The Use of LiDAR in Understanding the Ancient Maya Landscape

Caracol and Western Belize

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A major impediment to full reconstruction and characterization of ancient Maya civilization has been a persistent inability to adequately define the scope of ancient settlement. Because Maya ruins were usually located in areas of dense jungle, it was difficult to not only see but also to map and understand both the spatial extent of their ancient cities and the magnitude of their environmental

ABSTRACT

The use of airborne LiDAR (Light Detection and Ranging) in western Belize, Central America, has revolutionized our understanding of the spatial dynamics of the ancient Maya. This technology has enabled researchers to successfully demonstrate the large-scale human modifications made to the ancient tropical landscape, providing insight on broader regional settlement. Before the advent of this laser-based technology, heavily forested cover prevented full coverage and documentation of Maya sites. Mayanists could not fully recover or document the extent of ancient occupation and could never be sure how representative their mapped and excavated samples were relative to ancient settlement. Employing LiDAR in tropical and subtropical environments, like that of the Maya, effectively provides ground, as well as forest cover information, leading to a much fuller documentation of the complexities involved in the ancient human-nature interface. Airborne LiDAR was first flown over a 200 km^2 area of the archaeological site of Caracol, Belize, in April 2009. In April and May 2013 an additional 1,057 km^2 were flown with LiDAR, permitting the contextualization of the city of Caracol within its broader region and polity. The use of this technology has transformed our understanding of regional archaeology in the Maya area.

El uso de LiDAR (Light Detection and Ranging) instalado en un avión y sobrevolando el oeste de Belice en América Central, ha revolucionado nuestra comprensión de la din·mica espacial de los antiguos mayas y ha ayudado significativamente a establecer comparaciones con otras civilizaciones tropicales. Esta tecnologÌa ha permitido a investigadores demostrar con éxito las modificaciones humanas a gran escala realizadas en el antiguo paisaje tropical, revelando información sobre los patrones de asentamiento de una amplia región. La densidad y la extensión de la ocupación documentada por el LiDAR tienen implicaciones para los modelos sociales y polÌticos de la época cl·sica maya (550-900 d.C.). Antes de la llegada de esta tecnologÌa basada en l·ser, la densa cubierta forestal impedÌa la cobertura completa y la documentación de los lugares arqueológicos mayas. Mayanistas no podÌan recuperar plenamente o documentar el grado de ocupación antigua y nunca podÌan estar seguros de cu·n representativas eran sus muestras mapeadas y excavadas en relación al antiguo asentamiento. El empleo de LiDAR en ambientes tropicales y subtropicales, como el de los mayas, nos ofrece de manera efectiva información del terreno, tanto como la de la cubierta forestal, lo que lleva a una documentación mucho m·s completa de las complejidades involucradas en la antigua interfaz hombre-naturaleza. El LiDAR aerotransportado sobrevoló por primera vez en abril de 2009 un ·rea de 200 kilómetros cuadrados de la zona arqueológica de Caracol, Belice. Estos datos revitalizaron la arqueologÌa del paisaje del ·rea maya, proporcionando una imagen completa de una antigua ciudad—sus asentamientos, centros administrativos y rituales, caminos y terrazas agrÌcolas. En abril y mayo del 2013 una sección adicional de 1.057 kilómetros cuadrados fueron sobrevolados con LiDAR, asi permitiendo la contextualización de la ciudad de Caracol dentro de su región general fÌsica y polÌtica. Cuando se combina esta información con datos detallados de la excavación arqueológica, LiDAR proporciona un recurso sin precedentes para el an·lisis de las din·micas a largo plazo de la relación hombre-naturaleza en relación al aumento, el mantenimiento, y la caÌda de la antigua sociedad maya.

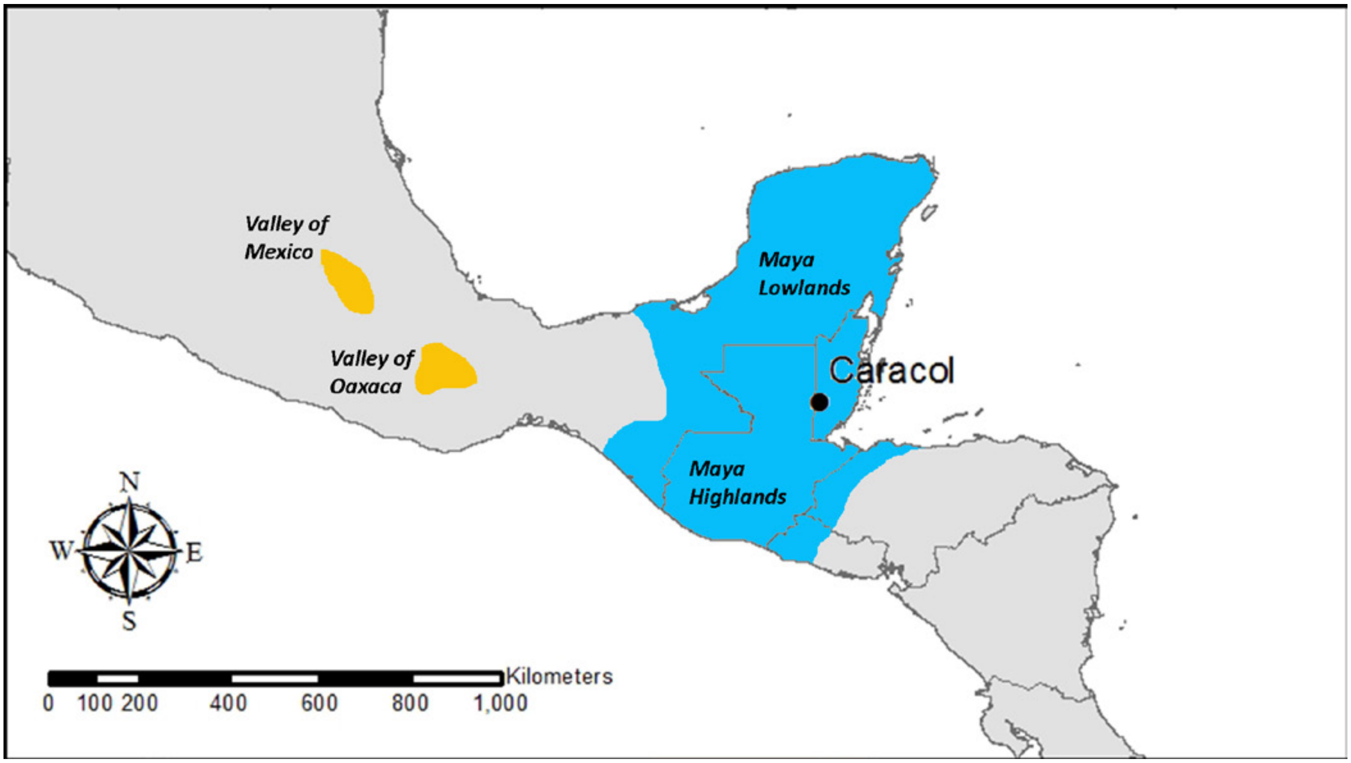

FIGURE 1. Map of Mesoamerica showing the location of the Valleys of Mexico and Oaxaca in relation to sites in the Maya area.

modifications. For a variety of reasons—including dense tropical vegetation, historical accident, limited resources, mapping difficulty, and theoretical predilections—many Maya sites remain severely under-recorded in terms of their overall scale and anthropogenic effects on the landscape. However, this situation is now changing. The use of LiDAR (Light Detection And Ranging) over large swaths of Maya landscapes has provided researchers with the ability to finally situate ancient Maya constructed remains at a regional scale. In some cases, the ancient Maya completely modified their environs and built large low-density urban centers far larger than had once been thought (A. Chase et al. 2011).

To a large degree the present state of lowland Maya regional survey is in direct contradiction to that found in highland Mesoamerica, specifically the Valleys of Mexico and Oaxaca (Figure 1). In the Mexican highlands, great pride is taken in the "full coverage" of landscapes that are largely denuded of plant and tree overlay (Balkansky 2006), making the ancient remains located there very accessible both on the ground and from the air. Because the extent of Mexican highland sites is more easily viewed in terms of the landscapes, developmental reconstructions of their prehistory has been far easier to accomplish (e.g., Blanton 2004; Blanton et al. 1999; Parsons 1990; Sanders et al. 1979). The ecological differences that are found between the Maya lowlands and the highland valleys of central Mexico have led to very divergent archaeological traditions between these two regions in terms of both survey and "grand theory." The fact that highland Mesoamericanists could more easily contextualize the spatial remains of past societies meant that these regions became the benchmarks for comparative schemes regarding the development of ancient economies, cities, states, and civilizations (Blanton 2004; Blanton et al. 1993; Chase et al. 2009). Issues of scale in the Mexican highlands could easily—and visually—be addressed by analyzing the full distribution of archaeological remains upon the landscape, something that was not possible in the Maya area until the advent of LiDAR.

