Understanding Ancient Maya Agricultural Terrace Systems through Lidar and Hydrological Mapping

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The agricultural terraces dispersed throughout the mountainous regions of the Maya area represent a significant ancient investment in managed agroecosystems. They also provide a tantalizing avenue for archaeologists to investigate how the ancient Maya modified and managed their landscape through geointensive agricultural strategies. Recently, lidar imagery has transformed how we understand the relic landscape of the ancient Maya, particularly in Belize's North Vaca Plateau (Chase, Chase, Awe, Weishampel, Iannone, Moyes, Yaeger, and Brown 2014). Lidar provides a visual representation of otherwise canopy-obscured ancient settlements and geointensive earthworks,

ABSTRACT

Lidar has been revolutionary to the understanding of ancient Maya anthropogenic landscapes. This is no more apparent than in western Belize, where the scale and resolution of these images have identified vast networks of agricultural terrace systems, revealing their true extent and density. This paper moves beyond the initial identification of terrace distribution to use lidar imagery in combination with digital elevation models (DEM) and hydrological mapping programs (Arc Hydro) to explore the drainage catchments associated with agricultural terraces at the ancient Maya site Waybil, a minor center within the Minanha polity in the North Vaca Plateau. We specifically address how the builders of these relic agricultural features worked with the natural topography to manipulate and create more effective catchments and drainage routes. Results from hydrological modeling describe how terraces created smaller drainage catchments by increasing lower levels of flow accumulation and redirecting routes laterally across the topography. Over a decade of research within this sub-region provides the necessary survey, excavations, and chronological datasets to accurately assess the efficacy of the combined methods for relic terrace drainage analysis.

Lidar ha sido revolucionario para la comprensión de los paisajes antropogénicos de la Antigua Maya. Esto ha sido evidente en el oeste de Belice, donde la escala y la resolución de estas imágenes han identificado enormes redes de sistemas de terrazas agrícolas, revelando su verdadero alcance y densidad. Este estudio va más allá de la identificación inicial de la distribución de terrazas utilizando imágenes lidar en combinación con los modelos digitales de elevación (DEM) y programas de mapas hidrológicos (Arco Hydro) para explorar las cuencas de drenaje asociadas con terrazas agrícolas en el antiguo sitio maya Waybil, un centro menor dentro del sistema Minaha en la Meseta Vaca Norte. Específicamente explicamos cómo los constructores de estas reliquias agrícolas trabajaron con la topografía natural para manipular y crear más eficaces, rutas de captación y el drenaje. Resultados de modelación hidrológica describen cómo terrazas crearon pequeñas cuencas de drenaje por aumento de niveles de acumulación de flujo y redirigir rutas lateralmente a través de la topografía. Más de una década de investigación dentro de esta sub-región nos provee los estudios, las excavaciones y los conjuntos de datos cronológicos para evaluar con precisión la eficacia de esta combinación de métodos al analizar el drenaje de terrazas de reliquia.

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but it also facilitates the construction of high-resolution digital elevation models (DEM) and, from there, the analysis of interactions between the landscape and water, sun, and soil. In this article, we present topographical information derived from lidar and coupled with the hydrological mapping tool kit, Arc Hydro (see Maidment et al. 2002), to create a more nuanced understanding of the structure of these agricultural systems in relation to the capture and drainage of water and sediment. Research will focus on the minor center of Waybil. Arc Hydro is an ArcGIS (ESRI 2014) based database management system used to map hydrological processes in modern systems, but with utility for relic landscapes, as well (see Barnhart 2001; Berking et al. 2010; Bolton et al. 2006; Dorshow 2012; Gillings 1995; Harrower 2010; Harrower et al. 2012; Kurashima and Kirch 2011; Ruane 2015; Uysal et al. 2010; Weaver et al. 2015; Wienhold 2013). We present the steps used to produce the Waybil hydrological maps and explore the insights they can provide concerning the agrarian manipulation of the landscape and the choices that must be made to ensure accuracy of the reconstruction. The first step is manipulating the lidar dataset to create DEM, and the second is the use of ArcGIS and Arc Hydro to recreate drainage catchments and quantify flow accumulation. Combining these reconstructions with archaeological and survey-derived background on agricultural terrace construction and function at Waybil, we discuss what can be gained by exploring the hydrological process in terms of agricultural terrace construction and function.

