Integrating Quantitative Lidar Analysis and Settlement Survey in the Belize River Valley

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Light detection and ranging (lidar) data provide an invaluable tool for the documentation and visualization of complete archaeological settlement systems in heavily vegetated environments. Airborne lidar is an active remote sensing system in which pulses of laser energy are discharged

ABSTRACT

Accurate and high-resolution airborne light detection and ranging (lidar) data have become increasingly important for the discovery and visualization of complete archaeological settlement systems in the Maya Lowlands. We present the results of systematic quantitative analysis of lidar data and ground verification for the major centers of Cahal Pech, Baking Pot, and Lower Dover in the Belize Valley. The Belize Valley is characterized by high density populations living in growing modern towns and villages, and by large-scale agricultural production. This urban environment presents a challenge to reconnaissance efforts since modern construction and agricultural activities have destroyed ancient ruins and created new vegetation patterns. Lidar data was analyzed within a GIS using the Topographic Position Index (TPI) to identify the location of possible archaeological remains. Small-scale, site-level TPI analysis helped identify more detailed archaeological features including small house mounds, terraces, and ditches. Results indicate that lidar data recorded for areas with dense vegetation (e.g., low brush and secondary regrowth) may be less reliable for identification of archaeological remains. The quantitative and qualitative differences between spatial analyses and pedestrian survey results among land cover types indicate that traditional settlement pattern study methods, including pedestrian survey, remain vital to ground-truthing all types of spatial data.

La información precisa y de alta información obtenida a través de la tecnología de detección y localización por láser aerotransportado (lidar por sus siglas en inglés) ha llegado a ser cada vez más importante para el descubrimiento y visualización de sistemas de asentamiento arqueológicos completos en las tierras bajas mayas. En este trabajo, presentamos los resultados del análisis cuantitativo y sistemático de datos obtenidos mediante lidar y su verificación terrestre en los sitios de Cahal Pech, Baking Pot y Lower Dower, localizados en el Valle del Río Belice. En comparación con otras regiones documentadas mediante la prospección aerotransportada lidar, el Valle de Belice se caracteriza por tener una alta densidad de población viviendo en los cada vez más grandes pueblos y aldeas modernos, así como por una producción agrícola de gran escala. Este ambiente urbano ha presentado un reto para los esfuerzos de reconocimiento ya que las construcciones modernas y las actividades agrícolas han destruido las ruinas antiguas y han creado nuevos patrones de vegetación (por ejemplo, campos agrícolas, rebrote denso). Los datos lidar fueron analizados en un Sistema de Información Geográfica (GIS por sus siglas en inglés) usando el Índice de Posición Topográfico (TPI por sus siglas en inglés) para identificar la ubicación de posibles vestigios arqueológicos. El análisis TPI de pequeña escala y a nivel de sitio permite la identificación de rasgos arqueológicos más detallados incluyendo pequeños montículos domésticos, terrazas y zanjas. Posibles vestigios arqueológicos identificados mediante los análisis TPI fueron comparados con prospección arqueológica terrestre. Los resultados indican que la información lidar registrada en áreas con vegetación densa puede ser menos confiable para la identificación de vestigios arqueológicos en comparación con la registrada en espacios más abiertos. Las diferencias cuantitativas y cualitativas entre los resultados de las prospecciones arqueológicas terrestre y TPI y entre los tipos de cobertura del suelo indica que los métodos tradicionales para estudiar los patrones de asentamiento, tales como la prospección terrestre, permanecen siendo vitales para verificar todos los tipos de datos espaciales.

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from an aircraft towards the ground surface. Laser pulses "penetrate" vegetation to record three-dimensional spatial data, which can be used to model the underlying terrain and to locate possible archaeological features on the ground surface (Crutchley and Crow 2010; Devereux et al. 2005; Doneus et al. 2008). While lidar data have been used in archaeological research for over a decade to model ancient landscapes and settlement systems, it is only more recently that archaeologists working in tropical environments worldwide have intensively integrated the technology into their research programs (e.g., Hawaii, Ladefoged et al. 2011; McCoy et al. 2011; Southeast Asia, Evans et al. 2013). Archaeological applications of lidar are especially active in the tropical lowlands of Mesoamerica and have allowed for the rapid acquisition of spatial data not previously possible from pedestrian survey in areas of dense vegetation (Figure 1). Lidar mapping has been used to document monumental architecture, residential mounds, and agricultural terraces at the Mexican sites of Angamuco (Fisher et al. 2011) and Izapa (Rosenswig et al. 2013, 2014), and the lowland Maya sites of Caracol (Chase et al. 2011, 2014), Mayapan (Hare et al. 2014), Calakmul (Reese-Taylor et al. 2014), El Pilar (Ford 2014; Pingle et al. 2015), in the Belize River Valley (Awe et al. 2015) and nearby Vaca Plateau area (Macrae and Iannone 2015), and in northern Yucatan (Hutson 2015).

Visual analyses of lidar data to document previously unknown archaeological and landscape features have received the most attention in Mesoamerican studies. Hillshade (i.e., "bare-earth") models or other techniques for visually rendering lidar data (e.g., color-classified rasters, Hutson 2015; "bonemapping," Pingle et al. 2015) using Geographic Information System (GIS) are used to visually highlight features with low topographic relief that may represent prehistoric features. While visual inspection and interpretation of modeled lidar data provide relatively detailed two-dimensional perspectives of archaeological landscapes, qualitative analyses offer only general size and locational data. Furthermore, ground-truthing of lidar mapping in many regions of lowland Mesoamerica has revealed that the accuracy of ground surface models can be affected by the topography, vegetation cover that can obscure more subtle features on the ground surface, and the types of archaeological features present (Challis et al. 2011; Doneus et al. 2008; Hutson 2015; Rosenswig et al. 2014; Prufer et al. 2015).

More recently, archaeologists have begun to use lidar as a powerful tool that combines quantitative and qualitative visual analyses to systematically identify and measure possible archaeological features in three dimensions (Awe et al. 2015; Moyes and Montgomery 2015; Pingel et al. 2015; Prufer et al. 2015; Rosenswig et al. 2014). We focus our lidar analysis on documenting the settlement systems around the ancient Maya sites of Cahal Pech, Baking Pot, and Lower Dover located in the upper Belize River Valley in the Cayo District of west-central Belize. Research at these sites has been ongoing since 1988 under the auspices of the Belize Valley Archaeological Reconnaissance (BVAR) Project. Compared to other regions in Mesoamerica with active lidar research programs, such as at Caracol in the Chiquibul Forest Reserve (Chase et al. 2011, 2012), the Calakmul Biosphere Reserve (Reese-Taylor et al. 2014), and El Pilar located in an archaeological forest reserve (Ford 2014; Pingel et al. 2015), the upper Belize River Valley possesses high-density populations living in an increasing number of modern towns and villages, as well as large-scale agricultural infrastructure that is continually growing. This urban environment challenges traditional archaeological survey methods, since modern activities have destroyed ancient ruins, and agricultural development is creating new vegetation patterns. To address these challenges, the BVAR project is integrating visual and quantitative spatial analyses of lidar data within the program of settlement survey to understand the extent and nature of prehistoric settlements in the upper Belize River Valley.

In this paper, we present a method for systematic quantitative analysis of lidar data using the Topographic Position Index (TPI). TPI analysis has been applied to landscape-scale spatial research questions in several disciplines, including geography and geology (Liu et al. 2009; Jones et al. 2000; McGarigal et al. 2009; Mulder et al. 2011; Schmidt and Hewit 2004; Tagil and Jenness 2008); landscape, forest, and animal ecology (Clark et al. 2012; Coulon et al. 2008; de la Giroday et al. 2011; Dickson and Beier 2007; Fei et al. 2007; Lacki et al. 2009; Pinard et al. 2012; Podchong et al. 2009; Squires et al. 2008); and climatology (Bunn et al. 2011; Etienne et al. 2010). The method has seen less use in archaeology, although some archaeologists have applied TPI analyses to spatial datasets to understand large-scale regional settlement patterns in relationship to landform classes (Berking et al. 2010; De Reu et al. 2013; Patterson 2008). TPI analyses can also help researchers to examine these same phenomena at smaller site-level scales using high-resolution lidar data (Awe et al. 2015; Ebert 2015; Ebert and Awe 2014, Ebert et al. 2016b). We combine TPI spatial analyses with visual interpretation techniques to determine the exact location of archaeological features, estimate their surface area and volume, and determine the nature of local settlement systems at Cahal Pech, Baking Pot, and Lower Dover.

