Chapter 22
Detection of Maya Ruins by LiDAR: Applications, Case Study, and Issues

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Abstract The study of ancient Mesoamerican landscapes and settlement has been significantly impacted in a positive way through the application of LiDAR (light detection and ranging). LiDAR has permitted the recovery of ground data from huge regional areas that are currently under a tropical canopy: the use of traditional methods of survey and mapping could never have resulted in the detailed data that are available through LiDAR. The analyses of LiDAR data are a conjunctive task that involves archaeologists with physicists and computer scientists. This interdisciplinary effort is producing new results and interpretations for all fields, but has also raised issues that need resolution, particularly involving data storage and distribution. LiDAR has already transformed the way in which Mesoamerican settlement survey is done, and future collection of LiDAR data will benefit Mesoamerica through helping to preserve a landscape of the past.

Keywords LiDAR • Settlement archaeology • Landscape archaeology • Maya • Mesoamerica

22.1 Introduction

For the ancient Maya area, LiDAR (light detection and ranging) has replaced all other remote sensing technologies as the most desirable tool for researching ancient settlement systems. In its ability to penetrate the tropical and subtropical canopy to reveal large areas of settlement, LiDAR is revolutionizing our understanding of the ancient Maya landscape and use of space (Chase et al. 2012). It is providing the means to study site size and population density, as well as large- and small-scale land modifications. Given the general absence of preexisting government or industry LiDAR surveys in Central America, archaeologists have served as the driving force for the procurement and expansion in the use of this technology in this part of the world, albeit with a reliance on individuals from other fields to help process the data.

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Similar to any new tool at an interface between disciplines, however, researchers are still learning how to use this new resource effectively.

LiDAR is not commonly used in Central America for environmental planning and construction projects to the same degree that it is in the United States and Europe, where the technology has a longer history of utilization for non-archaeological land management purposes (e.g., Johnson and Ouimet 2014: 11, on public database for New England states). Thus, in Central America LiDAR acquisition has usually been organized by independent archaeological researchers through grants or private funding; subcontracts are issued to undertake the LiDAR overflights that produce Log ASCII Standard (LAS) files. Different LiDAR companies, equipment, and strategies have been used to record the landscape, leading to some variability in the collection of point cloud data. Currently, although there is standardization for the LAS files and how the data are recorded, there is no official standardization for archaeological LiDAR processing or distribution anywhere in the world, and there are potential ethical concerns as well (discussed below). Yet, for the Maya area much of the collected point cloud data have become relatively standardized because the majority of overflights have been undertaken by the same entity, the National Center for Airborne Laser Mapping (NCALM) affiliated with the University of Houston and the U.S. National Science Foundation, leading to consistency in data presentation and post-processing.

With the exception of four reported LiDAR campaigns (Table 22.1), the archaeological LiDAR database for Mesoamerica has been largely produced by NCALM (Fernandez et al. 2014), although this may change in the near future as more archaeological projects procure LiDAR. The earliest LiDAR campaign in the Maya area was the one carried out at Caracol, Belize, in 2009 that established the value of this technology for large-scale settlement archaeology and landscape analysis, even in hilly and heavily forested areas (Chase et al. 2010, 2011a, b, 2012, 2013; Weishampel et al. 2010, 2013). The success of the Caracol LiDAR in documenting even slightly elevated archaeological remains spurred the use of this technology not only in Mesoamerica but also in other tropical areas, specifically at Angkor, Cambodia (Evans et al. 2013). Although the cost of LiDAR was initially of concern to many researchers (the 2009 LiDAR survey of 200 km^2 for Caracol cost US $171,000), archaeologists soon recognized that this technology was well worth the funds expended. Not only was more ground covered efficiently (traditional mapping methods would have required labor-intensive decades to do what was done in days), but the collected point cloud data were far more detailed than any survey data (providing elevation information and complete topographic data). Thus, each LiDAR campaign continues to establish the value of LiDAR data to Mesoamerican research agendas.