Our interest in LiDAR is an attempt to remedy regional settlement issues in the archaeology of the Maya lowlands. A significant difference between regional survey in the Maya area and highland Mexico is a reliance on surface collections. The history of highland Mexico is largely predicated on the surface collection of artifactual remains, with entire volumes outlining developmental sequences for prehistory being written based on surface collections (e.g., Kowalewski et al. 2009). In contrast, surface artifactual remains encountered in tropical Maya sites are often either not visible or constitute unreliable indicators of the full extent of past occupation (Chase and Chase 1990). Sherds, lithics, and other artifacts in the Maya area are usually covered by a humus layer resulting from the decomposition of organic material; earlier occupation is usually masked in residential

FIGURE 2. Excavation in the Maya area focuses on subsurface artifactual remains and architecture because of the dearth of surface materials; portrayed is an excavation at Caracol, Belize showing the recovery of architecture beneath the mounded earth.

groups by rebuilding efforts and monumental constructions are similarly hidden by later modifications (Figure 2).

Thus, largely because of environmental differences, regional archaeology in Mesoamerica has developed differently in the highlands and the lowlands. In central Mexico, regional archaeology has been predicated on surface collections and full survey and mapping of extensive land areas—often to the exclusion of actual excavation. In the Maya area, despite some valiant attempts, regional archaeology has been dependent on limited samples of excavation data that have been tied into an even less understood landscape. Detailed transects between major sites to understand settlement were rarely attempted, but when they were done—such as between Tikal and Uaxactun (Puleston 1983) and between Yaxha and Tikal (Ford 1986), they covered narrow spatial swaths and raised more questions than they answered. Until recently, full-coverage mapping of broad areas has been too expensive and laborious to be a possibility.

MAYA REGIONAL SURVEY: A BRIEF HISTORY

While early exploration of Maya sites (e.g., Maudslay 1983; Stephens and Catherwood 1855) focused on monumental architecture and stone monuments from site centers, early twentieth-century archaeological projects expressed an interest in locating residential areas and contextualizing site centers. One of the earliest settlement surveys within the Maya lowlands was undertaken at the Guatemalan site of Uaxactun, where an attempt was made to document residential groups that were situated adjacent to and surrounding the monumental architecture of that site (Wauchope 1934). These efforts led to a documentation of a relatively low density of residential groups, but did not focus on the scale and extent of the overall settlement.

From the very beginning of settlement work in the Maya area there was a concern over what constituted a site and how regions were integrated, but archaeological mapping of these regions was extremely limited. Importantly, the frameworks for understanding the ancient occupation of Maya sites were in constant flux, rotating between more complex frameworks focused on a multi-class society and simpler polar models of priests and peasants (Becker 1979). Because the scale of ancient Maya occupation was largely unknown, different models could be applied and changed almost at will. With the lack of detailed archaeological data and with the field firmly subsumed into anthropology in the Americas, these interpretive frameworks became grounded in the ethnographic study of contemporary Maya peoples (Becker 1979:8-11). Essentially, Robert Redfield's (1941,

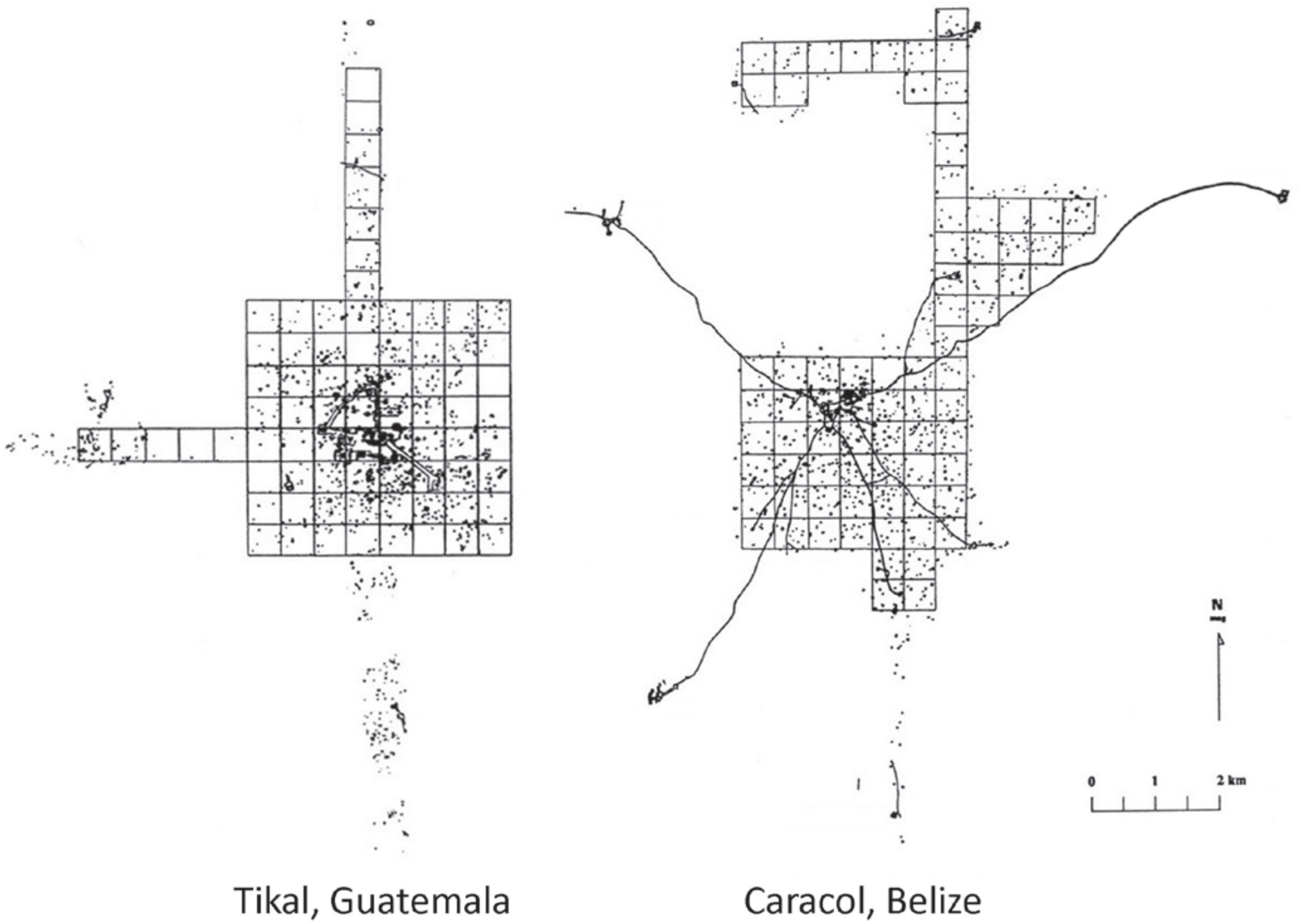

FIGURE 3. Comparison of mapped large Maya sites of Caracol and Tikal. Each dot represents a residential group and each grid cell is 500 x 500 m. Because of the scale, topography and landscape modifications are not shown (after Chase et al. 2009:Figure 3).

1947) model that contrasted "urban" (or elite) and "folk" (or "rural") cultures dominated the Maya area, with the monumental architecture of sites being viewed as being representative of an "urban" core and any residential settlement seen as representing a more "folk" sustaining area. By combining the perceived Maya settlement of concentrated monumental architecture and dispersed residential groups with modern Maya ethnographic data, it was widely thought that ancient Maya society was characterized by "vacant ceremonial centers," largely empty public architecture and plazas in which outlying rural peasants congregated for periodic festivals (Vogt 1968; Willey 1956).

It was not until 1961, with the publication of the 16 km^2 map of the Guatemalan site of Tikal (Carr and Hazard 1961) documenting the central portion of that site, that there was recognition of Maya residential settlement being embedded within and integrated with a monumental core (Coe and Haviland 1982:25). And it was not until substantial excavation was undertaken in the sizeable stone buildings located in site epicenters that there was recognition that they had actually been occupied residential areas (Adams 1974; Chase and Chase 2001b, 2004; Harrison 1999). Once established as residential units, the centrally located stone buildings were interpreted as "royal courts" that had been occupied by Maya elite (Inomata and Houston 2000, 2001). This, then, became the basis for an ethnohistorically-based concentric model of ancient Maya occupation in which the elites or nobles occupied the central stone architecture and the commoners or peasants lived around this center (see Marcus 1983). Yet, investigations of residential groups yielded great status differences in these residential units (Becker et al. 1999; Chase and Chase 2014; Haviland et al. 1985), interpreted as evidence for the existence of a multi-level society among the ancient Maya (A. Chase and D. Chase 1992, 1996). Thus, while some resolution began to be reached about the social complexity of ancient Maya society, the actual scale of organization for ancient Maya settlement was still problematic and could not be demonstrated. The postulated organizational complexity associated with larger Maya sites was often seen as anomalous (Houston et al. 2003:234-236), and the constraints of time, funding, and sub-tropical cover made the complete recording of settlement size and landscape features unfeasible.