TPI analyses were conducted on spatial data derived from lidar for a 124.2 km^2 area of the upper Belize River Valley composing the BVAR study area. We compare our TPI results to previous settlement pattern data recorded by BVAR pedestrian survey efforts. At Baking Pot, near total coverage block survey provides a comparison to gauge the precision and accuracy computer generated results. At Cahal Pech, TPI analyses were used to

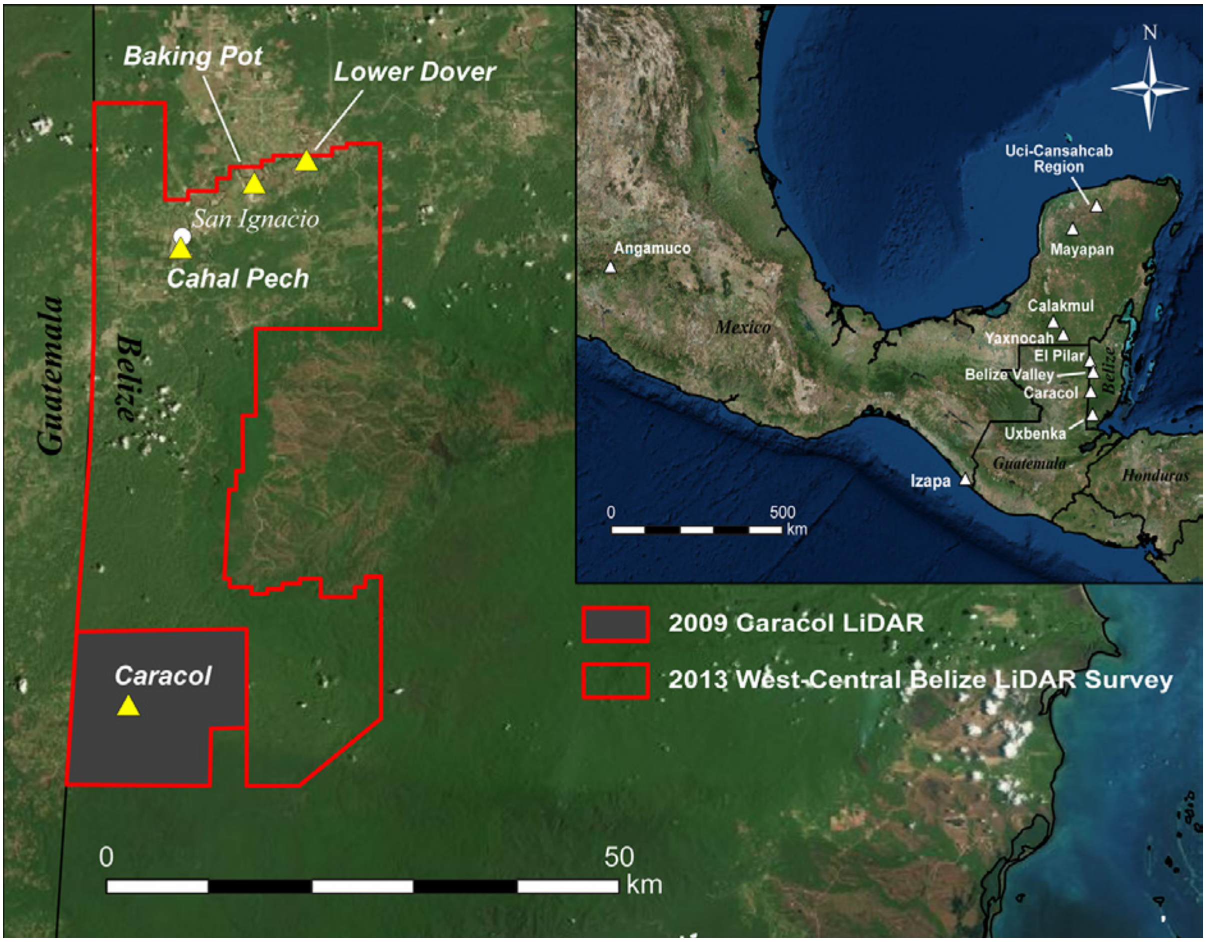

FIGURE 1. Map of West-Central Belize Lidar Survey area with the location of major Mesoamerican sites mentioned in text.

record possible archaeological features in previously un-surveyed areas for more targeted field reconnaissance and mapping. During the 2014 and 2015 BVAR field seasons, possible prehistoric features identified through TPI analyses at Cahal Pech were verified through pedestrian ground-truthing survey (Awe et al. 2015). When compared between areas with different land cover types, our results indicate that the analysis of lidar data recorded in heavily vegetated (e.g., low bush, secondary regrowth) areas may be less consistent in accurately identifying archaeological remains, as opposed to more open landscapes such as agricultural fields and pasture lands. The quantitative and qualitative differences between the TPI and pedestrian survey results, and among land cover types, indicate that traditional settlement pattern study methods, such as pedestrian survey, remain vital to ground-truthing all types of spatial data.

SETTLEMENT SURVEY IN THE UPPER BELIZE RIVER VALLEY

The upper Belize River Valley encompasses an area of approximately 125 km^2 extending about 30 km eastward and downriver from the ancient Maya site of Xunantunich and terminating at the site of Blackman Eddy (Figure 2). Geologically, the region is characterized by a series of limestone escarpments that border the alluvial bottomlands along the Belize River and its tributaries. The region has a long history of settlement archaeology, with the first settlement pattern studies in the Maya lowlands conducted by Gordon Willey and his colleagues in the 1950s (Willey et al. 1965). As part of their research program, Willey and his colleagues (1965) addressed questions of size, distribution, and configuration of settlements located around major centers in region. They proposed a three-tiered model of organization with residential house mounds at the smallest scale, to mid-level small *plazuela* groups, and finally large major polities (Willey et al. 1965). In the following decades, several other archaeological projects in the Belize River Valley conducted settlement research as a central component of their investigations (Awe 1992; Conlon 1993, 1995; Connell 2000; Ehret 1995; Fedick 1994; Ford 1990; Hoggarth 2012; Neff et al. 1995; Peuramaki-Brown 2012; Wyatt and Kalosky 2003; Yaeger 2000; Yaeger et al. 2011). The extensive amount of research in this region has made significant contributions to our understanding of ancient Maya settlement and political organization at many Belize River Valley sites (Awe 1992; Awe and Helmke 2005; Awe et al. 2014; Ball and Taschek 1991; Graham et al. 1989; LeCount et al. 2002; Lohse et al. 2006; Yaeger 2003).

To address the challenges posed by modern development in the Belize River Valley, BVAR has employed a block survey program