Following the collection of LiDAR data for Caracol by NCALM and with a recognition of its ability to successfully record ground data (Chase et al. 2010), there were other early LiDAR campaigns conducted in Mexico that did not use NCALM but also produced significant landscape data related to archaeological ruins (Fisher et al. 2011; Rosenswig et al. 2013; Zatina Gutierrez 2014); the Izapa database was subsequently amplified (Rosenswig et al. 2014). In 2011 and 2012

Table 22.1 Spatial distribution of LiDAR (light detection and ranging) in Mesoamerica

Site/region	Year flown	Area covered (km^2)	Density (points/m^2)
Caracol, Belize	2009	200	20
Izapa, Mexico (Airborne 1)	2010	42.2	3.2
Angamuco, Mexico (not NCALM)	2011	9	15
Uxbenka, Belize	2011	103	12
El Pilar, Belize (Mayaniquel)	2012	20	20
Mosquita, Honduras	2012	122	15–25
El Tajin, Mexico (INAH/PEMEX)	2012	Unknown	Unknown
Western Belize	2013	1057	15
Mayapan, Mexico	2013	55	40–42
Tres Zapotes, Mexico	2014	72	12–13
Chichen Itza/Yaxuna, Mexico	2014	50	15
Cansahcab, Mexico	2014	26	15
Yaxnohcah, Mexico	2014	90	15
Izapa, Mexico (Airborne 1)	2014	47.5	3.1
El Ceibal, Guatemala	2015	400	15
Teotihuacan, Mexico	2015	120	20
Michoacan, Mexico	2015	40	20
Zacapu, Mexico	2015	40	20

NCALM engaged in LiDAR campaigns in southern Belize (Prufer et al. 2015; Prufer and Thompson 2016; Thompson and Prufer 2015) and in Honduras (Preston 2013). One other non-NCALM campaign in 2012 covered the Belize site of El Pilar (Ford 2014). The largest LiDAR campaign carried out to date in the Maya area was undertaken in 2013 by NCALM and covered 1057 km^2 of western Belize (Chase et al. 2014a, b; Chase and Weishampel 2016; Ebert et al. 2016; Macrae and Iannone 2016; Moyes and Montgomery 2016; Yaeger et al. 2016). That same year, Mayapan was also overflown (Hare et al. 2014). In the summer of 2014, NCALM carried out a series of smaller campaigns in Mexico at Tres Zapotes, Chichen Itza/Yaxuna, Cansahcab, and Yaxnohcah. The results of these surveys are recorded by Hutson et al. (2016), Laughlin et al. (2016), Magnoni et al. (2016), and Reese-Taylor et al. (2016). In 2015, NCALM has flown LiDAR campaigns for El Ceibal, Guatemala (for Takeshi Inomata and Kazou Aoyama), for Teotihuacan (for Saburo Sugiyama), and for Michoacan (Christopher Fisher and Gregory Periera).

22.2 Case Study: Western Belize

Landscape and settlement archaeology in the Maya area came of age in 2009 with the original Caracol LiDAR survey of 200 km^2 at a density of 20 points/m^2 that immediately transformed Caracol from a 23 km^2 mapped site to one that filled most of the digital elevation model (DEM) (A. Chase et al. 2010, 2011a, b, 2012, 2013; Weishampel et al. 2010, 2013). The survey undertaken by NCALM was very successful in gaining bare earth results that proved to be accurate when compared to existing maps or ground-truthing. Additionally, although not inexpensive, the cost of the survey was substantially less than an investment in on-the-ground time to cover the same area. The data showed a sprawling Maya city with dispersed public architecture connected dendritically by a road system to an epicenteral complex that once housed the ruling family and its administrative units (Chase and Chase 2001). LiDAR also proved to be exceedingly accurate at locating land modifications with low elevation, from house mounds to terracing; the DEM demonstrated the extent of the already known intensively modified landscape covered with agricultural terracing (Chase and Chase 1998) and thousands of residential groups (Chase and Chase 2004).