AGRICULTURAL TERRACE BACKGROUND

Agricultural Terrace Function

Agricultural terraces are found predominantly in sloped topography and are constructed to satisfy several interrelated functions necessary for cultivating well-drained, fertile, but shallow soils (Kunen 2001:326). Terraces, in the most basic sense, are a retaining wall that functions to ameliorate erosion by retaining, trapping, and accumulating sediment to maintain and/or increase soil depth (Brooks 1998:125; Donkin 1979:34; Dunning and Beach 1994:58; Field 1966:11, 510; Hudson 1992:150–163; Kunen 2001:326; Rackham and Moody 1996:142; Spencer and Hale 1961:3; Treacy 1989:22; Treacy and Denevan 1994:95; Turner 1974:120). Creating a level planting surface upslope of the wall also increases the total area available for cultivation on a hillside (Fischbeck 2001; Neff 2008:51–52; Pollock 2007:58; Wyatt 2008:56). Agricultural terraces also play an important role in constructing an anthropogenic watershed. The placement of terrace walls parallel to slopes decreases their angle and increases their length, serving to divert water laterally across planting surfaces, as well as slowing its movement downhill (Dunning and Beach 1994:56; Liendo 1999; Treacy 1989:39; Turner 1974:120). This functions to disperse sediments (Dunning and Beach 1994:59) and increase soil moisture by slowing the velocity of runoff and facilitating directed water movement downwards (Beach et al. 2002:379; Brooks 1998:130; Kunen 2001:326; Morgan 1995:138; Rackham and Moody 1996:142; Treacy 1989:39; Wyatt 2008:56, 2015:459). Terraces are also recorded to run perpendicular to slopes functioning to restrict the horizontal flow of water and sediment as well as creating deep planting surfaces when bridging to two intersecting slopes (Brooks 1998:130; Chase and Chase 1998:70; Deneven 2001:176; Donkin 1979:131; Treacy and Denevan 1994:96). By retarding the flow of sediment and water, terraces function to retain and increase soil fertility. In addition to increasing water distribution and moisture retention, terraces act to divert excess water, which deters detrimental erosion, while the porous wall construction and other subtle water dispersal features assist in avoiding waterlogging planting surfaces (Beach et al. 2002:379; Brooks 1998:132; Chase and Chase 1998:70; Denevan 2001:179; Kunen 2001:326; Morgan 1995:137; Neff 2008:52 Treacy 1989:80; Treacy and Denevan 1994:105). Taken together, these qualities mean that terraces not only increase land area for cropping, but also extend the growing season in tropical areas, like the Maya world, where seasonal droughts prevail (Pollock 2007:58).

Agricultural Terrace Nomenclature

Agricultural terraces have been classified into different types based on the various approaches to their study; geomorphic distribution (Donkin 1979; Spencer and Hale 1961; Treacy 1989; Treacy and Denevan 1994), function (Hudson 1992; Morgan 1995; Moody and Groove 1990; Rackham and Moody 1996), and construction (Frederick and Krahtopoulou 2000; Soper 2002, 2006). These different approaches to classification are often intermingled, resulting in numerous variants of terrace types, with no single classification scheme accepted (Frederick and Krahtopoulou 2000:82). This study will utilize a three-type nomenclature of non-irrigated terraces, generally agreed upon in Central and South America. Several variants will be described within these three types, incorporating aspects of function and morphology from a local perspective (see Ashmore et al. 1994; Brooks 1998; Denevan 2001; Field 1966; Treacy and Denevan 1994; Neff 2008). For discussion on other nomenclatures refer to Rackham and Moody (1996), Moody and Groove (1990), Frederick and Krahtopouou (2000) and Morgan (1995).