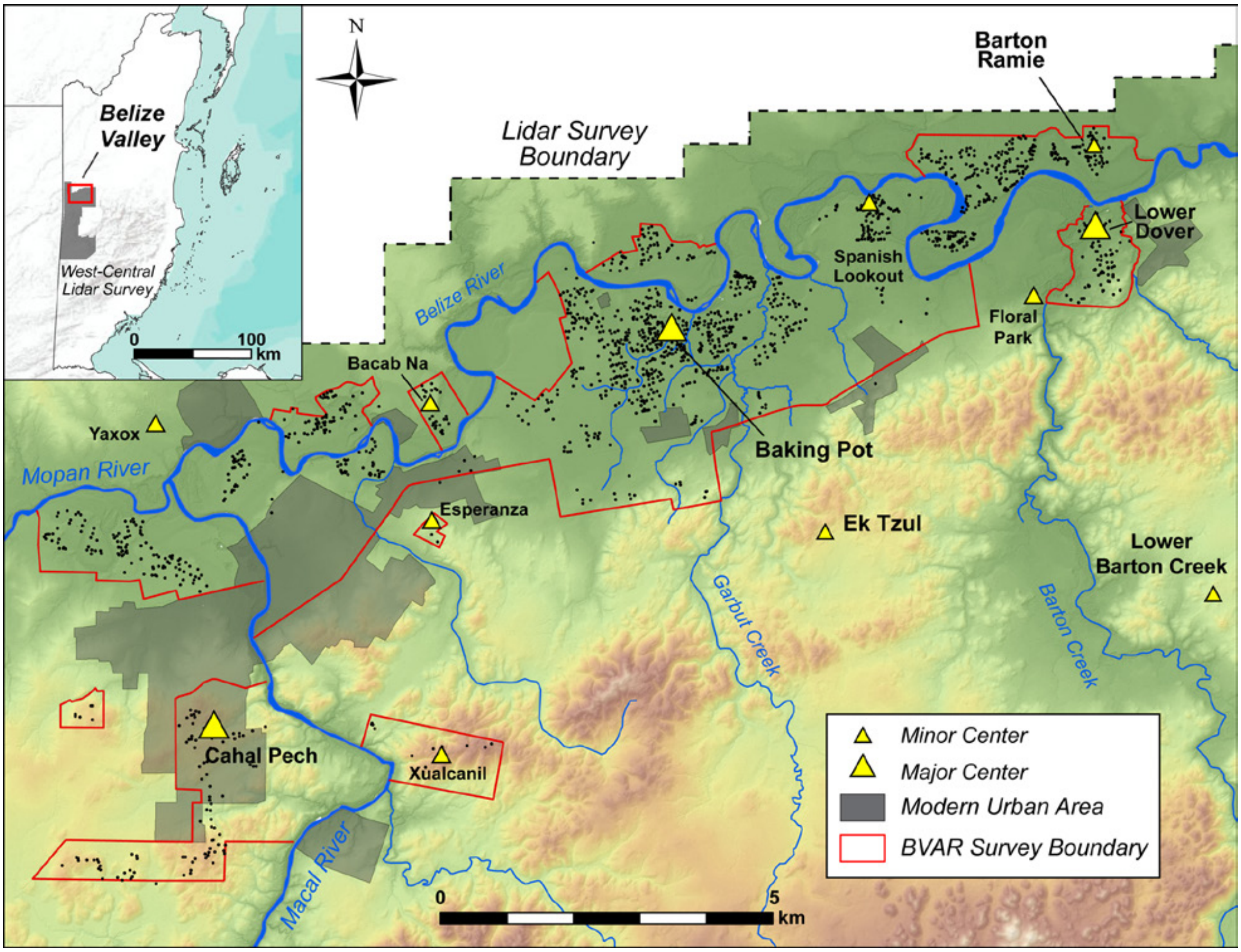

FIGURE 2. Map of lidar survey in the Belize Valley, with the Belize Valley Archaeological Reconnaissance (BVAR) Project regional settlement survey (1988–2015) and Barton Ramie survey (Willey et al. 1965) data. Inset shows extent of the West-Central Belize Lidar Survey (after Chase et al. 2014).

across the study area, which has allowed for the identification of a range of settlement scales above the level of house groups (Hoggarth et al. 2008). The long-term goal of current BVAR settlement research is to connect the Cahal Pech, Baking Pot, and Lower Dover survey areas to understand how settlement systems in the region varied between sites and across time and space. The Cahal Pech monumental site core is situated on top of a natural hill above the alluvial plain of the Belize River Valley, approximately 2 km south of the confluence of the Macal and Mopan Rivers within the modern town of San Ignacio. Initial settlement survey at Cahal Pech was undertaken between 1988 and 1992 and focused on documenting residential settlements immediately south of the site core that were threatened by the construction of the growing residential neighborhoods of San Ignacio (Awe 1992; Awe and Brisbin 1993). Between 2011 and 2014, settlement survey was extended north, further south, and west of the site core to document a range of settlements, from single house mounds to large house groups composed of five or more structures (Dorenbush 2013; Ebert 2015). Over 140 house groups within a 29-km^2 area have been documented around the Cahal Pech site core, most of which possess evidence for Late Classic (A.D. 500–800) occupation (Awe 1992; Awe and Brisbin 1993; Dorenbush 2013; Ebert 2015; Ebert and Awe 2014). Many of the larger groups were established by the Late Preclassic period (ca. 300 B.C.), with the settlement systems becoming increasingly stratified and complex during the Late Classic (Ebert et al. 2016a). There is limited evidence for occupation within the settlement during the Terminal Classic period (ca. A.D. 800–900), perhaps indicating that the political "collapse" of Cahal Pech between A.D. 850–900 may also have impacted residential groups associated with the site (Ebert et al. 2016a).

The site of Baking Pot is located approximately 10 km east of San Ignacio, on the southern bank of the Belize River. The area around the site has been heavily impacted by agricultural activity and cattle ranching over the last 50 years. While agricultural infrastructure has threatened, and in some cases destroyed, archaeological resources in the area, a great expanse of the residential settlement surrounding Baking Pot has been exposed in plow zones and pasture lands. Settlement research at Baking Pot was first undertaken by BVAR in 1992, expanding previous survey by Willey and his colleagues (Willey et al. 1965) around the site core. This early BVAR research was also focused on documenting residential settlement to the east and southwest of the site's epicenter (Conlon 1993, 1995, 1997; Conlon and Ehret 2000, 2001). The results of radiocarbon dating indicate that

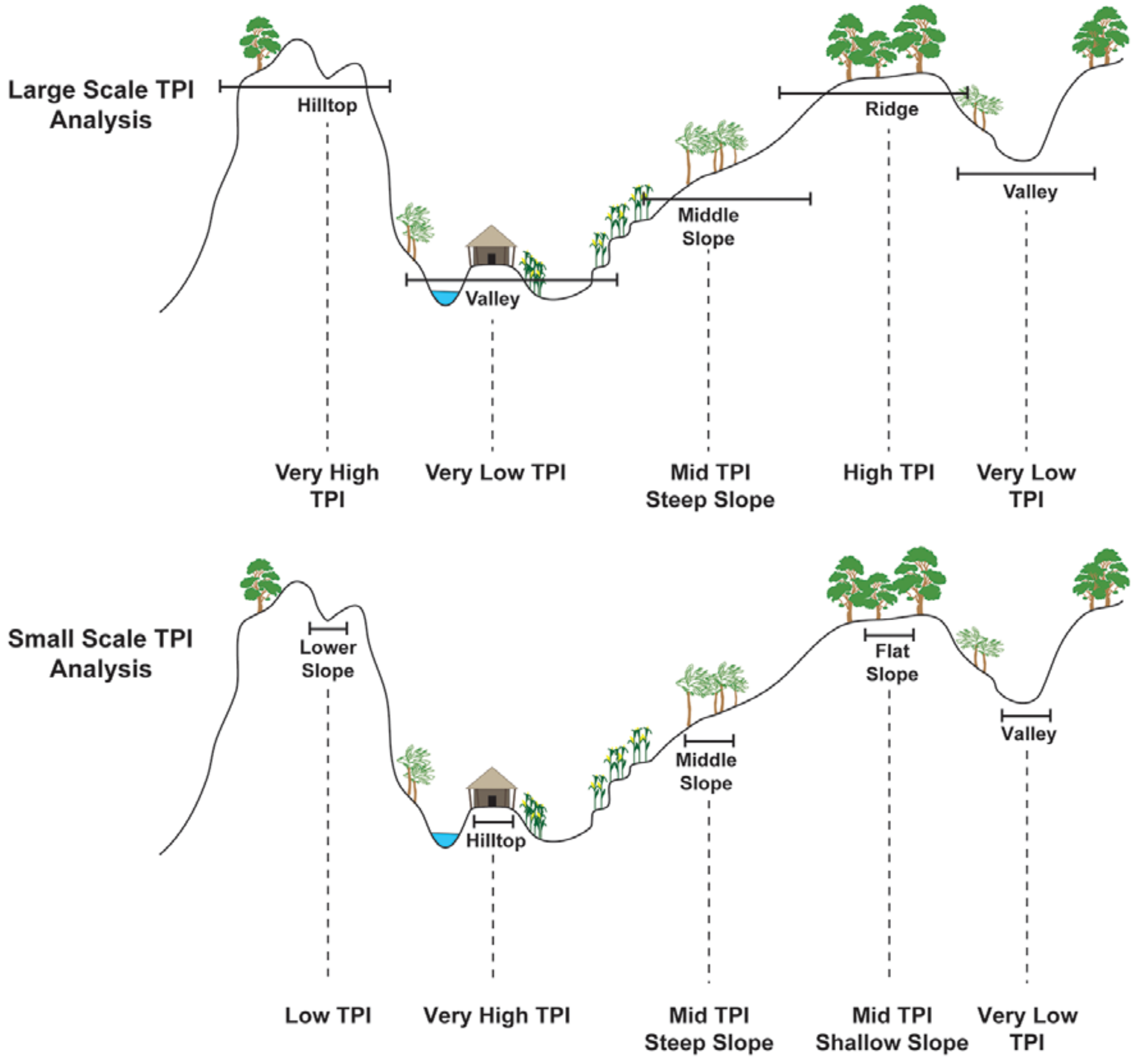

FIGURE 3. Comparison of expected topographic position index (TPI) values based on large-scale (top) and small-scale (bottom) analyses.

the Baking Pot site core was occupied as early as the Middle Preclassic period, between 400–200 cal B.C., and construction in Group A of the site core was initiated by the Late Preclassic period (ca. 100 B.C.–A.D. 250; Hoggarth et al. 2014). Monumental construction is first documented during the Early Classic period (ca. A.D. 250–500), with a peak in construction between A.D. 600–750 during the Late Classic period corresponding with the growth of population around the site. The second phase of settlement research began in 2007 and was implemented to investigate changes in domestic and settlement organization around the site center through time (Hoggarth et al. 2010). The second phase documented settlements to the southwest of the site core (Hoggarth et al. 2010), with some additional survey in this area around an extensive ditch system at the Bedran Group completed in 2015 (Ebert et al. 2015, 2016b).