The Caracol LiDAR survey had profound effects on settlement pattern work within the Maya area. First, the effectiveness of LiDAR in recording ancient bare earth remains in the tropics was conclusively shown; the technology was particularly effective at Caracol because the overlying canopy had not been overly disturbed by modern activities. Second, it demonstrated that some Maya settlements could indeed be categorized as urban centers, more specifically "low density agricultural cities" (Fletcher 2009), and confirmed the large areas that some ancient Maya metropolitan areas occupied. Third, it definitively established the scale of ancient Maya terraced agriculture (at least for one site) and effectively showed a completely anthropogenic landscape. It also served to confirm the mapped settlement data that indicated that control of water was distributed among the residential groups (Chase 2012, 2016), contradicting previous assumptions that small constructed reservoirs could not sustain large populations through the dry season (e.g., Scarborough and Gallopin 1991 for Tikal) and that control of water was almost completely in the purview of the Classic Maya elite (Lucero 2006). The LiDAR data raised other questions about the size and scale of other Maya centers that lay beyond the surveyed area, as well as about the full extent of Caracol "the city" and Caracol "the polity."

In 2013, the Western Belize Archaeological Consortium worked together to obtain another 1057 km^2 of LiDAR data both east of and north of the original 2009 DEM. This new LiDAR permitted a better regional interpretation by revealing the eastern extent of the city of Caracol, as well as the extent of a series of sites in the Maya Mountains and the Belize Valley (Chase et al. 2014a, b). Before this point in time, the largest traditionally mapped settlement area was located at Calkmul, Mexico and covered some 30 km^2 (Chase and Chase 2003: 115). What these newer data demonstrated was the diversity in settlement patterns and strategies that existed within a contiguous part of the east-central Maya area. The LiDAR also showed that the Caracol settlement extended further to the east, revealing new road systems that permitted the city's easy access to key metamorphic resources that were needed elsewhere in the Maya lowlands (Chase et al. 2014a). The northern, eastern, and southern limits of the Caracol metropolitan area were identified, demonstrating that the city covered at least 200 km^2 and was fully integrated by means of a series of dendritic causeways that connected public administrative and market spaces to the site epicenter (Fig. 22.1). There is no other settlement as large and as dense as

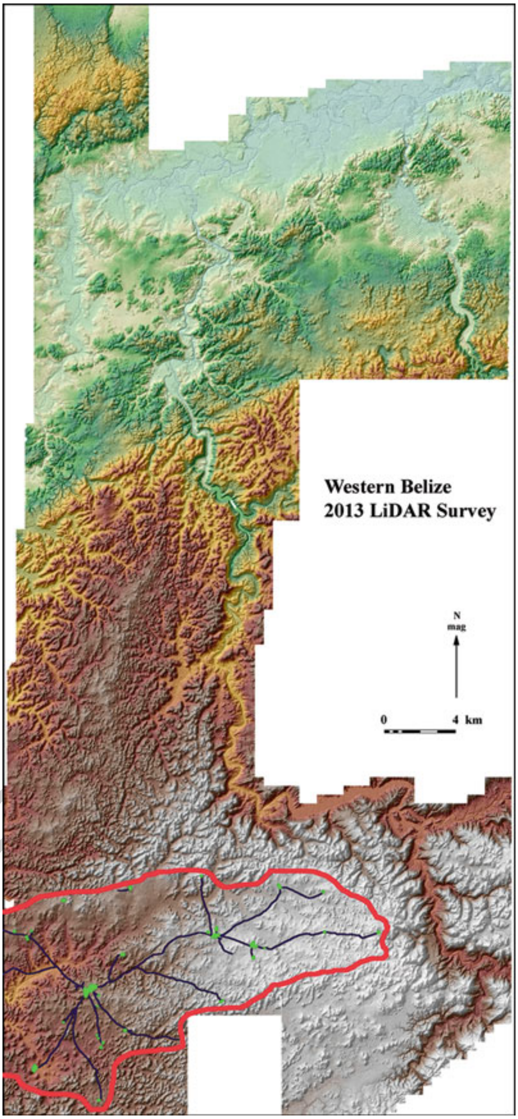

Fig. 22.1 The 2009 and 2013 digital elevation models (DEMs) combined to illustrate the area of western Belize that was covered and the approximate topography (*green* is low-lying land; *brown* and *white* are higher areas) and the extent of Caracol and its road system (outlined in *red* with roads in *blue* and public space in *green*)

Caracol within the area surveyed by LiDAR in 2013 (Figs. 22.2 and 22.3). Second-tier smaller settlements, covering a maximum spatial area of 1–5 km^2, are evident throughout the DEM and include the independent centers in the Belize Valley (Chase et al. 2014b: 8679). In general, however, the rest of the sites in the 2013 survey area are significantly smaller than Caracol.