Several projects attempted to document the scale of Maya sites (Figure 3). Traditional mapping projects were undertaken within and around urban cores, with some efforts being more extensive than others. However, monumental architecture was usually the central archaeological focus of these projects to the detriment of regional settlement; much of the emphasis on site centers was due both to the spectacular archaeological materials found in the larger Maya architecture and to the difficulty in mapping within a tropical environment. As indicated above, Tikal, Guatemala set the stage for new studies of ancient Maya settlement. The central 16 km^2 map was extended through a series of transects to cover some 23 km^2, eventually resulting in a population estimate for that site of over 90,000 people (Culbert et al. 1990; Puleston 1983). But, even with decades of research and settlement transects extending from the Tikal site center to other Guatemalan sites at Uaxactun (Puleston 1983), 26 km to the north, and Yaxha (Ford 1986), 36 km to the southeast, the full extent of the site and its articulation with surrounding areas could not—and still cannot—be completely addressed.

Following the Tikal efforts, multi-year projects combining site center and settlement work became the norm. Mapping at Dzibalchaltun, Mexico, documented a cruciform pattern for the central part of that site and recorded 8,507 structures in 19 km^2 (Stuart 1979). Entire site sectors between causeways at Coba, Mexico, were recorded (Garduno Argueta 1979), indicating a site that housed some 60,000 people (Folan et al. 1983). Settlement and road systems at Chichen Itza were found to be far more extensive than indicated on the original map made by the Carnegie Institution of Washington project (Cobos 2004). At Calakmul, a site with some 60,000 ancient inhabitants, 30 km^2 of central settlement were recorded (Folan et al. 2001), but mapping the broader region that encompassed these archaeological remains was not done. At Caracol, the central 12 km^2 of the site were recorded in block fashion like Tikal and Calakmul, but transects were extended into the region, ultimately resulting in 23 km^2 of coverage and a population estimate of over 100,000 people (Chase and Chase 2001). More recently, another significant mapping project was undertaken at Chunchucmil, Mexico, documenting dense urban settlement and a population of over 45,000 people in what many had presumed to be an inhospitable—and unsustainable—part of the Yucatán Peninsula (Dahlin et al. 2005).

However, the variability in the preservation of surface architecture and in site size and density across the Maya lowlands made comparative statements difficult (e.g., Culbert and Rice 1990) and, as some of the smaller Maya centers became the focus of archaeological research projects, our perspective about the ancient Maya became shaped by this limited sample. At Quirigua, Guatemala, the site center was found to be situated amidst a settlement buried below several meters of alluvial soil (Ashmore 2007) and, as a consequence, while settlement locales within the Motagua Valley could be determined (Schortman 1993), the actual residential groups surrounding Quirigua were more difficult to discern. Documentation of the neighboring region of Copan, Honduras (Baudez 1983; Fash 1991), suggested a low-density maximum overall valley-wide population of some 30,000 people with a higher density of settlement located only around the area of Copan's monumental architecture.

Efforts to gain a perspective on multiple sites within a region also were undertaken. In the Northern Lowlands, regional survey built upon the base provided by the Yucatán Atlas Project (Garza Tarazona de Gonzalez and Kurjack 1980), which had analyzed aerial photographs to identify Maya settlements across the Yucatán Peninsula. In the Southern Lowlands, an ambitious—and difficult—regional survey of the southeast Petén of Guatemala was carried out by Juan Pedro Laporte (1994; Escobedo 2008) in which his project mapped and recorded concentrations of monumental architecture over a vast region and then attempted to synthesize ancient political organization. For the most part, however, due to the difficulty of carrying out jungle survey, regional settlement studies in the Maya area generally did not attempt to document the total settlement or landscape modifications of large regions or zones. In the Usumacinta area of Guatemala, the centers of Dos Pilas and Aguateca were mapped, but not the region between them (Demarest 1997); part of this decision was based on an idea of the Maya as occupying smaller defensible city-states. At Piedras Negras, only one km^2 of settlement about the monumental architecture was recorded (Houston et al. 2001). Thus, to a large degree, models based on hieroglyphic interpretations, suggesting the existence of a series of small city-states, supported analysis that focused on single sites and their surrounding areas.

Despite over 100 years of investigation, the ancient Maya lowlands occupation over a vast region remains rather incompletely documented and understood (for syntheses of settlement efforts see Ashmore 1981; Culbert and Rice 1990; Sabloff and Ashmore 2007). The central areas of a number of sites have been extensively mapped—the result of herculean efforts given the jungle covering—but the demonstration of exactly how the sites articulated with their regions or each other was not easily or definitively shown.

CARACOL LIDAR AND ITS IMPLICATIONS

In April 2009 all of this changed. The Caracol Archaeological Project subcontracted with the National Center for Airborne Laser Mapping to overfly the site of Caracol, Belize, with LiDAR (see Glennie et al. 2013, for details on LiDAR). From April 26–30, the site was overflown and approximately 20 points per m^2 were recorded with lasers for an area of 199.7 km^2 with a vertical accuracy of 5-30 cm (southern part of Figure 4). These dates were purposefully selected because this was at the end of the dry season in Belize when the maximum numbers of leaves would be off the covering vegetation, ensuring better ground returns from the lasers. As previously detailed (A. Chase et al. 2011:390-391), the 2009 survey was flown at a height of 800 m and used an Optech GEMINI ALTM mounted on a Cessna Skymaster. Flightlines were 260 m apart and were flown in both east-west and north-south flight lines, resulting in 200 percent swath overlap. The aircraft flew at 80 m per second and the laser pulse rate was 100 KHz; the mirror scanner was set at 40 Hz and an angle of ± 21 degrees. Of the approximately 20 laser shots per m^2, an average of 1.35 laser shots per m^2 returned from the ground. Processing of the DEM was done by NCALM; the hillshades (see Devereux et al. 2008; Zaksek et al. 2011) were processed in ArcGIS v. 9 (ESRI Inc. 2009) and Surfer v. 9.9 (Golden Software 2010) software programs in combination with Perl and Arc Macro Language (AML) scripts.

The increased size of the study area, from 23 km^2 to 200 km^2, led to the discovery of additional residential settlement and infrastructure—causeways, agricultural fields, and reservoirs. The

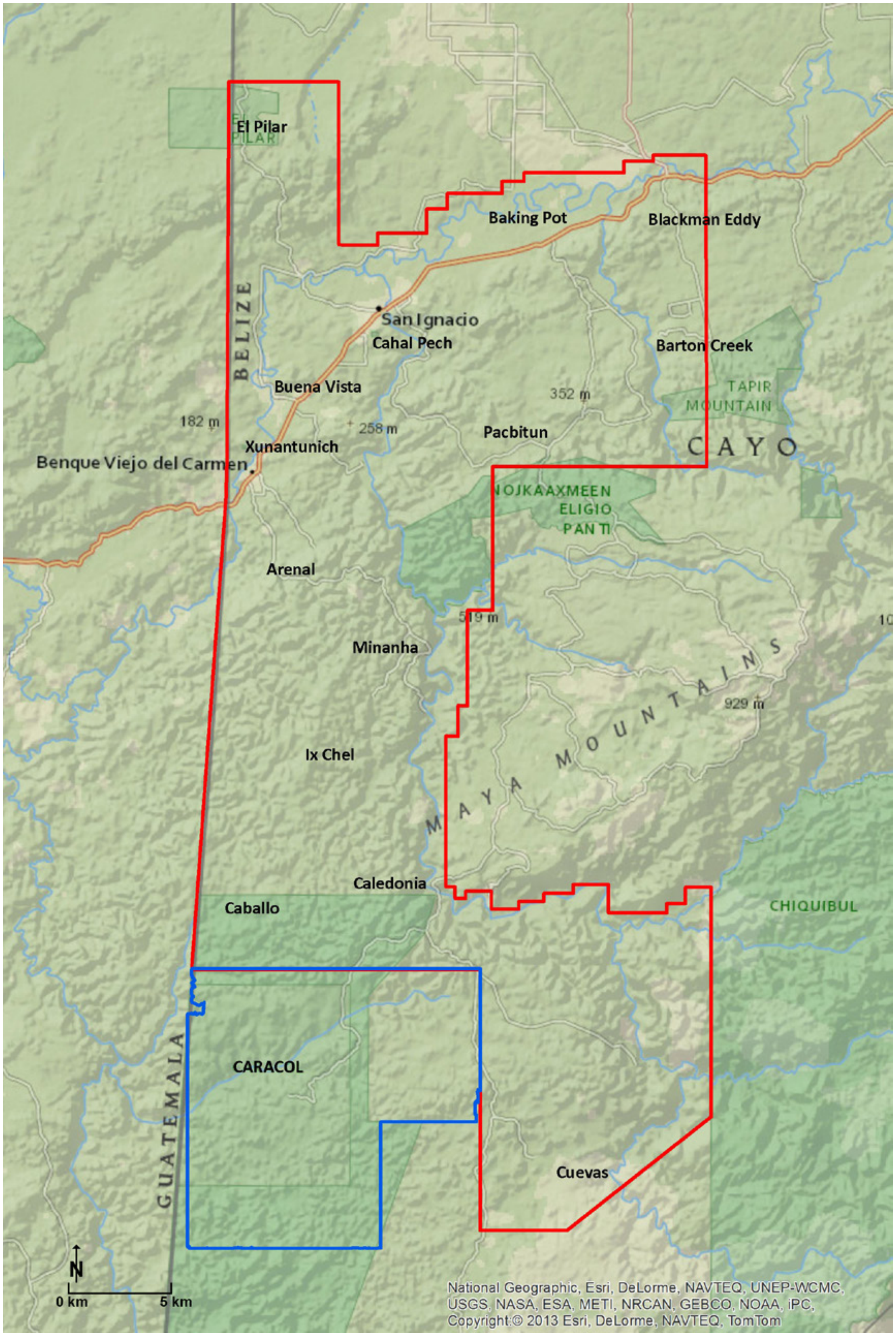

FIGURE 4. The 1257 km^2 of western Belize surveyed by NCALM with LiDAR: lower box around Caracol surveyed in 2009; remaining area surveyed in 2013.