Settlement research at Lower Dover has been less extensive and is ongoing. The monumental site core and settlement were first explored and mapped by BVAR researchers beginning in 2010 (Guerra 2011). The site is located on the southern bank of the Belize River directly across from Barton Ramie and approximately 6 km downriver from Baking Pot, and has not been heavily impacted by modern development compared to Cahal Pech and Baking Pot. Survey efforts at Lower Dover have focused on recording settlement located between Upper and Lower Barton Creeks, immediately south of the monumental epicenter (Guerra 2011; Guerra et al. 2015; Petrozza 2015; Petrozza and Awe 2014; Petrozza and Biggie 2014). Initial reconnaissance at the site suggested that over 120 house mounds are present within the Lower Dover hinterlands (Guerra 2011), with 60 mounds and surface scatters verified through block survey and with the aid of visual analyses of hillshade model derived from lidar data (Petrozza 2015). While there is some evidence for Late Early Classic (ca. cal A.D. 485–650) occupation within the Lower Dover site core (Guerra et al. 2015), the majority of residential mounds recorded within the Lower Dover settlement date between A.D. 700–900 during the Late Classic period (Spanish Lookout ceramic complex) and are usually relatively small isolated structures composed of modified bedrock (Petrozza 2015:70).

TABLE 1. Classification of Topographic Position Based on Standard Deviations from the Elevation (after Weiss 2001).

Class	Description	Breakpoints
1	Hilltop	TPI > 1 St. dev.
2	Upper slope	.5 St. dev. < TPI ≤ 1 St. dev.
3	Middle slope	-.5 St. dev. < TPI < .5 St. dev., Slope > 5°
4	Flat slope	-.5 St. dev. < TPI < .5 St. dev., Slope ≤ 5°
5	Lower slope	-1 St. dev. < TPI ≤ -.5 St. dev.
6	Valley	TPI ≤ -1 St. dev.

Accurate and high-resolution airborne lidar data have recently been integrated into the BVAR survey program to help understand the organization of ancient Maya settlement in the Belize River Valley (Awe et al. 2015; Ebert 2015; Ebert et al. 2016b). Airborne lidar survey for the BVAR study area in the Belize River Valley was conducted in 2013 as part of the West-Central Belize Lidar Survey flown by the National Center for Airborne Laser Mapping (NCALM). The West-Central survey supplements the 2009 Caracol survey area, covering a total of 1,057 km^2 (see Chase et al. 2014 for a detailed description the West-Central Lidar Survey methods and data processing).

METHODS

For this study, we used the Topographic Position Index (TPI) to identify archaeological features (referred to as "possible mounds") at the sites of Cahal Pech, Baking Pot, and Lower Dover. We chose TPI analysis because it is a simple, repeatable method that is easily performed on spatial data within existing GIS databases. TPI analysis produces a raster, or a spatial data model composed of an array of equally sized cells, with cell values reflecting the difference between the elevations in a particular cell and the average elevation of cells within a specified search radius (Jenness 2006; Weiss 2001). Positive TPI values indicate that the cell is higher and steeper on average than neighboring cells, and significantly high values suggest that the cell represents a high point within a specified search radius (i.e., hilltop). Cells with negative TPI values are located in areas with lower elevation and less sloping (i.e., a valley).

TPI analyses can be conducted at different scales, depending upon the research questions being addressed. Scale is determined by the selected search radius size, which defines the number of cells considered in the calculations (Figure 3; Weiss 2001). Large-scale, regional TPI analyses can be used to identify major landform types across a region (e.g., canyons, ridge lines). Small-scale TPI analysis can also be applied to more locally defined spatial datasets in order to identify detailed topographic features (Jenness 2006). Small-scale TPI studies are especially applicable to archaeological settlement studies since possible mounds may be represented by higher TPI values within localized areas (Awe et al. 2015).

Pre-processed lidar point cloud data (see Chase et al. 2014 for data processing methods) were analyzed using the LAS (i.e., lidar data exchange file) data set tools in ArcGIS 10.3. A high-resolution (1 m) digital terrain model (DTM) for the study area was created from first and second lidar ground return points. Analyses were performed using an open access TPI extension for ArcGIS v. 9.3-10.x (Jessness 2006). An annular (doughnut-shaped) search area was used to classify slope position within 1 km^2 sub-sample blocks, where cells within 2 m and 15 m from the sample points were considered in TPI calculations. These search parameters were based upon the observation that residential architectural groups at Cahal Pech (Ebert 2015) and Baking Pot (Jobbová 2009) are an average distance of 15 m from one another. The search neighborhood thus can identify variations of topography within each sample block, including areas with high TPI values and elevations within and between residential mound groups.

TPI rasters were classified based on standard deviations from the elevation, reflecting the variability of elevation within each sample block (Table 1; see also Weiss 2000). Cells with the highest values represented "possible mounds," or features on the ground surface that resembled archaeological features (Awe et al. 2015), and were exported as individual shapefiles for additional quantitative analyses within ArcGIS. Area, volume, and elevation for each shapefile were calculated using the several tools in the ArcGIS 3D Analyst toolbox. Area was derived using the "Interpolate Shape" tool, which converted 2D polygon shapefiles into 3D polygon features by interpolating z-values for input features based on the DTM derived from the lidar point cloud. The "Add Z Information" tool was used to calculate the maximum, minimum, and average elevation for each possible mound. Volume was derived using the "Polygon Volume" tool and represents the area between the DTM surface and the average elevation of the polygon features. In order to produce a conservative estimate of the number of mounds in the study area, possible mounds with volumes less than 8 m^3 (Ashmore 1981) or surface areas less than 25 m^2 (Yaeger 2003) were eliminated from the sample, since they are likely too small to have been residences. These smaller features identified by TPI may represent non-residential architecture, including field houses, kitchens, and other ancillary structures. Alternatively, they may be the result of modern bioturbation (e.g., dirt pulled up by tree fall, bull-dozed areas) or locations of lower-resolution within the lidar point cloud (Ebert 2015; Ebert and Awe 2014; see also Hutson 2015).