Among the other intersite differences are the strategies that were utilized to produce the structural layout of the various centers and their agricultural adaptations. The site of Caballo mimics Caracol's use of agricultural terraces and causeways, but

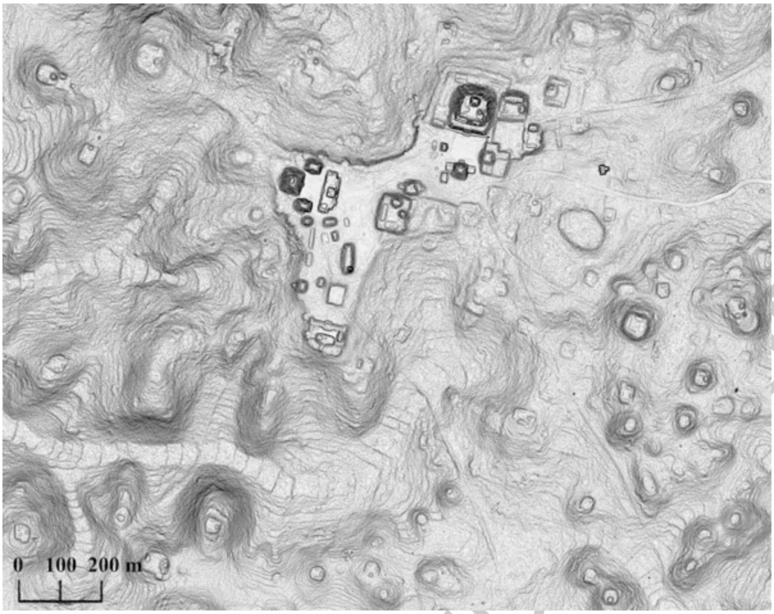

Fig. 22.2 The Caracol site epicenter, showing the public architecture, roads, residential settlement, and agricultural terracing. North is to top of page

at a smaller scale and without joining public architectural plazas together (Fig. 22.4). Minanha exhibits the use of terracing but does not use causeways (Iannone 2009). Yaxnoh uses causeways to connect small groups, but does not evince the agricultural terracing of Caracol (Chase et al. 2014b). In the Belize Valley, the site of Buena Vista does not employ agricultural terracing (Peuramaki-Brown 2014); Cahal Pech utilized a system of causeways to join outlying residential groups to the site epicenter (Cheetham 2004); and Baking Pot utilized internal causeways to unite its central public architecture (Chase et al. 2014b: 8682) and an agricultural strategy involving ditched fields that were effectively irrigated with water from the Belize River (Ebert et al. 2015). The layouts of all these centers relative to their landscapes indicates that significant variability existed not only in site sizes and populations but also within the strategies employed among Classic Period Maya communities to produce livelihoods.

LiDAR and other remote sensing technologies do not directly provide time depth. The point cloud data give an accurate portrayal of the palimpsest of features that are evident on the ground surface at the time of collection, but not their dating, although sequential events can be derived from the remote sensing data when features overlie one another or other information is available. Because of the long history of archaeological research in western Belize, time depth can be ascribed to some of the architectural constructions that are visible in the archaeological landscape. In particular, the architectural constructions constituting public space