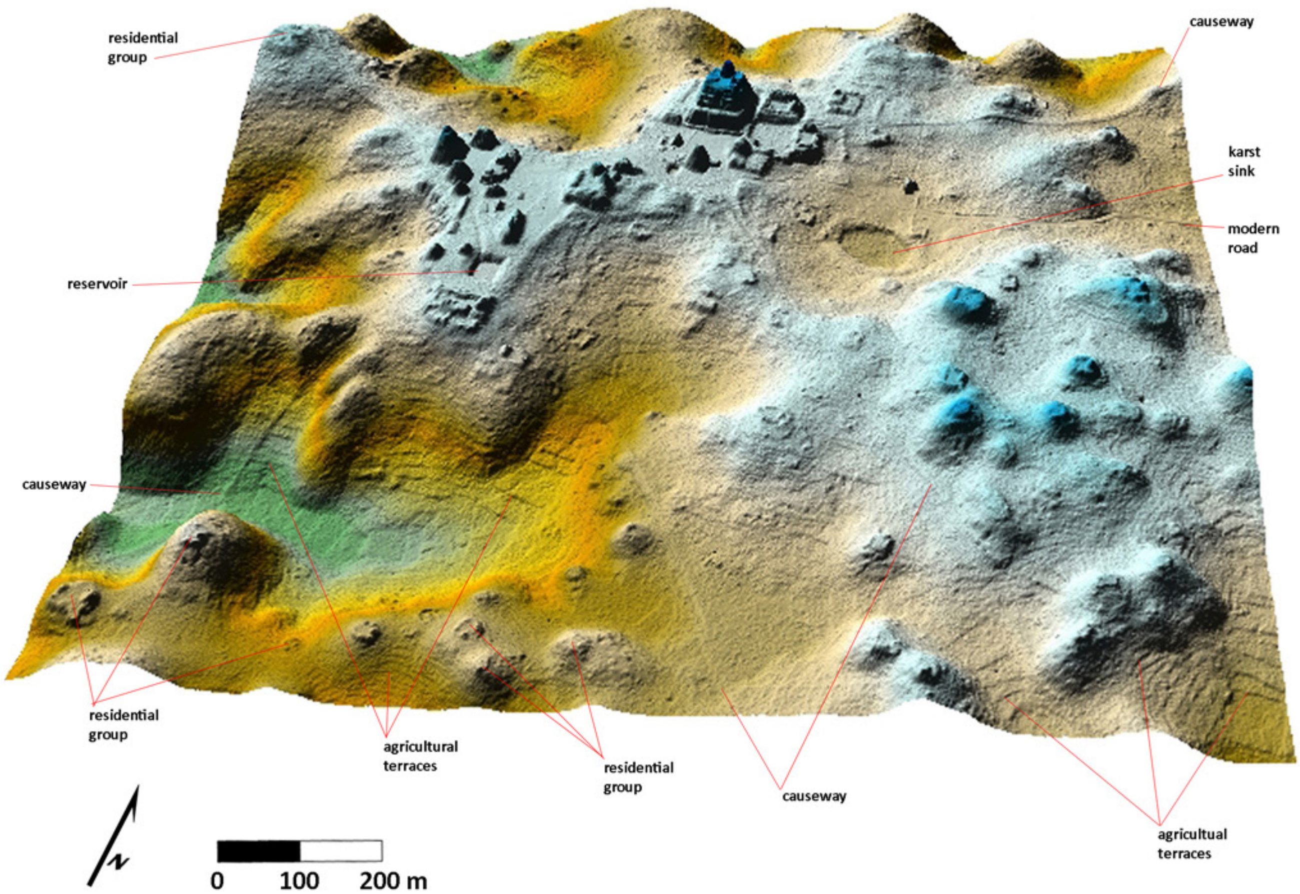

FIGURE 5. 2.5D LiDAR of epicentral portion of Caracol.

results firmly demonstrated not only the scale of this ancient Maya city, but also a fully anthropogenic landscape (Chase et al. 2010; A. Chase et al. 2011). The LiDAR confirmed that Caracol (Figure 5)—along with the previously named and investigated sites of Hatzcap Ceel and Cahal Pichik—formed a single urban settlement, extending over at least 177 km^2 and incorporating almost 160 km^2 of continuously terraced landscape. Rather than seeing the region as dotted by multiple small centers, it became possible to conclusively show that a single integrated site occupied the landscape (Figure 6). These same data also demonstrated that so-called "low-density" Maya urbanism was consistent with urban developments in other tropical areas, such as Angkor, Cambodia (Evans et al. 2013; Fletcher 2009).

LiDAR provided the ability to finally demonstrate the scale upon which the ancient Maya operated and provided the tools to examine how the Maya distributed themselves over their landscape by yielding full-coverage regional survey. How they managed water in a waterless environment could now be analyzed in great detail and in multiple ways. LiDAR provided a detailed topography that showed not only the ancient agricultural terracing (Chase and Chase 1998), but also the actual slope of the landscape and these fields. Furthermore, it became possible to isolate both deep depressions into the earth that represented sinkholes and potential caves (Weishampel et al. 2011) as well as more shallow depressions often located near residential groups that represented constructed reservoirs (Chase 2012; Chase and Weishampel 2014). The articulation of Maya settlement and field systems in terms of the topography became clear. For the first time, a complete Maya region could be visually portrayed in terms of topography, settlement, field systems, reservoirs, and roadways. Needless to say, the wealth of these data has had an impact on our interpretations of the ancient Maya (D. Chase et al. 2011).

While the size of Caracol and its multitude of agricultural terraces were initially viewed—and sometimes dismissed—as being "unique" in terms of Maya landscapes, it now appears that the site is typical of other large Maya cities (e.g., Tikal, Calakmul, Coba, Chichen Itza), both in terms of scale and intensity of agricultural practices. Additionally, the anthropogenic nature of much of the Maya landscape—and its various permutations—is becoming more self-evident. By providing detailed and extensive spatial data, LiDAR forces a consideration of the complexity of the ancient-Maya human-nature interface (D. Chase and A. Chase 2014). These newer data supplement our understanding of the Classic period (A.D. 250-900) Maya that is gained from their hieroglyph record, forcing us to rethink how Maya societies were organized socially, economically, politically, and religiously.