The possible mounds were also visually verified against the color-classified TPI rasters (Figure 4A). Based on a comparison of six different lidar visualization methods, Hutson (2015) suggests that color-classified rasters provide one of the most reliable methods for the identification of archaeological features. We

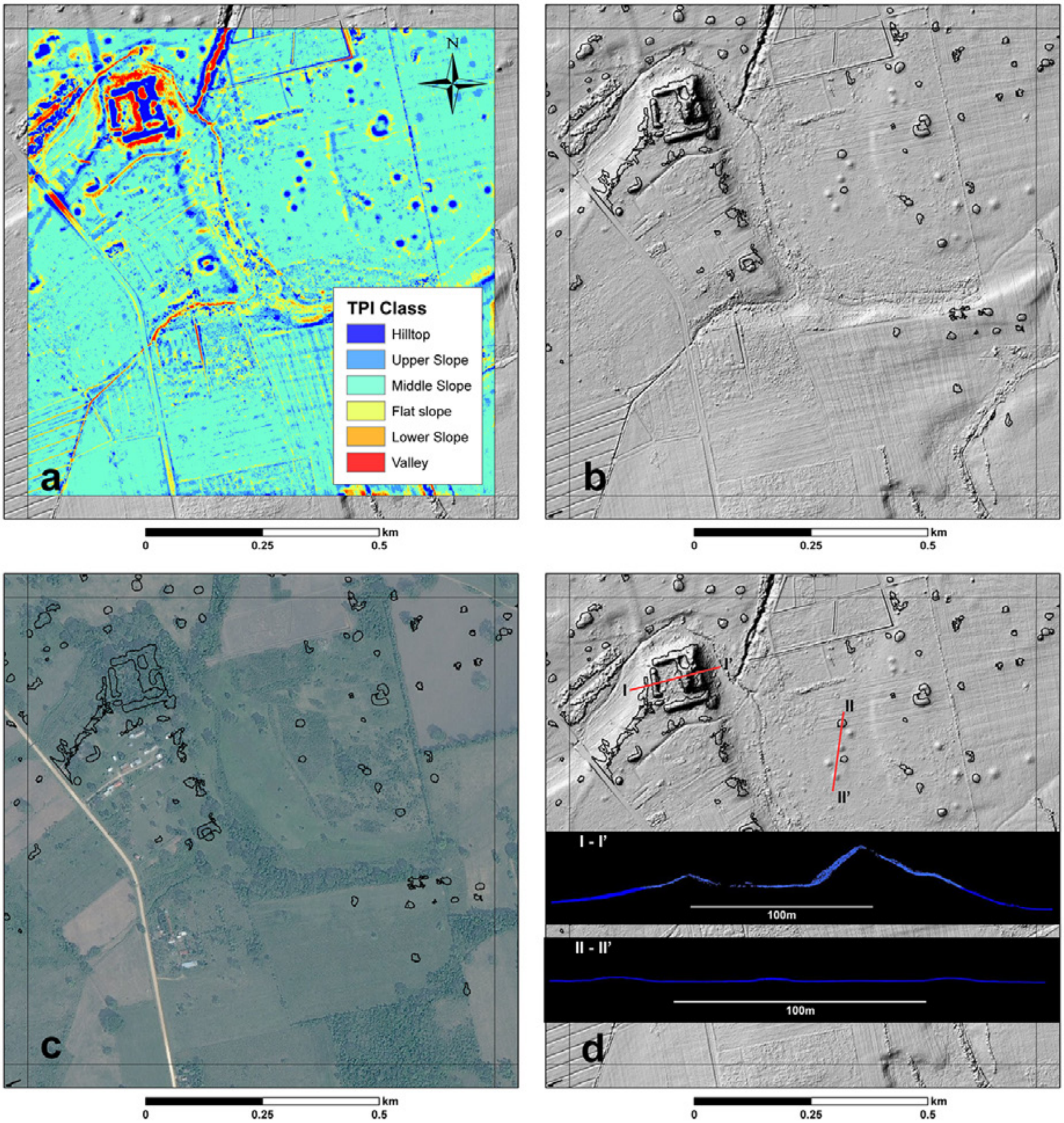

FIGURE 4. Example 1 km² sub-sample analysis block around Baking Pot Group B: (a) topographic position index (TPI) raster by color-classified standard deviations corresponding with Table 1; (b) hillshade model derived from lidar digital terrain (DTM) with possible mounds identified by TPI highlighted; (c) possible mounds compared to Landsat 8 satellite imagery capture December 16, 2014; (d) profiles of monumental architecture in Group B (I-I') and residential mounds (II-II').

also used several other visual techniques to eliminate modern features, such as houses, and natural features, including tree growth/falls, which may have been misidentified as possible mounds. This included systematic visual inspect of a hillshade model produced from lidar data for the Belize Valley (Figure 4B); visual inspection of Landsat 8 satellite imagery captured on December 16, 2014 (Figure 4C); and producing profile views of features identified as possible mounds using the LAS extension tools in ArcGIS (Figure 4D).

RESULTS

Regional Topographic Position Index Analysis Results

For the complete study area around the sites of Cahal Pech, Baking Pot, and Lower Dover, our TPI analyses identified a total of 1,742 possible mounds, not including features associated with the monumental site cores of those major polities (Figure 5). Table 2 provides average metrics described above the

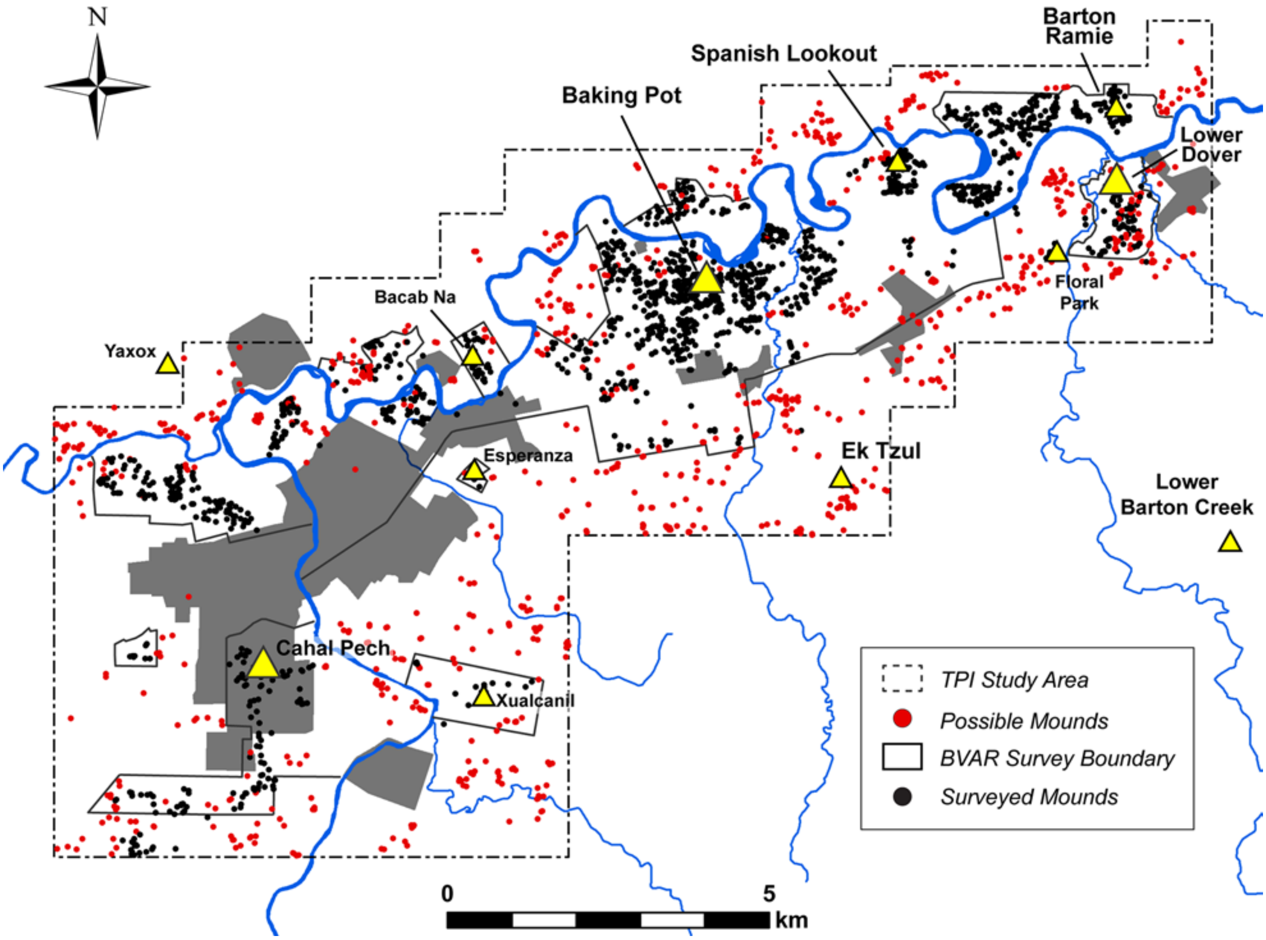

FIGURE 5. Map of Belize Valley Archaeological Reconnaissance (BVAR) Project lidar study area, showing locations of possible mounds and mounds previously surveyed by BVAR.

methods section for each possible mound identified (see also Supplemental Documentation Table 1). We also do not include the mounds composing the newly discovered small center of Ek Tzul, located ~3.6 km southeast of Baking Pot, in the estimate of possible mounds (Awe et al. 2015). This site was first documented through visual inspection of a hillshade model derived from lidar data and was thought to be composed of only two major plazas. TPI analyses, however, have identified a third large plaza to the east of the main site core, which may also contain monumental architecture. Possible mounds not associated with the monumental cores of major centers ranged from single isolated structures to large elevated platform groups that typically compose what have been characterized as minor centers, such as the sites of Bacab Na, Floral Park, and Xualcanil (Helmke and Awe 2012). Several other large previously undocumented sites, which could also be characterized as minor centers (e.g., the sites of Ek Tzul and Lower Barton Creek, the latter of which is not covered by the lidar coverages considered in this study), have previously been identified through our application of TPI analyses (Awe et al. 2015). While minor centers are typically smaller (spatially and architecturally) than major centers, they often possess some characteristics of the larger sites (e.g., nucleated monumental epicenters, pyramidal temple structures, eastern triadic temples, elite burials; Helmke and Awe 2012).

