee Turner and Peter Harrison's (1983) identification and excavation of raised fields in the 1970s and 1980s around Pulltrouser Swamp and both early aerial reconnaissance by Siemens (1982) along parts of the Rio Hondo and more recent aerial reconnaissance and by Eleanor Harrison-Buck (2014) in the Crooked Tree Wildlife Sanctuary. Taken together new LiDAR research along the New River and Rio Bravo illustrate a wide distribution of wetland agroecological systems across Northern Belize and identify Northern Belize as a key breadbasket in the Maya region.

When we dive deeper into the Aventura LiDAR, at a site-focused level, we can identify local agroecological infrastructures that related people and land. This notable aspect of the Aventura LiDAR research allows us to develop a complex human geography. By human geography, I am referring to the complex relationships that link people, settlement, agricultural, and environment.

Across the Aventura 1 sq km pedestrian survey area surveyors identified five pocket *bajos* (Grauer 2017; Nissen 2016; Robin, Grauer, and Nissen 2015; Robin et. al. 2017; Robin et. al. 2019). Kacey Grauer (2020, 2021a) describes pocket *bajos* as karstic depressions less than 2 square kilometers in area and her excavation and phytolith research has documented that pocket *bajos* at Aventura were water sources for the ancient community, although many are dry today. Grauer (2021b) additionally identified that pocket *bajos* were located adjacent to areas of commoner architecture as well as elite and civic architecture.

LiDAR has expanded our view of pocket *bajos* at Aventura and indicates they comprised a significant part of the square footage of the city and were important parts of the infrastructure of

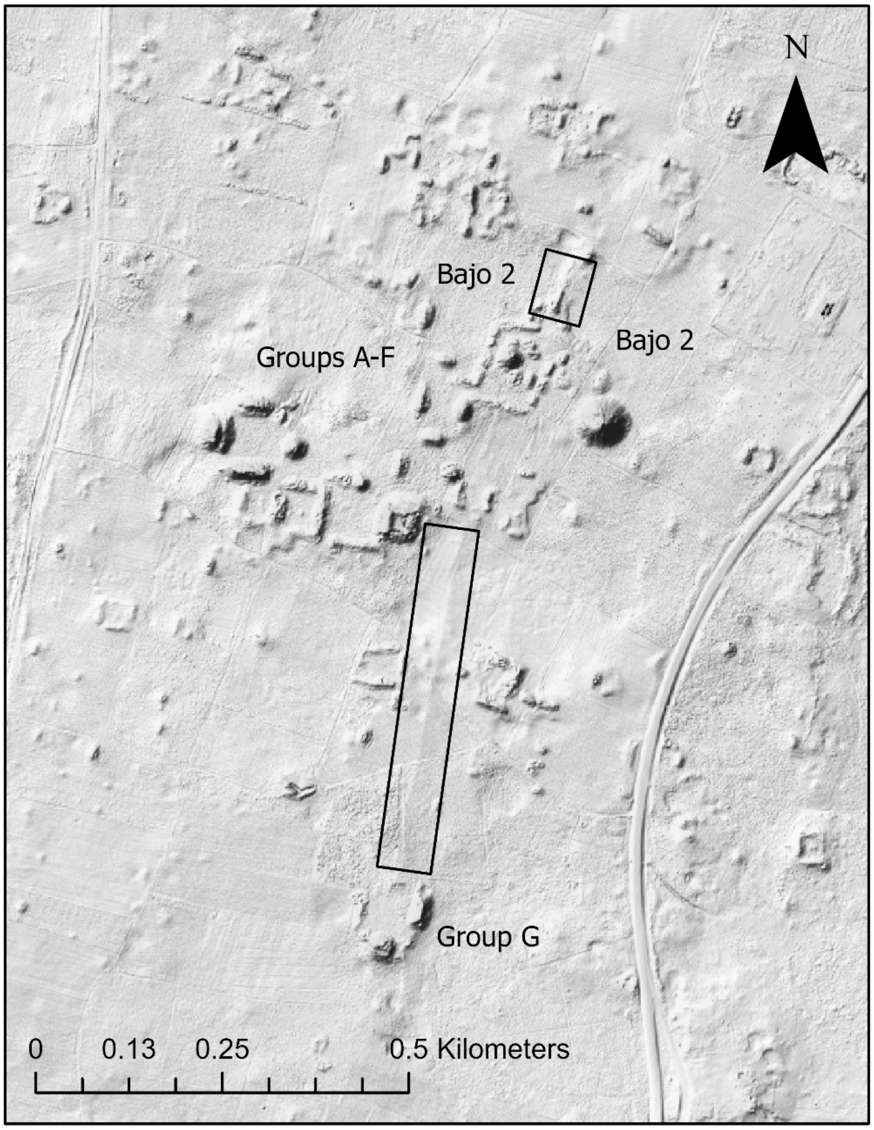

Figure 6. Close up of LiDAR visualization of Aventura's central area. Black rectangles surrounded causeways. The larger southern causeway connects site core Groups A-F and Group G and crosses Pocket *Bajo* 1. The smaller northern causeway crosses Pocket *Bajo* 2.

the city (Figure 5). Aventura was a city built surrounding pocket *bajos*. The LiDAR data expands our identification of pocket *bajos* associated with commoner settlement, a finding that is even more significant given the previous discussion of the limitations of the LiDAR work in identifying Aventura's smallest mounds.

Grauer (2020, 2021a, b) excavated three of the pocket *bajos* identified in the Aventura pedestrian survey and associated commoner and elite households. As just noted, Grauer's micro studies of phytoliths from pocket *bajos* identified that they were water features for the city in the past. Her household excavations indicated that commoners and elites alike at Aventura had access to water from pocket *bajos* to meet biophysical and spiritual needs (Grauer 2021b). Bringing the LiDAR data into the picture we can see how multiple lines of evidence from LiDAR's macro lens, to a household lens, to the micro lens of phytolith studies come together to paint a picture of water access that cross-cuts hierarchical division at Aventra, as Grauer's research has identified.

Aventura was not alone in terms of its decentralized access to water resources. Drawing upon Caracol's LiDAR data, Adrian Chase (2016) documented 1590 reservoirs across the city's urban settlement of civic architecture, elite architecture, and commoner architecture.

The Aventura LiDAR survey covers a smaller area than most LiDAR surveys due to the proximity of the site to modern communities. This smaller area draws our attention to the interior features that make up the infrastructure of the city (Figure 6).

During the pedestrian survey, Zachary Nissen (2016) painstakingly mapped an ephemeral causeway at Aventura that was barely visible on the ground surface. The causeway led from Aventura's main ceremonial complex, Groups A-F, to a secondary ceremonial complex, Group G. The LiDAR survey elevates Nissen's careful ground research, by visualizing the full extent of the causeway. An intriguing aspect of the causeway is that it crosses Pocket *Bajo* 1. A second elevation divides the eastern and western portions of Pocket *Bajo* 2. The exact significance and use of these roadways, particularly as they cross pocket *bajos*, pends future excavations, however they do indicate another way pocket *bajos* were incorporated into the fabric of the city.

Conclusion

At Aventura, LiDAR research illustrates a human geography that links people, settlement, agricultural, and environment. Raised field agricultural systems at Aventura along the New River, and systems of *bajos* and pocket *bajos*, provide a window into understanding Aventura's environmental positioning, wetland resources, and agrarian roots as well as insight into a broader New River agricultural-environmental system.

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