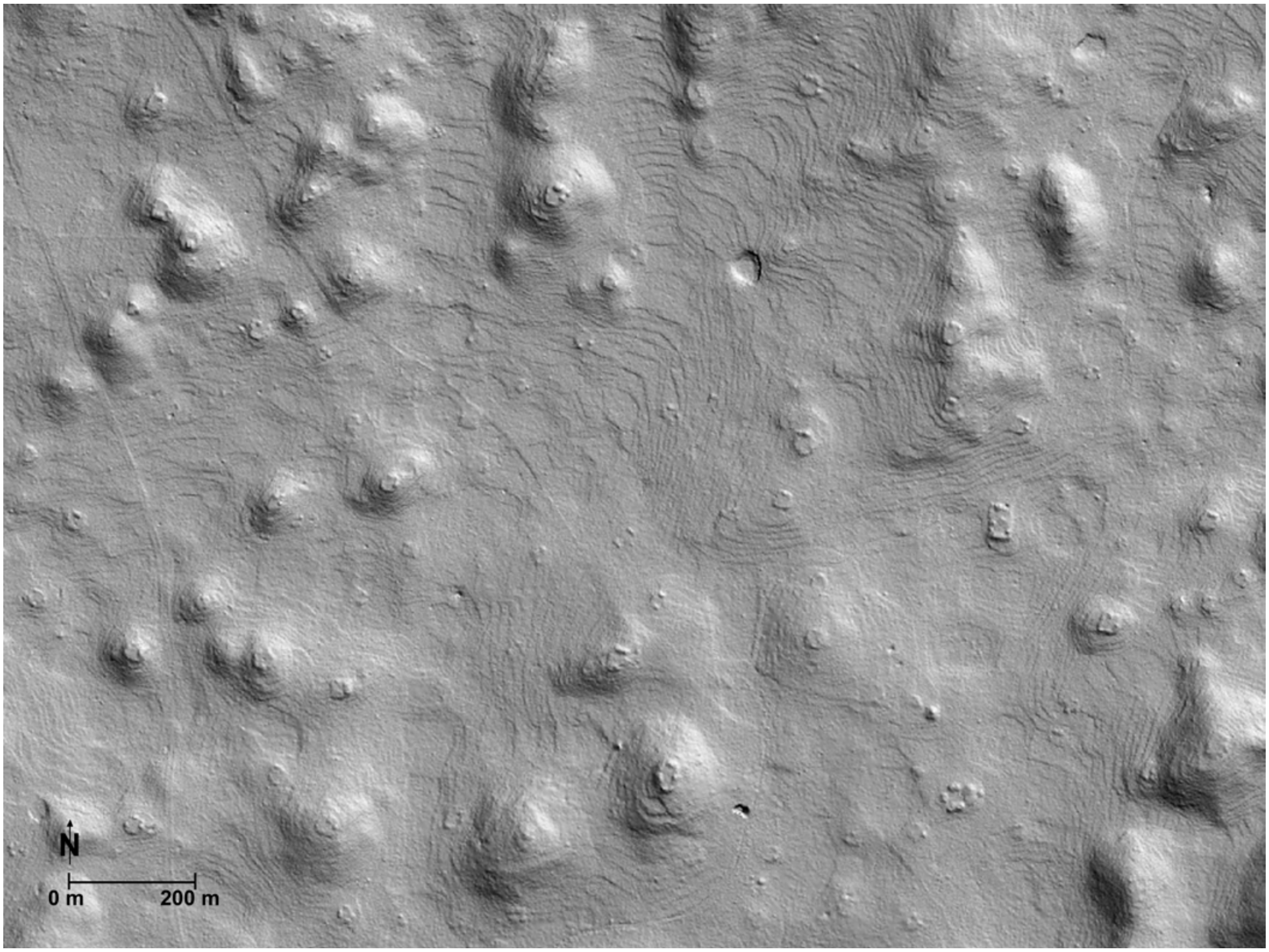

FIGURE 6. 2D LiDAR showing typical landscape in the Caracol settlement containing almost continuous terracing and fairly evenly spaced Maya residential groups.

THE WESTERN BELIZE LIDAR SURVEY

However, an even larger spatial sample of LiDAR data was needed in order to better place Caracol within its landscape and to understand regional Maya settlement patterns. These data were acquired for a consortium of researchers working in western Belize in 2013, again as a result of a subcontract with the National Center for Airborne Laser Mapping (NCALM). From April 27–May 10, 2013, NCALM flew an additional total of 1057 km^2 at 15 points per m^2 that bracketed Caracol to the east and to the north and additionally covered the Belize Valley (see Figure 4), and resulted in an average of 2.8 ground returns per m^2. The 2013 NCALM campaign utilized the same equipment and plane used in 2009. However, the plane was flown at an elevation of 600 m and a ground speed of 60 m per second with 325 survey lines that were 137 m apart, resulting in 300 percent swath overlap. The laser had a pulse rate of 125 kHz and a scan frequency of 55 Hz. The scan angle was 18 degrees. Processing of the data was done by NCALM, as in 2009 LiDAR, and the visualizations have used the same programs.

The area recorded to the east of Caracol was undertaken in order to determine both Caracol's eastern boundary and its relationship to the site of Cuevas. Additional causeways were found to extend east of Caracol. One ran due east from New Maria camp to a terminus 3 km away (Figure 7); another ran from Hatzcap Ceel 3.5 km east to a terminus and then continued another 4 km to yet another terminus. These new causeways mean that it was possible to use the Caracol road system to effectively move from one side of the Vaca Plateau to the other, bypassing the area of rough terrain directly north of Caracol (Chase and Chase 2012). While Caracol is in a limestone environment, these eastern causeways connect the site directly to the only region of the central Maya lowlands containing metamorphic rock (Graham 1987). Based on archaeological research undertaken along the shores of the Macal River (Awe 2005; Brian Woodye, personal communication 2009), granite manos and metates, needed for subsistence production by the ancient Maya, were being produced on a large-scale basis along the banks of this river. Thus, it is likely that granite metates and manos were being transported along the Caracol road system and eventually to consumers in the central Petén—providing clues to Caracol's location and initial prosperity. To the southeast

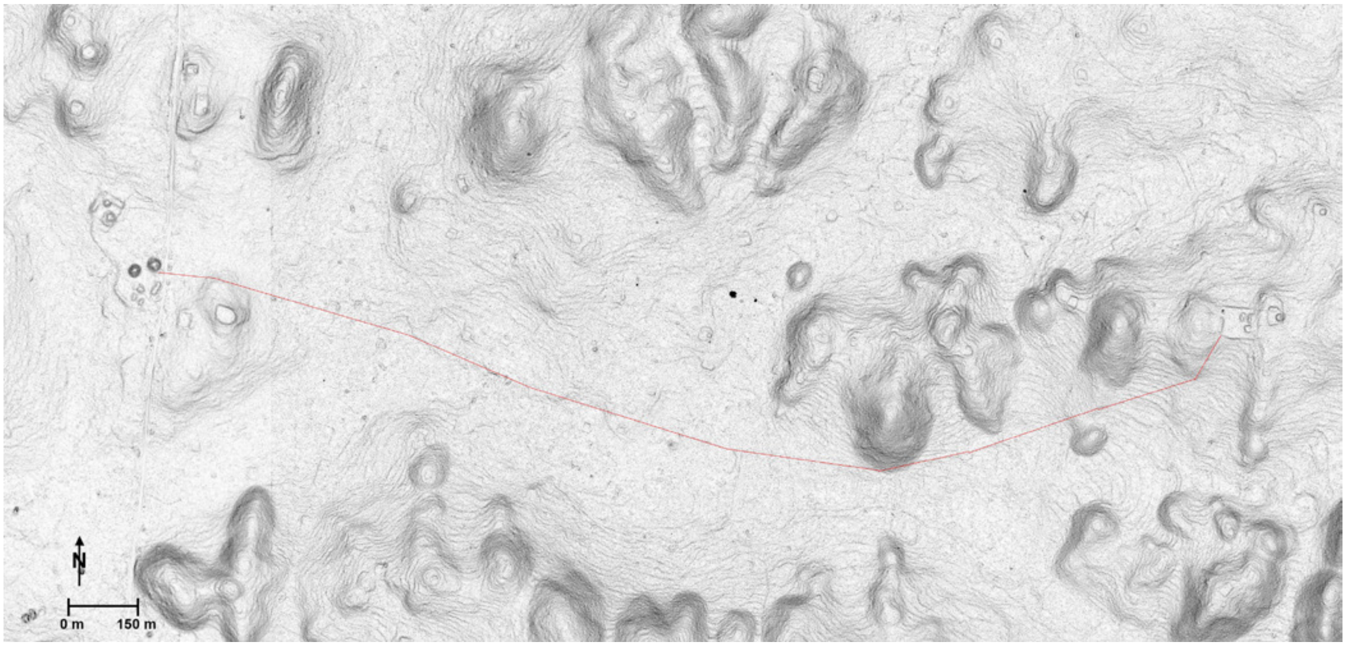

FIGURE 7. Causeway extending east from Caracol's New Maria Camp terminus to a new public plaza with ballcourt.

in this new LiDAR, both residential settlement and agricultural terracing drops off substantially as one approaches the small site of Cuevas (Moyes et al. 2012). However, a new terminus was located approximately 1 km north of Cuevas on top of a hill and a 5 km long causeway, running due east, linked this terminus to the known site of Monkeytail, mapped and archaeologically tested by Brian Woodye in the 1990s.

The area covered by LiDAR to the north of Caracol ran from the Belize-Guatemala border on the west and the Macal River on the east through some very rough karst terrain. Yet, the entire area is dotted with nodes of public architecture. Plateau areas where the terrain is not too severe are completely covered in agricultural terraces and settlement. However, the karst hills present clear breaks between settlement areas. The site of Caballo, located on a flat plain, is separated from Caracol by 5 km of severe karst. Yet, it is surrounded by agricultural fields and exhibits several large nodes of public architecture linked by an east-west causeway system (Figure 8). While separate from Caracol, it was clearly within its sway based on the presence of a giant Ahau altar at the site, which is a Caracol iconographic signature (Grube 1994:100). North of Caballo, the sites of Ix Chel and Yaxnoh are visible atop ridges; both sites have causeways linking together architectural groups. The sites of Minanha (Iannone 2005), Arenal (Tashek and Ball 1999), and Caledonia (Awe 1985) are all visible, but so too are isolated nodes of public architecture resembling E Groups (Chase and Chase 1995).

The area covered by the 2013 LiDAR also incorporated most of the Belize Valley, extending to include the border site of El Pilar to the north and going past the site of Pacbitun to the east to the newly found site of Barton Creek. All of the known sites from the Belize Valley (see Garber 2004, LeCount and Yaeger 2010) are clearly visible. Xunantunich is larger than the current map indicates, with palisades along the southern part of the site core and monumental eastern constructions in evidence near the Mopan River (Figure 9). The nodal regularity in site spacing along the Belize River, something commented on by a variety of researchers (Driver and Garber 2004; Flannery 1977; Helmke and Awe 2012) is also evident—as is the lack of significant settlement away from the river in the lower part of the Belize Valley. The broader implications of the settlement patterns revealed by this LiDAR survey are discussed elsewhere (Chase et al. 2014).