Bench terraces, often associated with dry-slope terraces, are one of the most common types and exhibit a number of variants. Their stair like appearance, ascending in serial rows parallel to

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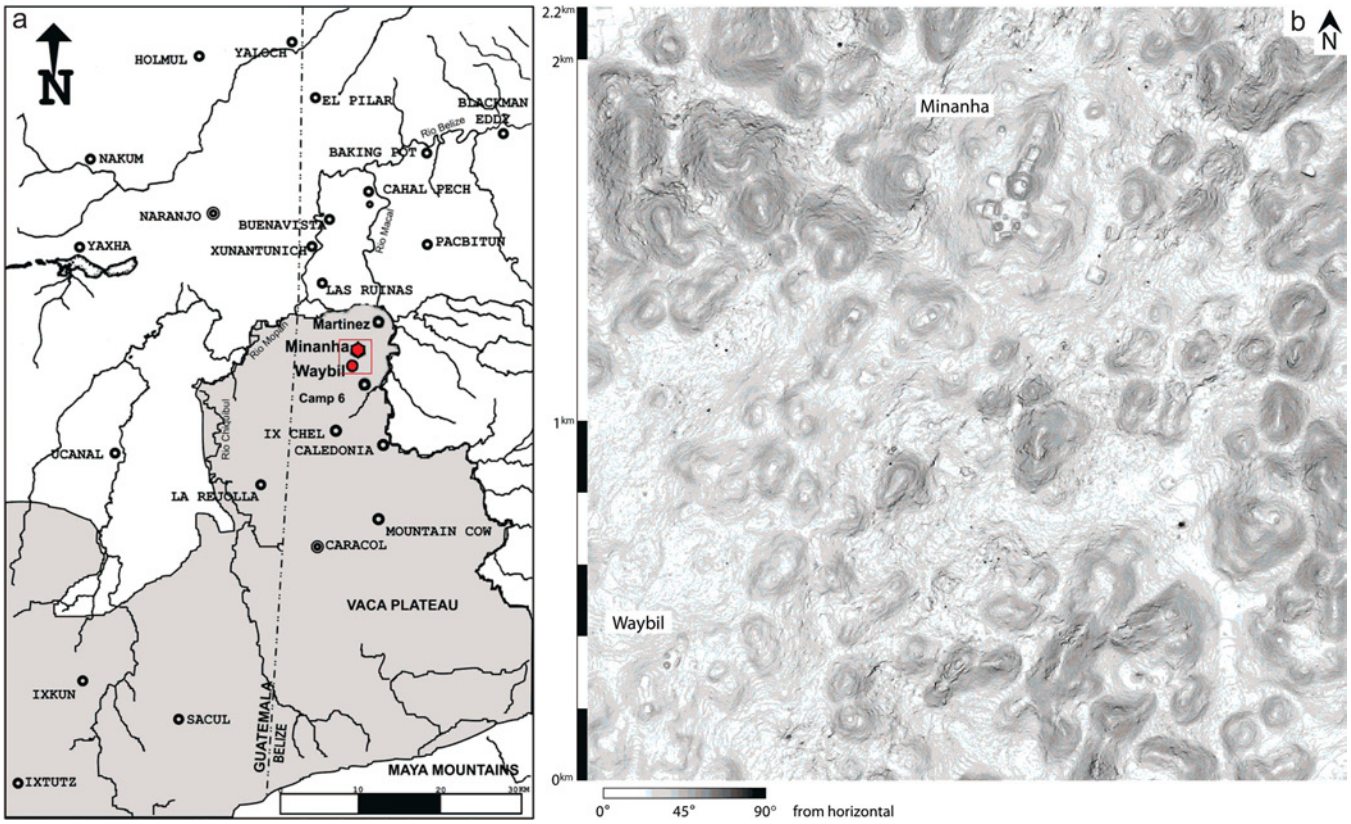


FIGURE 1. The North Vaca Plateau, Belize: (a) Minanha and surrounding centers; (b) Minanha and the associated minor center of Waybil.