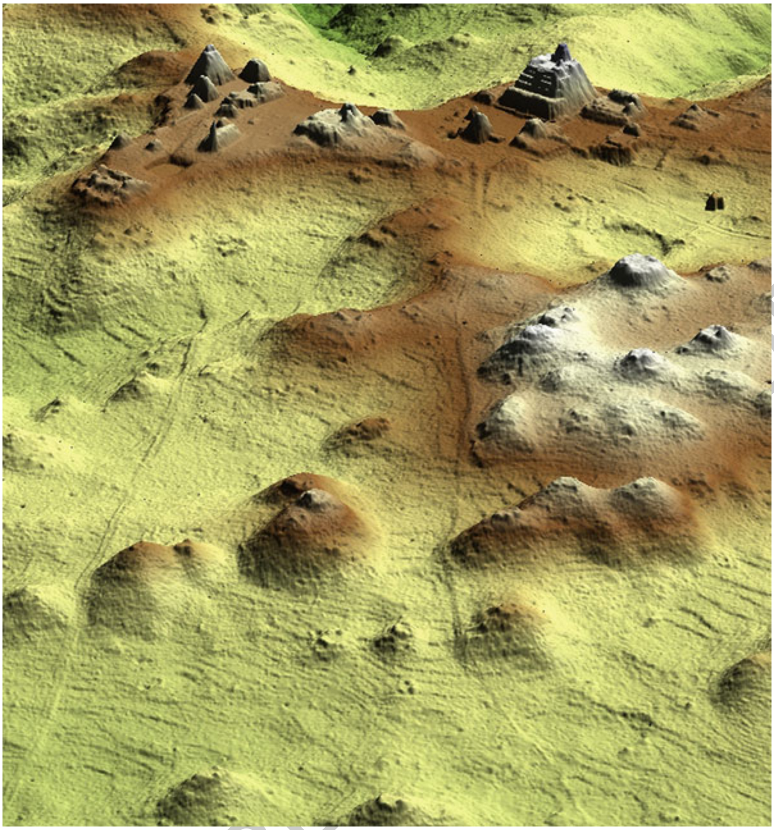

Fig. 22.3 A 2.5 D LiDAR image of the Caracol epicenter looking northwest; compare with Fig. 22.2

for initial Maya centers followed a stock plan, called an "E Group" (Freidel et al. 2016), consisting of a western pyramid and a long eastern platform usually associated with three buildings. This building assemblage is usually the initial public architecture constructed at a Maya site and remains largely unchanged through time at many centers because of ritual significance. However, far more of these E Groups were identified in the LiDAR than had been previously documented, providing clues as to the initial spacing of Maya centers in western Belize (Chase et al. 2014: 8685). Other nodes of public architecture are similarly visible in the LiDAR, and the archaeological work that has been done on many of these sites permits their constructions to be placed within a temporal framework (Garber 2004). The 2013 LiDAR campaign discerned defensive features only in two locations, at Xunantunich (Chase et al. 2014a: 216) and at El Pilar, which has now been dated to the Late Preclassic period before 250 AD (Ford 2015). Assuming a similar date for the Xunantunich feature, these data provide a glimpse into the hostile relationships among sites at the onset of the Classic Period (ca. 250 AD) that may not have been

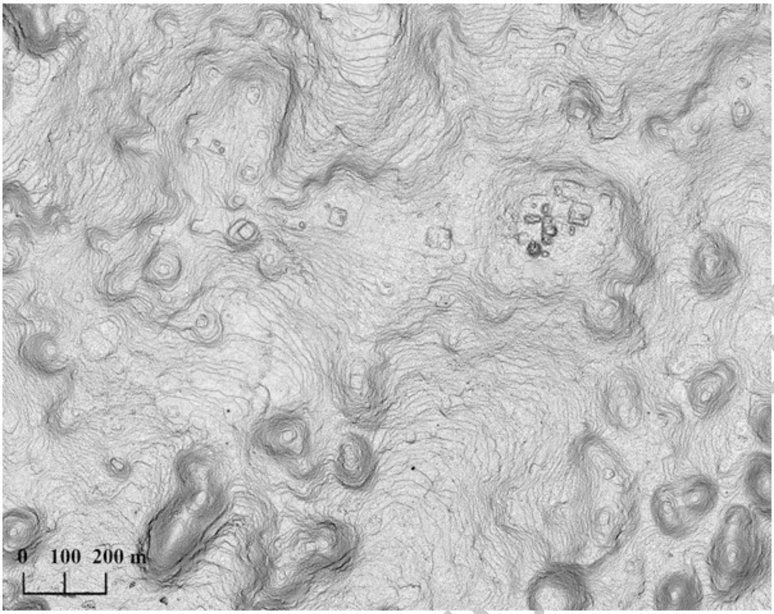

Fig. 22.4 The site of Caballo, Belize showing the public architecture and settlement enmeshed in an elaborate system of agricultural terracing. *Black dots* in mounds are looters' pits; north is to top of page

gained otherwise. It is important to note, however, that dating the archaeological features seen in the LiDAR still must be deduced from the extant archaeological data.