TABLE 2. TPI and Possible Mound Identification Results for the Belize Valley Archaeological Reconnaissance (BVAR) Project Study Area.

	Mound Height (m)	Surface Area (m^2)	Volume (m^3)	Mound Slope (degrees)
Min.	.10	25.39	8.02	1.45
Max.	16.12	4927.01	9944.52	63.52
Mean	1.5	204.80	195.83	10.61

TABLE 3. Land Cover Data for Each Surveyed Zone within the Cahal Pech Settlement

Survey Zone	Land Class	General Vegetation Height (m)	Vegetation Characteristics	Ground Return points per m²
1	Pasture	Low (< 1m)	Low- to medium-high grass, actively used for livestock	4.8
2	Orchard	Medium (~1.5–2 m)	Orange trees with cleared areas in between	5.7
3	Forest	High (> 2 m)	High primary canopy with lower scrub understory	4.4

Approximately 806 of the possible mounds identified by our spatial analyses had been identified during previous pedestrian survey efforts by BVAR (Awe 1992; Awe and Brisbin 1994; Cheetham et al. 1993; Conlon 1993; Conlon and Awe 1995; Iannone 1996; Hoggarth 2012; Powis 1996) and by several other archaeological projects conducting research in the Belize River Valley (Willey and Bullard 1965; Willey et al. 1965). Throughout our analyses, however, we noticed that a large number of mounds that were previously documented through pedestrian survey ($n = 651$) were not identified in computer generated spatial analyses. Many of these mounds were too small to meet the criteria to be confidently identified through TPI as possible mounds. In several cases, these mounds were not visible on either hillshade models or color-classified TPI rasters. The majority ($n = 496$) of documented mounds not identified through TPI analyses are located around the sites of Baking Pot, Barton Ramie, and the minor center of Spanish Lookout in the northeastern portion of the study area. Barton Ramie was surveyed by Willey and colleagues in the 1950s, and, since that time, the area has experienced continual disturbance through agricultural activity, likely accounting for differences in the number of mounds that can be identified either visually or through quantitative TPI analyses compared to survey results from over 65 years ago. Baking Pot and the minor center of Spanish Lookout have also experienced similar disturbance. Both sites were surveyed by BVAR, and many of the archaeological features documented consisted of scattered architectural and artifactual debris within plow zones (Hoggarth et al. 2008). A smaller number of previously surveyed features north and south of Cahal Pech ($n = 66$) were also not identified by TPI analyses (e.g., the Melhado Group, Willey and Bullard 1956). Many of these features are located in zones that are rapidly being urbanized and where mounds have been lost in the wake of modern construction activity.

Land Cover Classification Analyses and Ground-Truthing

The landscape of the upper Belize River Valley is continually changing, and modern construction and agricultural development have the potential to affect the accuracy of both visually qualitative and quantitative identification of possible mounds and other archaeological features (Höfle and Pfeifer 2007; Hutson 2015; Prufer et al. 2015; Rosenswig et al. 2014; Yoon et al. 2008). To evaluate the influence of these effects on our lidar-based TPI analyses, we compared our results TPI analyses to land-cover classification of high-resolution (~.5 m) multi-spectral GeoEye-1 multispectral (red, blue, green, and near infrared bands) satellite imagery for the site of Cahal Pech (Figure 6). The GeoEye-1 imagery was captured on October 22, 2009, and was provided courtesy of a DigitalGlobe Foundation Imagery Grant awarded to the senior author. Cahal Pech was chosen as a case study because of the relative lack of survey at the site compared to other sites investigated by BVAR. The landscape around Cahal Pech also is characterized by a wide range of land cover types, including agricultural land plowed for fields, orchards, and urban zones. While the GeoEye-1 image dates several years earlier than the date of the West-Central Lidar Survey, we chose this image because of a low percentage of cloud cover for the BVAR study area (~6 percent cloud cover). Additionally, most of the land cover zones located within the settlement area have remained unchanged since 2009.

Ground cover classification was performed using the ENVI 4.5 program on a false-color composite images composed of three bands (after Griffin 2012; Chowdhury and Schneider 2004):

- Principal component band 1(PC1), which captures the largest amount of spectral variation in the imagery data and is used to filter out noise and reduce data dimensionality.
- Texture variance band 1 (Var1) was used to discriminate between different vegetation types (Chowdhury and Schneider 2004:110). Texture variation values provide a measure of heterogeneity and represent the difference between each pixel value in an image and the mean value for all pixels in the given search radius. For the Belize River Valley area, and especially around Cahal Pech, forested areas and urban zones have higher texture variance compared to agricultural areas characterized by plowed fields and pasture lands. In this study, Var1 was calculated based on the first three principal components bands.
- Normalized difference vegetation index (NDVI) band transforms multi-band data into a single band of values to represent vegetation "greenness." High NDVI values represent vegetation that is greener relative to the other pixels in the dataset. These pixels appear lighter in color since greener vegetation (e.g., forest canopy) reflects more energy in the near infrared band, compared to less-green vegetation (e.g., agricultural fields). The NDVI band was calculated from Landsat bands 4 and 3 (near infrared and red bands respectively).

Supervised land-cover classification of the composite image was performed using the maximum likelihood classifier in ENVI. Based on a range of values selected in training sites (areas of known land class types), pixels across the image were grouped according to the highest probability that they fall into a particular class. Supervised classification identified five primary ground cover classes, including bodies of water, urban areas, forested