ISSUES STILL TO BE RESOLVED

The future of regional archaeology in the Maya region is exceedingly promising. First, additional LiDAR needs to be flown to record ancient landscapes before they are severely modified by modern encroachment (Weishampel et al. 2012). We know that there are environmental variations among the areas occupied by the ancient Maya; their adaptations likewise were not uniform and are evident in the variety of permutations that can be found in the archaeological record (Chase and Scarborough 2014). LiDAR can provide insight into these alternative adaptive strategies. However, it will be important to collect data from large areas to analyze not only human adaptations, but also the boundaries and relationships among sites and polities. Important archaeological work has been undertaken toward defining the boundaries and borders between Piedras Negras, Guatemala, and Yaxchilan, Mexico (Golden et al. 2008), but LiDAR coverage provides the tools for researchers to define relationships among Maya polities at a scale and level of detail that has not previously been possible.

Perhaps most importantly, LiDAR can provide the framework for studying the human-environment dynamic. Without excavation, scholars can effectively research a series of questions about ancient human adaptation. Reservoirs can be identified

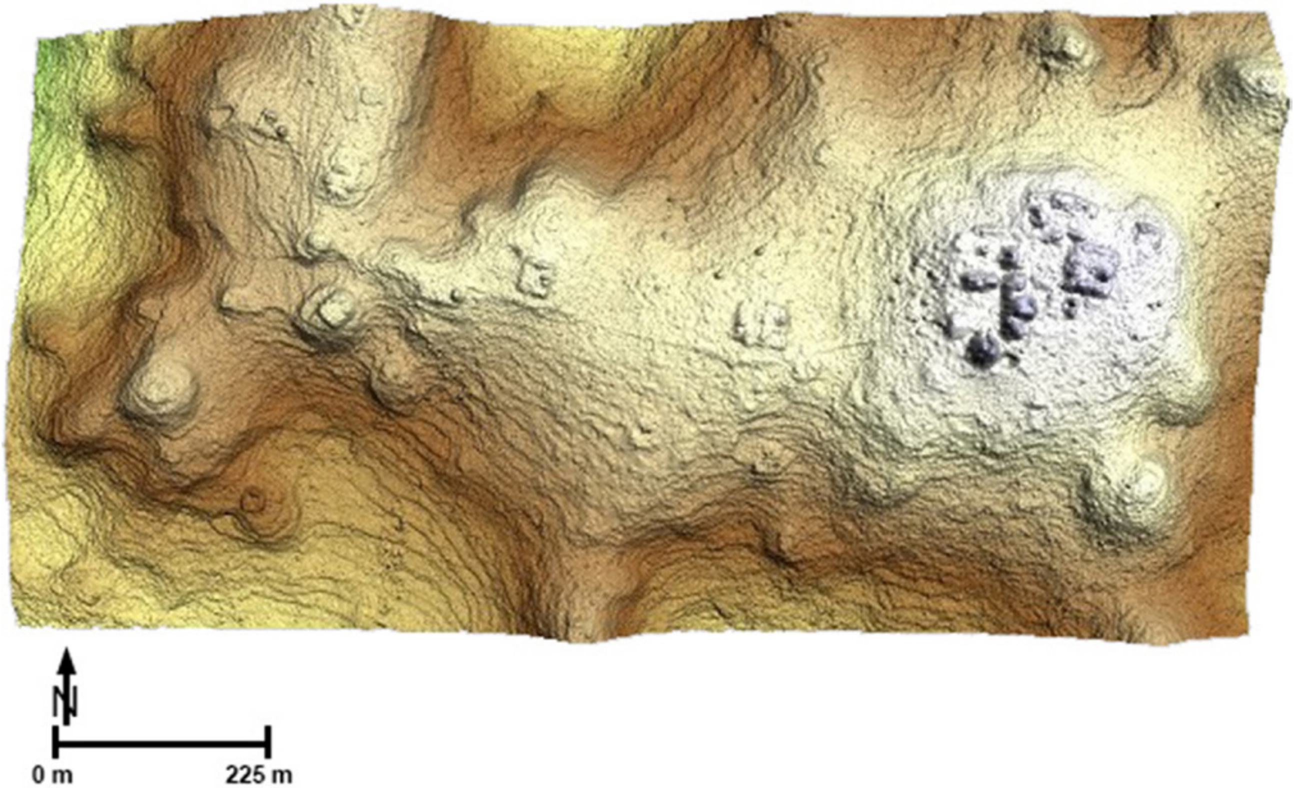

FIGURE 8. The site of Caballo in 2.5D LiDAR.

FIGURE 9. 2D LiDAR image of Xunantunich, Belize showing large constructions on the river bank. Shadow of the modern town of Benque Viejo shows on the southern bank of the river.

and measured to model the number of people that could be supported. The labor expended in making large-scale land modifications can be estimated. The flow of water across the landscape can be tested to determine the effectiveness of constructed terraces in maintaining soils and distributing moisture. The field area per household or neighborhood can be identified. Essentially, the difficulties in carrying out remote on-the-ground research in a dense jungle are largely removed in the Maya region through the use of LiDAR-assisted large-scale landscape archaeology.

However, LiDAR does not remove the necessity of carrying out on-the-ground fieldwork in order to ascertain dating and determine function– or to frame questions and research designs. The soil depth and Maya construction methods make it very unlikely that the collection of surface artifactual remains will ever become the codified discipline that it is in highland Mexico (Kowalewski et al. 2009) or other parts of the world (e.g., Alcock and Cherry 2004, Sullivan et al. 2007). However, because many Maya and Mesoamerican constructions are raised, the use of this technique will permit the relatively full documentation of site scales and articulations. What will not be represented in these data, without excavation, are the temporal depth of the archaeological features being viewed or the associated artifactual remains. The future issues, then, within regional archaeology in the Maya area will be similar to general problems that the discipline faces today: sampling, dating, and interpretation. These are concerns that go far beyond just regional archaeology. Thus, while traditional questions in Maya archaeology may remain to be dealt with, LiDAR has removed a major interpretational obstacle by permitting the large-scale contextualization of ancient Maya remains (Chase et al. 2012).

CONCLUSION

Regional archaeology in the Maya area is at a crossroads. With the advent of LiDAR, it is now possible to contextualize Maya archaeological remains in terms of their landscapes at large spatial scales. However, because of the rich archaeological background and the sizeable databases that exist for the Maya area, the combination of LiDAR and archaeology promises to yield very complicated and detailed pictures of ancient Maya societies and to overturn long-held, yet incorrect, ideas about these sophisticated and complex people. Full-coverage regional survey in highland Mexico has been phenomenally successful in providing comparative models of societal evolution. The comparative cases that now will derive from the Maya area—ones combining full-coverage survey with detailed excavation—will provide far richer understandings of how civilization and urbanism arose and throve in Mesoamerica. From this base, Maya landscapes can effectively be compared and contrasted with human urban adaptations elsewhere in the ancient and modern world.

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Data Availability Statement

In accord with the wishes of the Institute of Archaeology in the country of Belize, the LiDAR data reported on in this paper are not available to the general public in order to protect the country’s archaeological resources from further looting. However, a limited portion of the LAS digital files may be provided to qualified professional researchers for valid teaching and learning purposes; these digital data may be requested from the senior author.

REFERENCES CITED

Adams, Richard E.W.
1974 A Trial Estimation of Classic Maya Palace Populations at Uaxactun. In *Mesoamerican Archaeology: New Approaches*, edited by Norman Hammond, pp. 285-296. Duckworth, London.

Alcock, Susan E., and John F. Cherry (editors)
2004 *Side-by-Side Survey: Comparative Regional Studies in the Mediterranean World.* Oxbow Books, Oxford, England.

Ashmore, Wendy (editor)
1981 *Lowland Maya Settlement Patterns.* University of New Mexico Press, Albuquerque.
2007 *Settlement Archaeology at Quirigu·, Guatemala.* Quirigu· Reports Volume 4. University of Pennsylvania Museum of Archaeology and Anthropology, Philadelphia.

Awe, Jaime J.
1985 Archaeological Investigations at Caledonia, Cayo District, Belize. M.A. Thesis, Department of Anthropology, Trent University, Peterborough, Ontario.
2005 Salvage Excavations in the Areas Impacted by the Challilo Dam. Manuscript on file at Institute of Archaeology, Belize.

Balkansky, Andrew K.
2006 Surveys and Mesoamerican Archaeology: The Emerging Macroregional Paradigm. *Journal of Archaeological Research* 14:53-95.

Baudez, Claude
1983 *Introduccion a la arqueologia de Copan, Honduras.* 3 vols. Secretaria de Estado en el Despacho de Cultura y Turismo, Honduras.

Becker, Marshall J.
1979 Priests, Peasants, and Ceremonial Centers: The Intellectual History of a Model. In *Maya Archaeology and Ethnohistory*, edited by Norman Hammond and Gordon Willey, pp. 3-20. University of Texas Press, Austin.

Becker, Marshall J., and Christopher Jones
1999 *Excavations in Residential Areas at Tikal: Groups with Shrines.* Tikal Report 21. University of Pennsylvania Museum of Archaeology and Anthropology, Philadelphia.