sloping topography, and level planting surfaces identifies these terraces. Variations of bench terraces can include, but are not limited to, contour, linear, broad field, and foot slope. Contour terraces conform to the contours of hill slopes (Beach et al. 2002:386; Brooks 1998:132; Donkin 1979:32; Fedick 1994:120; Neff 2008:52; Treacy 1989:81). Linear terraces are independent of the topography and constructed in uniform horizontal lines (Brooks 1998:132; Kunen 2001:326; Treacy and Denevan 1994:98–100). Broad field terraces are located on more gentle slopes exhibiting a much wider planting surface than other bench terraces (Brooks 1998; Denevan 2001:180). Footslope or valley floor terraces, similar to Brooks's (1998) segmented terraces, are located independent of other terrace tiers creating large, flat plots of land at the base of steep slopes (Beach et al. 2002:387; Dunning and Beach 1994:59–60; Kunen 2001:327; Neff 2008:52; Treacy and Denevan 1994:100–101). Box terraces fall outside the traditional description of bench terraces, but are associated with dry-sloped terrace in the Maya area. Located on moderately flat land often in close association with residential complexes, these terraces create rectangular plots considered seedbeds or intensively cultivated gardens (Beach et al. 2002:386; Dunning and Beach 1994:58; Kunen 2001:326; Neff 2008:52).

Cross-channel (weir) terraces are non-contour in placement, functioning to collect and distribute the soil and water resources in a constricted area. They are found running perpendicular to the slope of smaller subsidiary valleys between the residual hills, seasonal drainage channels, between contour terraces, and other locations of constricting topography (Beach et al. 2002:380; Deneven 2001:176; Dunning and Beach 1994:58; Kunen 2001:326; Treacy and Denevan 1994:96; Wyatt 2008:54). As a result, these terraces are usually short in length, crossing the restricted topography, and tall in height, collecting the accumulated sediments (Brooks 1989:130; Donkin 1979:131).

Sloping fields are similar to bench terraces in their positons on valley sides and general conformity to contours. However, the planting surfaces are sloped, opposed to the flat bench types (Brooks 1998:130). These terraces are noted in higher elevations and have not, to our knowledge, been identified in the Maya area.

THE WAYBIL CASE STUDY

Waybil is a subsidiary site of the small Minanha polity, located in the North Vaca Plateau of west-central Belize (Figure 1a). Research at the site was carried out as part of studies conducted since 1998 by the Social Archaeology Research Program (SARP) at Minanha and its associated minor centers, directed by Gyles Iannone (Iannone and Schwake 2013). Iannone's research program addresses the role of Minanha within its greater sociopolitical and socio-ecological sphere (Iannone 2006:1; Iannone et al. 2008:149). Waybil, situated 1.92 km southwest of Minanha, fell within the SARP Phase III research that focused specifically on minor centers and their dynamic relationship with the greater

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Minanha polity and its royal court (Figure 1b; Iannone 2008; Iannone and Schwake 2013). In this area, the role of terrace agriculture at minor centers is fundamental to understanding the larger context of the polity-wide economic and social system.

Phase III research included extensive excavations and survey within a 500-m-x-500-m survey zone to reconstruct the history, distribution, and function of the Waybil agricultural terraces and their associated planting surfaces. Excavations were conducted over three field seasons, focusing on the epicenter (Schwake et al. 2013), surrounding settlement units (Demarte et al. 2013:59), and relic agricultural terraces (Macrae 2013; Macrae and Demarte 2012). Theodolite survey of the entire survey zone mapped 15 settlement groups, comprising 46 structures and 8 solitary buildings. Survey in 50 percent of the study area mapped agricultural terrace and water management features (Demarte and Alfano 2013; Iannone et al. 2011). High-resolution DEM reconstructions based on lidar data were combined with settlement and terrace survey to digitize the entirety of the Waybil agricultural terrace systems and settlement units (Figure 2).

Settlement chronology was determined by a widespread sampling strategy and analysis of ceramics. This included plaza excavations in every settlement group and strategic structure excavations in the epicenter and some of the larger settlement units (Demarte et al. 2013). This work revealed an occupational history that stretches from the Late Preclassic (400 B.C.–A.D. 100) to Early Postclassic (A.D. 900–1200; Hills et al. 2013). Agricultural terrace construction and use at Waybil was shown to have begun during the Late Terminal Preclassic (A.D. 100–250) and ended during the Terminal Classic (A.D. 810–900). All the settlement units and solitary structures exhibit a Late Classic (A.D. 675–810) component, although two settlement units exhibit dates extending outside the Late Classic. Five terrace walls and 13 planting surfaces were investigated, and all except one wall and its adjacent two planting surfaces exhibit a Late Classic component. This strong temporal connection to a single period of occupation, the Late Classic, makes Waybil an ideal case for the study of agricultural terraces because we can assume, within a ca. 150-year span, approximate contemporaneity of terrace use, and thus we can analyze their interaction across the landscape to understand them as a single hydrological system. Thus, the Waybil terraces provide an excellent opportunity to understand the use of single-event terrace planting surfaces in conjunction with terrace walls, settlement, and local topography.