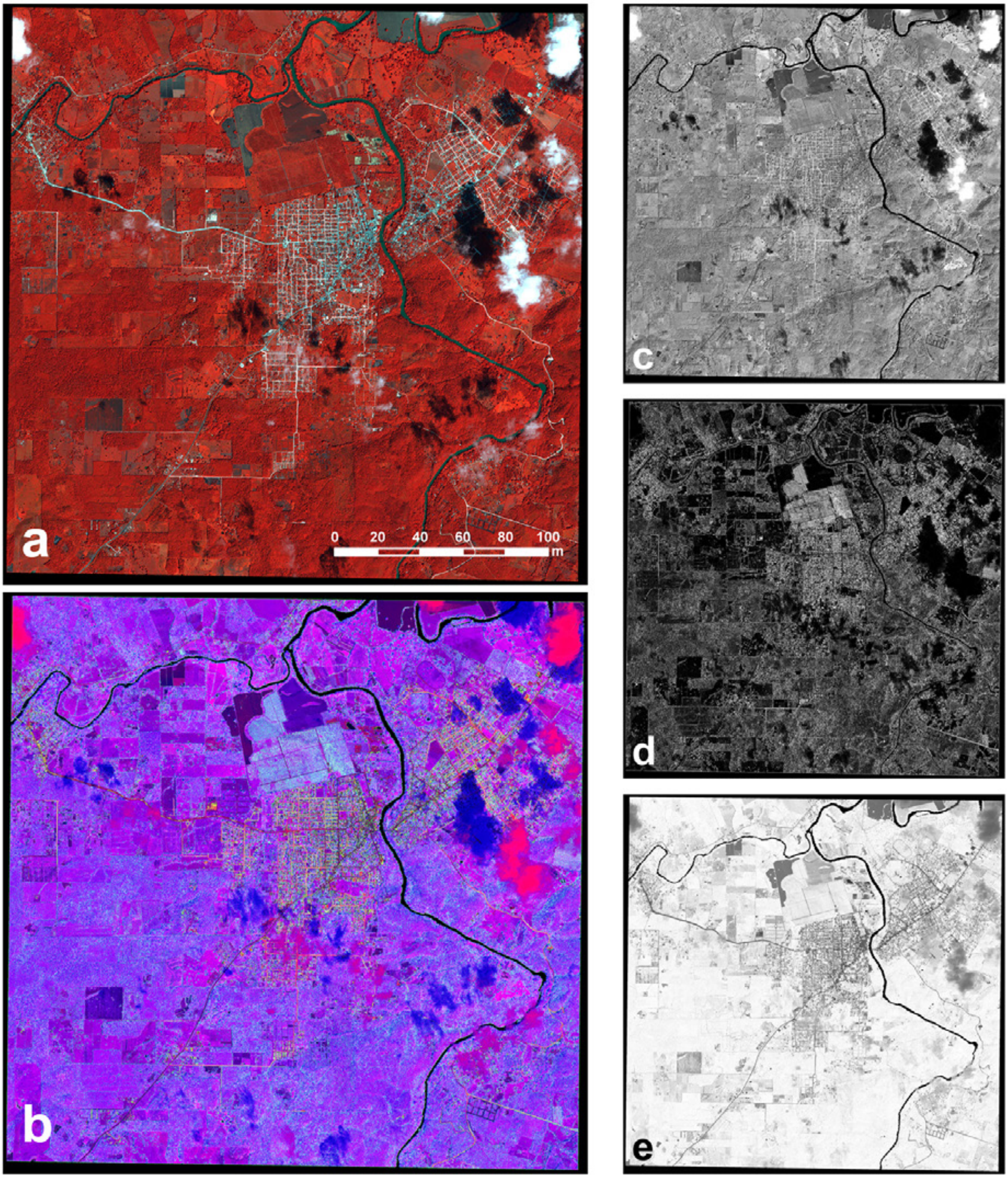

FIGURE 6. GeoEye-1 multispectral satellite imagery: (a) False color-infrared 3-band image; (b) composite image of PC1 (c), Var 1(d), and NDVI (e). Imagery provided courtesy of the DigitalGlobe Foundation.

areas, agricultural areas (both pasture land and fields), and orchards.

Preliminary ground-truthing of TPI results for Cahal Pech took place during the 2014 BVAR field season. The total surveyed area was approximately 1.85 km^2, which was divided into three survey zones to the north and southwest of the site core (Figure 7). Survey zones were selected to assess the accuracy of TPI analysis based on land cover types and to compare TPI and survey results between developed land (pasture and orchard) and relatively undeveloped areas (forested). Table 3 describes the types and characteristics of vegetation cover found in each survey zone, the general height of vegetation, and ground returns (number of points that penetrate vegetation and hit the ground surface before returning to lidar sensor) per square meter.

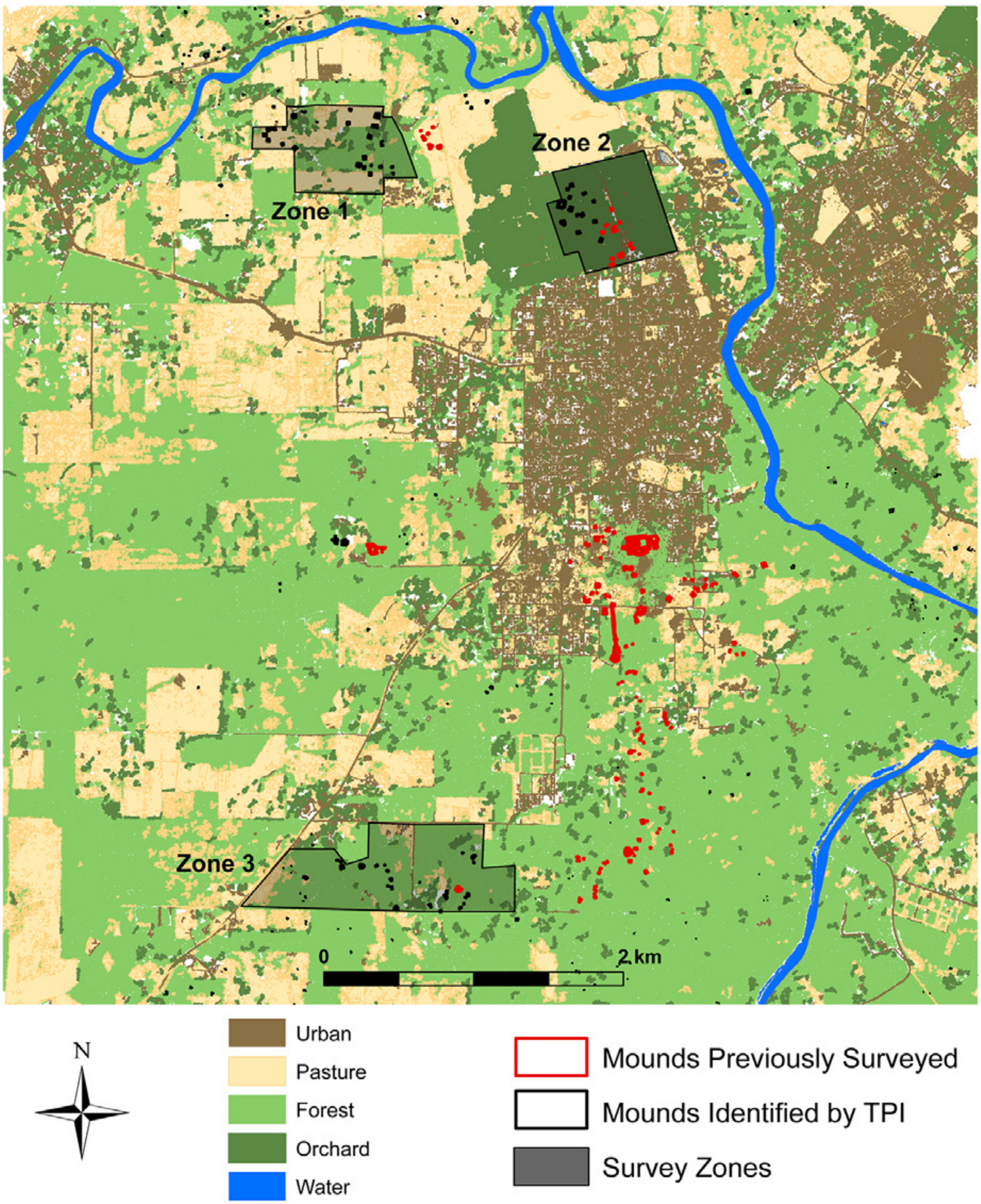

FIGURE 7. Map of ground-truthing survey zones at Cahal Pech overlaid onto a land cover classification. Settlements documented from previous pedestrian survey are denoted in red, and possible mounds identified from topographic position index (TPI) analysis of lidar are in black.

Surveyed areas were also chosen because of a lack of modern construction. Additionally, we chose to ground-truth lidar results in areas without established agricultural fields that might impede pedestrian ground-truthing. GPS coordinates were recorded for each mound identified during systematic transects across each survey zone. Mounds were mapped using a combination of tape-and-compass and total station mapping. Surface collection of diagnostic ceramics was performed during ground-truthing to identify the relative date of terminal occupation based on Belize River Valley ceramic typologies (e.g., Awe

TABLE 4. Results of Ground-Truthing Based on Cahal Pech Land Cover Classification. Values Are Rounded to the Nearest Tenth.

Survey Zone 1 – Pasture	**Possible Mounds Ground-Truthed**	**Possible Mounds not Ground-Truthed**	**Surveyed Mounds not Identified from LiDAR**	**Percent Possible Mounds Ground-Truthed**
Number of Mounds	19	19	3	49%
Mean Height (m)	.5	1.5	.4	
Mean Area (m²)	321.5	194.1	360.2	
Mean Volume (m³)	101.0	130.8	109.4	
Mean Slope (degrees)	2	6	1	
Survey Zone 2 – Orchard				
Number of Mounds	11	4	4	73%
Mean Height (m)	.6	.6	.5	
Mean Area (m²)	230.6	62.6	188.9	
Mean Volume (m³)	31.2	16.2	46.0	
Mean Slope (degrees)	8	6	2	
Survey Zone 3 –Forest				
Number of Mounds	20	30	18	41%
Mean Height (m)	1.3	1.9	.8	
Mean Area (m²)	86.6	55.3	32.0	
Mean Volume (m³)	74.5	53.7	15.3	
Mean Slope (degrees)	18	17	8	

1992; Gifford 1976). In some cases, surface collection was not performed because of poor ground surface visibility, such as in grassy pastures. The majority of surveyed sites with diagnostic ceramic materials had terminal occupational phases dating to the Tiger Run and Spanish Lookout ceramic phases during Late and Terminal Classic periods (ca. A.D. 600–900).