Blanton, Richard E.
2004 Settlement Pattern and Population Change in Mesoamerican and Mediterranean Civilizations: A Comparative Perspective. In *Side-by-Side Survey: Comparative Regional Studies in the Mediterranean World*,

edited by Susan Alcock and John F. Cherry, pp. 206-240. Oxbow Books, Oxford, England.

Blanton, Richard E., Gary M. Feinman, Stephen A. Kowladewski, and Linda M. Nichols
1999 *Ancient Oaxaca: The Monte Alban State.* Cambridge University Press, Cambridge, England.

Blanton, Richard E., Stephen E. Kowalewski, Gary M. Feinman, and Laura M. Finsten
1993 *A Comparison of Change in Three Regions.* 2nd ed. Cambridge University Press, Cambridge, England.

Carr, Robert F., and James E. Hazard
1961 *Map of the Ruins of Tikal, El Peten, Guatemala.* Tikal Report 11. University Museum Monograph. University of Pennsylvania Museum of Archaeology and Anthropology, Philadelphia.

Chase, Adrian S.Z.
2012 Beyond Elite Control: Water Management at Caracol, Belize. Bachelors thesis, Department of Archaeology, Harvard University, Cambridge, Massachusetts.

Chase, Adrian S.Z., and John F. Weishampel
2014 Water Capture and Agricultural Terracing at Caracol, Belize as Revealed Through LiDAR. *Remote Sensing* 6, in press.

Chase, Arlen F., and Diane Z. Chase
1990 Los Sistemas Mayas de Subsistencia y Patron de Asentamiento: Pasado y Futuro. In *Los Mayas: El Esplendor de Una Civilizacion*, edited by L. Yanez-Barnuevo Garcia and Andres Ciudad Ruiz, pp. 38-48. Sociedad Estatal Quinto Centenario, Turner Libros, S.A., Madrid.
1995 External Impetus, Internal Synthesis, and Standardization: E Group Assemblages and the Crystalization of Classic Maya Society in the Southern Lowlands. *Acta Mesoamericana* 8:87-101. Markt Schwaben Verlag A. Surwein, Germany.
1996 A Mighty Maya Nation: How Caracol Built an Empire by Cultivating Its "Middle Class." *Archaeology* 49(5):66-72.
1998 Scale and Intensity in Classic Period Maya Agriculture: Terracing and Settlement at the "Garden City" of Caracol, Belize. *Culture and Agriculture* 20(2):60-77.
2001a Ancient Maya Causeways and Site Organization at Caracol, Belize. *Ancient Mesoamerica* 12(2):273-281.
2001b The Royal Court of Caracol, Belize: Its Palaces and People. In *Royal Courts of the Ancient Maya: Volume 2: Data and Case Studies*, edited by Takeshi Inomata and Stephen D. Houston, pp. 102-137. Westview Press, Boulder, Colorado.
2004 Terminal Classic Status-Linked Ceramics and the Maya 'Collapse": *De Facto* Refuse at Caracol, Belize. In *The Terminal Classic in the Maya Lowlands: Collapse, Transition, and Transformation*, edited by Arthur Demarest, Prudence Rice, and Don Rice, pp. 342-366. University Press of Colorado, Boulder.
2012 Belize Red Ceramics and Their Implications for Trade and Exchange in the Eastern Maya Lowlands. *Research Reports in Belizean Archaeology* 9:3-14.
2014 Houses, Households, and Residential Groups at Caracol, Belize. *Research Reports in Belizean Archaeology* 11:3-17.

Chase, Arlen F., Diane Z. Chase, Jaime J. Awe, John F. Weishampel, Gyles Iannone, Holley Moyes, Jason Yaeger, Katheryn Brown, Ramesh L. Shresthra, William E. Carter, and Juan Fernandez Diaz
2014 Ancient Maya Regional Settlement and Inter-Site Analysis: The 2013 West-Central Belize LiDAR Survey. *Remote Sensing* 6, in press.

Chase, Arlen F., Diane Z. Chase, Christopher T. Fisher, Steve Leisz, and John F. Weishampel
2012 Geospatial Revolution and Remote Sensing LiDAR in Mesoamerican Archaeology. *Proceedings of the National Academy of Sciences* 109(32):12916-12921.

Chase, Arlen F., and Vernon L. Scarborough (editors)
2014 *The Resilience and Vulnerability of Ancient Landscapes: Transforming Maya Archaeology through IHOPE.* Archaeological Papers of the American Anthropological Association, Arlington, Virginia.

Chase, Arlen F., Diane Z. Chase, and Michael E. Smith
2009 States and Empires in Ancient Mesoamerica. *Ancient Mesoamerica* 20(2):175-182.

Chase, Arlen F., Diane Z. Chase, and John F. Weishampel
2010 Lasers in the Jungle: Airborne sensors reveal a vast Maya landscape. *Archaeology* 63(4):27-29.

Chase, Arlen F., Diane Z. Chase, John F. Weishampel, Jason B. Drake, Ramesh L. Shrestha, K. Clint Slatton, Jaime J. Awe, and William E. Carter
2011 Airborne LiDAR, Archaeology, and the Ancient Maya Landscape at Caracol, Belize. *Journal of Archaeological Science* 38:387-398.

Chase, Diane Z., and Arlen F. Chase (editors)
1992 *Mesoamerican Elites: An Archaeological Assessment.* University of Oklahoma Press, Norman.

Chase, Diane Z., and Arlen F. Chase
2014 Path Dependency in Rise and Denouement of a Classic Maya City: The Case of Caracol, Belize. In *The Resilience and Vulnerability of Ancient Landscapes: Transforming Maya Archaeology through IHOPE*, edited by Arlen F. Chase and Vernon Scarborough. Archaeological Papers of the American Anthropological Association, Arlington, Virginia (in press).

Chase, Diane Z., Arlen F. Chase, Jaime J. Awe, John H. Walker, and John F. Weishampel
2011 Airborne LiDAR at Caracol, Belize and the Interpretation of Ancient Maya Society and Landscapes. *Research Reports in Belizean Archaeology* 8:61-73.

Cobos, Rafael
2004 Chichen Itza: Settlement and Hegemony during the Terminal Classic Period. In *The Terminal Classic in the Maya Lowlands*, edited by Arthur A. Demarest, Prudence M. Rice, and Don S. Rice, pp. 517-544. University of Colorado Press, Boulder.

Coe, William R., and William A. Haviland
1982 *Introduction to the Archaeology of Tikal, Guatemala.* Tikal Report 12. University Museum Monograph 46. University of Pennsylvania Museum of Archaeology and Anthropology, Philadelphia.

Culbert, T. Patrick, Laura J. Kosakowsky, Robert E. Fry, and William A. Haviland
1990 The Population of Tikal, Guatemala. In *Precolumbian Population History in the Maya Lowlands*, edited by T. Patrick Culbert and Don S. Rice, pp. 103-121. University of New Mexico Press, Albuquerque.

Culbert, T. Patrick, and Don S. Rice (editors)
1990 *Precolumbian Population History in the Maya Lowlands.* University of New Mexico Press, Albuquerque.

Dahlin, Bruce H., Tim Beach, Susan Luzzadder-Beach, David Hixson, Scott Hutson, A. Magnoni, E. Mansell, and David E. Mazeau
2005 Reconstructing the Subsistence Economy at Chunchucmil, Yucatan, Mexico: A Case for a Convergence of Evidence Argument. *Ancient Mesoamerica* 9:1-15.

Demarest, Arthur A.
1997 The Vanderbilt Petexbatun Regional Archaeological Project 1989-1994: Overview, History, and Major Results of a Multidisciplinary Study of the Classic Maya Collapse. *Ancient Mesoamerica* 8:209-227.

Devereaux, B.J., G.S. Amable, and P. Crow
2008 Visualization of LiDAR Terrain Models for Archaeological Feature Detection. *Antiquity* 82:470-479.

Driver, David, and James E. Garber
2004 The Emergence of Minor Centers in the Zones between Seats of Power. In *The Ancient Maya of the Belize Valley: Half a Century of Archaeological Research*, edited by James Garber, pp. 287-304. University Press of Florida, Gainesville.

Escobedo, Hector (editor)
2008 *Registro de Sitios Arqueologicos del Sureste y Centro-oeste de Peten. Monografias Atlas Arqueologico de Guatemala.* Direccion General del Patrimonio Cultural y Natural, Guatemala.