22.3 Growing Pains: Issues to Be Resolved

The introduction of LiDAR to settlement archaeology and landscape studies in Mesoamerica has led to a series of methodological, technical, and institutional issues that need to be addressed (Chase et al. 2016). Perhaps the most difficult issue facing practitioners of LiDAR is the variation in ground cover that characterizes the Maya area (Chase et al. 2014). Vegetation differences caused by slash-and-burn or milpa agriculture and by hurricanes also means that traditional LiDAR vegetation removal algorithms may not be effective in generating bare earth points in certain environments (Crow et al. 2007), a problem that affects a significant part of Mesoamerica (Fernandez et al. 2014). This difficulty is particularly seen in areas of milpa regrowth, in areas of heavy scrub forest such as the Northern Maya lowlands, and in areas of grass regrowth as in the Belize Valley. This issue caught the attention of researchers at the site of Uxbenka in southern Belize, where Keith

Prufer and his colleagues (2015: 9) were able to demonstrate the devastating effects that slow regrowth after milpa farming and hurricanes had on the ability to detect ground features; the density of vegetation leads to a significant reduction in ground returns that can linger for more than a decade. LiDAR point clouds are quite clean beneath old growth forest, which is why the initial Caracol landscape recorded by LiDAR was so clear. However, in areas of clearing and regrowth, the point clouds are affected, making interpretation more difficult.

Archaeologists are generally not computer scientists and often cannot alter algorithms or reclassify the LAS point cloud data to make different interpretations. Thus, for Mesoamerican archaeology, the interpretation of LiDAR data is fed through off-the-shelf programs such as ARC-GIS and Surfer to generate digital elevation models (DEMs) that are used for analysis. Even the basic processing of point cloud data by entities such as NCALM uses off-the-shelf software to clean and assemble bare earth DEMs, although they also can make modifications to the programs being utilized. Collaboration between archaeologists and physicists/engineers means that a better product is achieved. For instance, when occupation at the site of Lower Dover, Belize could not be easily identified in the initial DEM produced for the 2013 Western Belize LiDAR Survey, the data were reclassified by NCALM in such a way as to more accurately remove the vegetation so that the mounded remains could be more easily discerned. In the northern lowlands, the topography is composed of natural hillocks that mimic constructed mounds; when combined with modern landscape disturbance and scrub vegetation, it can be very difficult to discern already mapped house mounds in some cases. Again, reworking the algorithms resolved much of this problem and brought the larger mounds into sharper relief. In some cases, however, identification of the less elevated smaller structures still remains problematic, but eventually technology and computer programs or algorithms will resolve their visualization as well.

Ultimately, we will benefit from best practices and standardization for the density and kinds of aerial LiDAR data produced, although at the same time realizing that this cannot be a strict end goal because "ALS observations can be highly customized to achieve specific levels of performance" (Fernandez-Diaz 2014: 9995). Differences in how airborne LiDAR is collected (elevation, flight path, flight speed, pulse type, pulse wavelength, scan frequency, scan angle, etc.) have implications for the quality and kinds of point clouds that result (Fernandez-Diaz et al. 2014). Rosenswig and his colleagues (2014: 2) argue that the bare earth returns are what really count, and for archaeological uses, these returns are often the most essential. For the Izapa data, flown by an independent contractor, he argues that a density of 3.1 points/km^2 provides a similar density of ground points to Caracol's 20 points/km^2 in that both data sets are above 1 point/km^2; a subsequent publication argued that a ground point density of 0.7 (with a range from 0.0 to 6.9) provides a similar level of mound identification (Rosenswig et al. 2014: 7). Although both the vegetation present and the size of archaeological features of interest will ultimately determine both the spatial resolution of DEMs and number of ground points required to achieve that resolution, it should be kept in mind that any DEM cell lacking a ground return is often assigned one algorithmically through inverse distance weighting, spline interpolation, or kriging (often the latter). Thus, these points have their values selected to mimic the surrounding ground returns. By their nature, built archaeological features often fail to mimic the underlying topography and, as such, any LiDAR campaign should endeavor to record sufficient points to minimize (and preferably eliminate) terrain cells with no ground returns. Essentially, all the mitigating factors involved in the collection and production of the LiDAR data must be considered (Fernandez-Diaz et al. 2014: 9962, 9967). As a final note, other uses of LiDAR data, in particular for three-dimensional (3D) modeling and algorithmic manipulation of raw LAS files, greatly benefit from higher densities of bare earth returns, so there may be no absolute answer to a minimum desired point density.