Survey Zones 1 and 2 were located north of the Cahal Pech site core near the confluence of the Mopan and Macal Rivers. Survey Zone 1 was approximately .45 km^2 and located in a pasture characterized by low to medium grass, which was actively used at the time of survey for livestock. Large mounds were easy to find in these areas, while smaller mounds could be observed only after cutting of grass in some cases. The TPI analysis identified 39 possible mounds, and ground-truthing documented only 22 mounds (Table 4, Supplemental Documentation 2). Survey Zone 2 was approximately .60 km^2 and was located in a modern orange orchard, which was relatively free of any underbrush. TPI analysis identified 15 possible mounds in Zone 2, and ground-truthing verified the presence of 11 of the possible structures. Survey also documented an additional four mounds not identified by computer analyses. Survey Zone 3 was approximately .80 km^2; it was located in a forested area to the southwest of the Cahal Pech site core and characterized by high primary growth forests with a lower, scrubby understory. Relatively little modern development had occurred on the land, though the southwestern portion of the zone had recently experienced some bulldozing activity. TPI analysis of this zone identified 49 possible mounds, and survey documented 38 mounds.

DISCUSSION

The integration of high-resolution lidar data into archaeological settlement survey has contributed significantly to our understanding of complex archaeological landscapes in tropical regions throughout the world. Analysis of lidar data allows for the reconstruction of site organization where pedestrian survey, hampered by thick vegetation, has documented only a small sample of settlement around large monumental centers. Archaeologists working in the tropics of Mesoamerica have used modeled lidar data to identify architecture and other archaeological features through a variety of visual techniques (Chase et al. 2011, 2014; Hutson 2015; Rosenswig et al. 2013, 2014). These studies also found that smaller mounds less than 1m in height, which in many cases may compose the majority of archaeological features within lowland Maya settlement systems, are often more difficult to identify using these methods. The lidar data analysis conducted for the Belize River Valley sites of Cahal Pech, Baking Pot, and Lower Dover demonstrates the utility of quantitative spatial analysis beyond visual analysis for the identification of less prominent architectural features. In order to identify the range of features that compose the settlement system at these three sites, we performed TPI analysis on a high-resolution 1 m DTM generated from lidar ground point data (Awe et al. 2015). TPI analyses also provided estimates of metrics for identified features including location (UTM coordinates), volume, surface area, and height of possible mounds that were used to identify these features with ground-truthing during survey.

Our analyses of lidar data in the Belize River Valley also illustrate some of the challenges facing archaeologists when using new technologies for settlement survey in modern urban areas. Urban growth often destroys or covers sites. Agricultural activities, on the other hand, affect lidar data analysis and survey in two primary ways. First, the leveling of mounds during development can obscure these features. At Baking Pot, for example, a large number of mounds located during pedestrian survey were not documented by spatial analyses. At Cahal Pech, ground-truthed mounds in Survey Zones 1 and 2 were lower and less sloping on average than possible mounds identified through TPI analyses. Ground-truthed mounds not identified by TPI were often leveled (slope less than 3°) by agricultural activities, so that they were only visible during survey based on the presence of very low mounds or artifact scatters (Awe et al. 2015; Ebert 2015). Second, the processes of agricultural development may also create modern features that resemble ancient mounds. In the pastures of Survey Zone 2 at Cahal Pech, possible mounds located with TPI analysis (n = 19) were often composed of mounded earth moved during the construction of stock ponds (Awe et al. 2015; Ebert 2015).

Areas with less infrastructural development, such as forested areas located in Survey Zone 3 at Cahal Pech, also indicated discrepancies between lidar data analysis and survey results. Several other researchers have addressed the impacts of vegetation on the ability to use lidar data to detect archaeological features (Crow et al. 2007; Hutson 2015; Prufer et al. 2015; Rosenswig et al. 2014). Based on height-above-ground measurements derived from lidar point cloud data, Rosenswig and colleagues (2014) have argued that varying heights of vegetation in costal Chiapas around the site of Izapa did not significantly affect the accuracy of lidar in different vegetation zones. Hutson (2015), on the other hand, suggests that the types of vegetation may be a limiting factor for the results of lidar analyses (see also Crow et al. 2007 and Prufer et al. 2015). Hutson preformed pedestrian vegetation survey in northern Yucatan to understand the effect of vegetation types on ground point return density and, in turn, the visibility of ancient features. His results indicate that scrub and regrowth forests with medium height vegetation had the lowest number of ground return points, correlating with the lowest percent of features visible with lidar.

We performed land cover classification analysis at Cahal Pech based on a high-resolution GeoEye-1 multispectral satellite image. We chose this method in part because of our large survey area, where pedestrian vegetation survey (much like pedestrian archaeological survey) is not easily achieved. Ground-truthing at Cahal Pech in Survey Zone 3 documented the presence of 40 mounds, only 18 of which (41 percent) were identified as possible mounds by TPI analyses (Ebert 2015). This area also had the lowest number of ground return points out of the three zones targeted for ground-truthing, a factor likely affecting the accuracy of both spatial and visual analyses in areas with similar land cover types. Despite the ability of lidar to "penetrate" vegetation, these results suggest that DTMs created from ground points may be less reliable in forested areas compared to more open spaces like orchards. Combining TPI analyses with other methods of lidar dataset analyses, such as color-classified histograms (Hutson 2015) or "bonemapping" (Pingle et al. 2015) that have been used at other sites visually highlight possible archaeological features may help to resolve these issues. Additionally, while we chose to classify the land cover and vegetation types based on satellite imagery because of the rapid nature of these analyses, future work will also use other methods to compare land cover and lidar accuracy. This will include using the lidar point cloud to generate height-above-ground data for land cover types (Rosenswig et al. 2014) and pedestrian vegetation survey in some areas. These data will be used to generate a biomass index for the urbanizing zones in the upper Belize River Valley that may provide a quantifiable comparison between vegetation and feature identification under various densities of ground cover.

CONCLUSIONS

As the incorporation of lidar becomes more common in archaeological research in tropical regions around the world, researchers are introducing new techniques to grapple with the effects of modern activities on these data. This paper presented one method, Topographic Position Index analysis, which can be combined with more traditional visual analysis of lidar data to document more discrete archaeological features. We performed TPI analyses for a 124.2 km^2 study area around the major sites of Cahal Pech, Baking Pot, and Lower Dover. We tested the results of TPI analyses by ground-truthing in three previously surveyed areas around the site of Cahal Pech composed of three distinct vegetation types based on land cover classification of multispectral satellite imagery. While mounds were detected, measured, and visibly present in areas with relatively little ground cover such as orchards and pastures, analyses conducted in forested areas were less accurate. The quantitative and qualitative differences between the TPI analyses for these areas and ground-truthing survey results and among vegetation cover types indicate that traditional settlement pattern study methods, such as pedestrian survey, remain vital to ground-truthing all types of spatial data. Archaeological applications of lidar research are still in their infancy, and researchers are beginning to refine methods of data processing and interpretation to combat challenges posed by landscapes composed of myriad land cover types. The integration of quantitative analyses and visual analyses of remotely sensed lidar data provides archaeologists with an essential tool for planning more efficient, targeted, and cost-effective survey programs.

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Data Availability Statement

The West-Central Belize Lidar Survey (co-PI Jaime Awe, Northern Arizona University) provided access to lidar, through funding by the Alphawood Foundation. Spatial analyses resulting from analyses of lidar data recorded the 3D locational data of possible archaeological features (i.e., residential mounds) within the Belize Valley Archaeological Reconnaissance (BVAR) project's study area in the Belize River Valley, Cayo District, Belize. Supplemental documentation attached to the manuscript reports data associated with each identified possible feature. Final research results and lidar data will be archived within a data repository housed in the Department of Anthropology at Northern Arizona University (NAU). Lidar data will also be stored in the electronic data archives at the Belize Institute of Archaeology (NICH) in Belmopan, Belize. Please contact Dr. Jaime Awe (Assistant Professor in the Department of Anthropology at NAU and Member Emeritus of Belize the Institute of Archaeology) for access to the data presented in this article:

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