Evans, Damian H., Roland J. Fletcher, Christophe Pottier, Jean-Baptiste Chevance, Dominique Soutif, Boun Suy Tan, Sokrithy Im, Darith Ea, Tina Tin, Samnang Kim, Christopher Cromarty, Stephane De Greef,

Kasper Hanus, Pierre Baty, Robert Kuszinger, Ichita Shimoda, and Glenn Boornazian
2013 Uncovering Archaeological Landscapes at Angkor Using LiDAR. *PNAS* 110(31):12595-12600.
Fash, William L.
1991 *Scribes, Warriors, and Kings: The City of Copan and the Ancient Maya.* Thames & Hudson, New York.
Flannery, Kent
1977 Linear Stream Patterns and Riverside Settlement Rules. In *The Mesoamerican Village*, edited by Kent Flannery, pp. 173-180. Academic Press, New York.
Fletcher, Roland
2009 Low-Density, Agrarian-Based Urbanism: A Comparative View. *Insights* 2:2-19.
Folan, William J., Ellen R. Kintz, and Larraine A. Fletcher
1983 *Coba: An Ancient Maya Metropolis.* Academic Press, San Francisco.
Folan, William J., Larraine A. Fletcher, Jacinto May Hau, and Lynda Florey Folan
2001 *Las Ruinas de Calakmul, Campeche, Mexico: un lugar central y su paisaje cultural.* Universidad Autonoma de Campeche, Campeche, Mexico.
Ford, Anabel
1986 *Population Growth and Social Complexity: An Examination of Settlement and Environment in the Central Maya Lowlands.* Anthropological Research Papers, No. 35. Arizona State University, Tempe.
Garber, James E. (editor)
2004 *The Ancient Maya of the Belize Valley: Half a Century of Archaeological Research.* University Press of Florida, Gainesville.
Garduno Argueta, Jaime
1979 Introduccion al patron de asentamiento del sitio de Coba, Quintana Roo. Escuela Nacional de Antropologia e Historia, Mexico.
Garza Tarazona de Gonzalez, Silvia, and Edward B. Kurjack
1980 *Atlas Arqueoiogico del Estado de Yucat·n.* 2 vols. Instituto Nacional de Antropologia e Historia, Mexico.
Glennie, C.L., William E. Carter, Ramesh L. Shrestha, and W.E. Dietrich
2013 Geodetic Imaging with Airborne LiDAR: the Earth's Surface Revealed. Reports on Progress in Physics 76. 086801 (24pp) DOI:10.1088/0034-4885/76/8/086801 (IF 13.23).
Golden, Charles, Andrew K. Scherer, Arturo R. Munoz, and Rene Vasquez
2008 Piedras Negras and Yaxchilan: Divergent Political Trajectories in Adjacent Maya Polities. *Latin American Antiquity* 19:249-274.
Graham, Elizabeth
1987 Resource Diversity in Belize and Its Implications for Models of Lowland Trade. *American Antiquity* 54:253-267.
Grube, Nikolai
1994 Epigraphic Research at Caracol, Belize. In *Studies in the Archaeology of Caracol, Belize*, edited by Diane Z. Chase and Arlen F. Chase, pp. 83-122. Monograph 7. Pre-Columbian Art Research Institute, San Francisco.
Harrison, Peter D.
1999 *The Lords of Tikal: Rulers of an Ancient Maya City.* Thames & Hudson, London.
Haviland, William A., Marshall J. Becker, Anne Chowning, Keith A. Dixon, and Karl Heider
1985 *Excavations in Residential Areas of Tikal: Non-Elite Groups without Shrines.* Tikal Report 20. University of Pennsylvania Museum of Archaeology and Anthropology, Philadelphia.
Helmke, Christophe, and Jaime J. Awe
2012 Ancient Maya Territorial Organization in the Belize Valley. *Contributions in New World Archaeology* 4:59-90.
Houston, Stephen D., Hector Escobedo, Mark Child, Charles Golden, Richard Terry, and David Webster
2001 In the Land of the Turtle Lords: Archaeological Investigations at Piedras Negras, Guatemala, 2000. *Mexicon* 22(5):97-110.
Houston, Stephen D., Hector Escobedo, Mark Child, Charles Golden, and Rene Munoz
2003 The Moral Community: Maya Settlement Transformation at Piedras Negras, Guatemala. In *The Social Construction of Ancient Cities*, edited by Monica L. Smith, pp. 212-253. Smithsonian Institution Press, Washington, D.C.
Iannone, Gyles
2005 The Rise and Fall of an Ancient Maya Petty Royal Court. *Latin American Antiquity* 16:26-44.
Inomata, Takeshi, and Stephen D. Houston (editors)
2000 *Royal Courts of the Ancient Maya: Volume.1: Theory, Comparison, and Synthesis.* Westview Press, Boulder, Colorado.
2001 *Royal Courts of the Ancient Maya: Volume 2: Data And Case Studies.* Westview Press, Boulder, Colorado.
Kowalewski, Stephen A., Andrew K. Balkansky, Laura R. Stiver Walsh, Thomas J. Pluckhahn, John F. Chamblee, Veronica Perez Rodriguez, Verenice Y. Heredia Espinoza, and Charlotte A. Smith
2009 *Origins of the Nuu: Archaeology in the Mixteca Alta, Mexico.* University Press of Colorado, Boulder.
Laporte, Juan Pedro
1994 Ixtoton, Dolores, Peten: entidad politica del noroeaste de las montanas Maya. *Atlas Arqueologico de Guatemala No. 2.* Universidad de San Carlos, Guatemala.
LeCount, Lisa J., and Jason Yaeger (editors)
2010 *Classic Maya Provincial Politics: Xunantunich and Its Hinterlands.* University of Arizona Press, Tucson.
Marcus, Joyce
1983 On the Nature of the Mesoamerican City. In *Prehistoric Settlement Patterns: Essays in Honor of Gordon R. Willey*, edited by Evon Vogt and Richard Leventhal, pp. 195-242. University of New Mexico Press, Albuquerque.
Maudslay, Alfred P.
1983 *Biologia Centrali America: Archaeology.* 5 vols. R.H. Porter and Dulau and Company, London. 1983 facsimile ed. In 6 vols. University of Oklahoma Press, Norman.
Moyes, Holley, Laura Kosakowsky, Mark Robinson, and Barbara Voorhies
2012 Better Late Than Never: Preliminary Investigations at Las Cuevas. *Research Reports in Belizean Archaeology* 9:221-231.
Parsons, Jeffrey R.
1990 Critical Reflections on a Decade of Full-Coverage Regional Survey in the Valley of Mexico. In *The Archaeology of Regions: A Case for Full-Coverage Survey*, edited by Susan Fish and Stephen Kowalewski, pp. 7-31. Smithsonian Institution, Washington, D.C.
Puleston, Dennis E.
1983 *The Settlement Survey of Tikal.* University Museum Monograph 48. University of Pennsylvania Museum of Archaeology and Anthropology, Philadelphia.
Redfield, Robert
1941 *The Folk Culture of Yucatan.* University of Chicago Press, Chicago.
1947 The Folk Society. *The American Journal of Sociology* 52:293-308.
Sabloff, Jeremy A., and Wendy Ashmore
2007 An Aspect of Archaeology's Recent Past and its Relevance in the New Millennium. In *Archaeology at the Millenium*, edited by Gary M. Feinman and T. Douglas Price, pp. 11-32. Springer, New York.
Sanders, William T., Jeffrey R. Parsons, and Robert S. Santley
1979 *The Basin of Mexico: Ecological Processes in the Evolution of Civilization.* Academic Press, New York.
Schortman, Edward M.
1993 *Archaeological Investigations in the Lower Motagua Valley, Izabal, Guatemala: A Study in Monumental Site Function and Interaction.* Quirigu· Reports III. University Museum Monograph 80. University of Pennsylvania Museum of Archaeology and Anthropology, Philadelphia.
Stephens, John L., and Frederick Catherwood
1855 *Incidents of Travel in Yucatan.* Harper and Brothers, New York.

Stuart, George E.
1979 *Map of the Ruins of Dzibilchaltun, Yucatan, Mexico*. MARI Publication 47. Tulane University, New Orleans.

Sullivan, Alan P., Philip B. Mink, and Patrick M. Uphus
2007 Archaeological Survey Design, Units of Observation, and the Characterization of Regional Variability. *American Antiquity* 72:322-333.

Taschek, Jennifer T., and Joseph W. Ball
1999 Las Ruinas de Arenal, Belize—Preliminary Report on a Subregional Major Center in the Western Belize Valley (1991-1992 Excavations). *Ancient Mesoamerica* 10(2):215-235.

Vogt, Evan
1968 Some Aspects of Zinacantan Settlement and Ceremonial Organization. In *Settlement Archaeology*, edited by K.C. Chang, pp. 154-173. National Press Books, Palo Alto.

Wauchope, Robert
1934 *House Mounds of Uaxactun, Guatemala*. Publication 436. Carnegie Institution of Washington, Washington, D.C.

Weishampel, John F., Jessica N. Hightower, Arlen F. Chase, and Diane Z. Chase
2012 Use of Airborne LiDAR to Delineate Canopy Degradation and Encroachment along the Guatemala-Belize Border. *Tropical Conservation Science* 5(1):12-24.

Weishampel, John F., Jessica Hightower, Arlen F. Chase, Diane Z. Chase, and Ryan A. Patrick
2011 Detection and Morphologic Analysis of Potential below-Canopy Cave Openings in the Karst Landscape around the Maya Polity of Caracol Using Airborne LiDAR. *Journal of Cave and Karst Studies* 73(3):187-196.

Willey, Gordon R.
1956 The Structure of Ancient Maya Society: Evidence from the Southern Lowlands. *American Anthropologist* 58(5):777-782.

Zaksek, Klemen, Kristof Ostir, and Siga Kokalj
2011 Sky-View Factor as a Relief Visualization Technique. *Remote Sensing* 3:398-415.

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