A final issue to be resolved is how LiDAR data should be stored and distributed. Funding agencies and some LiDAR providers have suggested that the collected data, or some portion of it, should be made publically available after a short period of time; however, this expectation may be at odds with countries in Mesoamerica that have experienced significant loss of cultural heritage from looting and site destruction. LiDAR can serve as a roadmap for many Maya sites, and the public posting of these maps with their geolocations could act to easily lead looters directly to their quarry. Thus, U.S. mandates regarding data management and accessibility may be seen as inappropriate for the countries that house Maya sites. Belize instituted a policy that prohibits raw LiDAR data from being publically distributed and asks that published LiDAR images not provide geo-coordinates (Chase et al. 2014: 218). Although discussions have taken place and concerns have been raised, neither Guatemala nor Mexico currently has policies in place regarding the accessibility and distribution of LiDAR data. As our technology improves and the cost decreases, all this may become moot. Google Earth already provides free satellite images for most of the world to most internet users. Eventually, higher-resolution data, and perhaps even LiDAR, will be collected from space, and it may be that the companies that own the satellites or requisition the surveys will also deem that they can distribute the data as they see fit, meaning that there will not even be a nominal role for nations in terms of regulating and approving their own landscape, let alone airspace. These are uncharted concerns that need to be addressed by the research communities and affected governments before better technology with more power and resolution becomes available.

22.4 Final Remarks

LiDAR has proven to be an extremely useful technology for detecting Maya ruins. It can recover information on a scale much larger than traditional survey (Chase et al. 2014a). As indicated by the work at Caracol, Belize, LiDAR is extremely effective at revealing remains below heavy forest cover and can be used to differentiate human modifications on the landscape even in areas with extremely hilly terrain. By revealing remains at both a large scale and low elevation, it is possible to make interpretations about the ancient landscapes that might not otherwise have been possible. LiDAR is not inexpensive, but when contextualized in terms of the sizeable landscapes that are revealed and the time involved, the technology is cost efficient. However, on-the-ground mapping is still necessary for ground-truthing and for recording archaeological features with little or no elevation, and additional investigation is necessary to provide dates and functions for archaeological remains.

In some cases, LiDAR documents what had been expected but could not be proved with sampling, such as the extent of terracing at Caracol (Chase and Chase 1998, 2014; Chase et al. 2011b). LiDAR effectively shows how much of a landscape was modified, revealing not only the size of a settlement area but also its terraced agricultural fields and reservoirs. The scale of agricultural terracing and control of water flow over the landscape recorded in the Caracol LiDAR rivals the complexity of ancient agricultural features found in Southeast Asia, South America, and other parts of the world (Chase and Weishampel 2016; Chase et al. 2011). The 2013 campaign also revealed that there is substantial variation in the size of ancient Maya sites; they range in scale from small centers covering less than 1 km^2 (village) to massive cities covering more than 200 km^2. Although the size of ancient Maya sites could be only guessed at in the past, LiDAR provides a complete landscape that proves the scale and extent of these ancient settlements.

As more and more landscape areas are recorded with LiDAR in Mexico, Belize, Guatemala, Honduras, and El Salvador, researchers will continue to gain a much fuller understanding of and appreciation for the ancient peoples who once occupied these areas. The technology has resulted in the recognition that the ancient Maya had very large complex societies with the capacity for sustainability through the creation of completely anthropogenic environments. LiDAR is useful not only for recording ancient Maya cities and landscapes but also for helping to manage the cultural heritage and tourism of these locations. It is important that the recording of these landscapes with LiDAR continue and that we obtain as detailed and complete a record of the Maya area as is possible before modern encroachment destroys much of the ancient land use patterns that can still be seen in the recovered point clouds.

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