METHODS

Light Detection and Ranging (Lidar) & Digital Elevation Models (DEM)

Light Detection and Ranging (lidar) methods for generating high-resolution elevation data are described in detail elsewhere (see Ackermann 1996; Axelsson 1999; Doneus et al. 2008; Fernandez-Diaz et al. 2014; Wehr and Lohr 1999). In our survey, point-lidar utilized continuous, short bursts of laser pulses to filter through the small holes in the dense canopy cover of the Maya lowlands and data were presented as a point cloud with a ground resolution ranging from 5 to 30 cm depending on the density of canopy cover (Chase et al. 2012; Hightower et al. 2014). The lidar dataset was acquired as part of a consortium of archaeologists working in west-central Belize and was conducted by the National Center for Airborne Laser Mapping (NCALM) between April 27 and May 10, 2013. Classification of the raw lidar data was completed in the software platform TerraScan version 13.009 (Terrasolid 2014) and distributed as las files and a DEM. For more information on the acquisition and processing of this lidar dataset, refer to Chase, Chase, Awe, Weishampel, Iannone, Moyes, Yaeger, Brown, et al. (2014) and Fernandez-Diaz et al. (2014). At Waybil, the lidar point-cloud consists of 6,738,078 point returns. Of these, 426,698 are classified as ground returns, with ~1.7 ground returns per square meter. However, these points are not evenly distributed across the survey zone (Supplemental Figure 1).

Surface modeling, especially elevation modeling of landscapes, combines primary and secondary sources to create a digital elevation model (DEM). However, datasets need to be manipulated through interpolation techniques to create a continuous DEM surface (see Conolly and Lake 2006). Interpolation techniques are used to fill gaps between observations, predicting the missing data. There are several methods of interpolation including, as examples, Natural Neighbor, Kriging, Splining, and Inverse Distance Weighting (Arun 2013; Childs 2004; Conolly and Lake 2006; Polat et al. 2015). In this study, we used the local operator technique inverse distance weighting (IDW) to examine the immediate neighboring cells to create the interpolated data. IDW, introduced by Shepard (1968), functions by examining a large sample of neighboring observations surrounding the missing data point, with each observation being assigned a specific power that is inversely weighted based on its linear distance (Conolly and Lake 2006:95). In this manner, points further away will contribute less, but immediately adjacent points do not contribute wholly, to the reconstruction. During analysis, technicians have the ability to select the number of neighboring observations to be included. The influence that each neighboring cell has on the interpolated data can be modified by changing its weight. Based on the large number of point returns that occur within a lidar dataset, this method proves accurate and falls within the computational ability of most computers (Joseph and Kang 2011; Liu 2008).

The decision to create a new DEM, rather than use the one provided by NCALM, was based on a desire to control all the variables during interpolation that could influence hydrological modeling. This did not necessarily increase the accuracy of the surface model, but did facilitate an assessment of interpolation techniques for feasibility within a small study area that had been subjected to extensive survey. Natural Neighbor interpolation provides a weighted average over the neighboring points of the interpolated value using Delaunay triangulation (Sibson 1981). Spline interpolation, often illustrated as bending a sheet of rubber through each input point, produces a polynomial surface based on minimum curvature (Conolly and Lake 2006:97; Floater and Iske 1996; Franke 1982). While both interpolation methods produced excellent visibility of both larger settlement units and more aggressive agricultural terraces, they sacrificed the ability to define less pronounced changes in the landscape for the creation of a smoother surface (Childs 2004). These interpolation methods tended to generalize the topography to a level not well suited for hydrological analysis. Further, the Spline method encountered difficulties interpolating points within the high number of close proximity point-returns provided by lidar.

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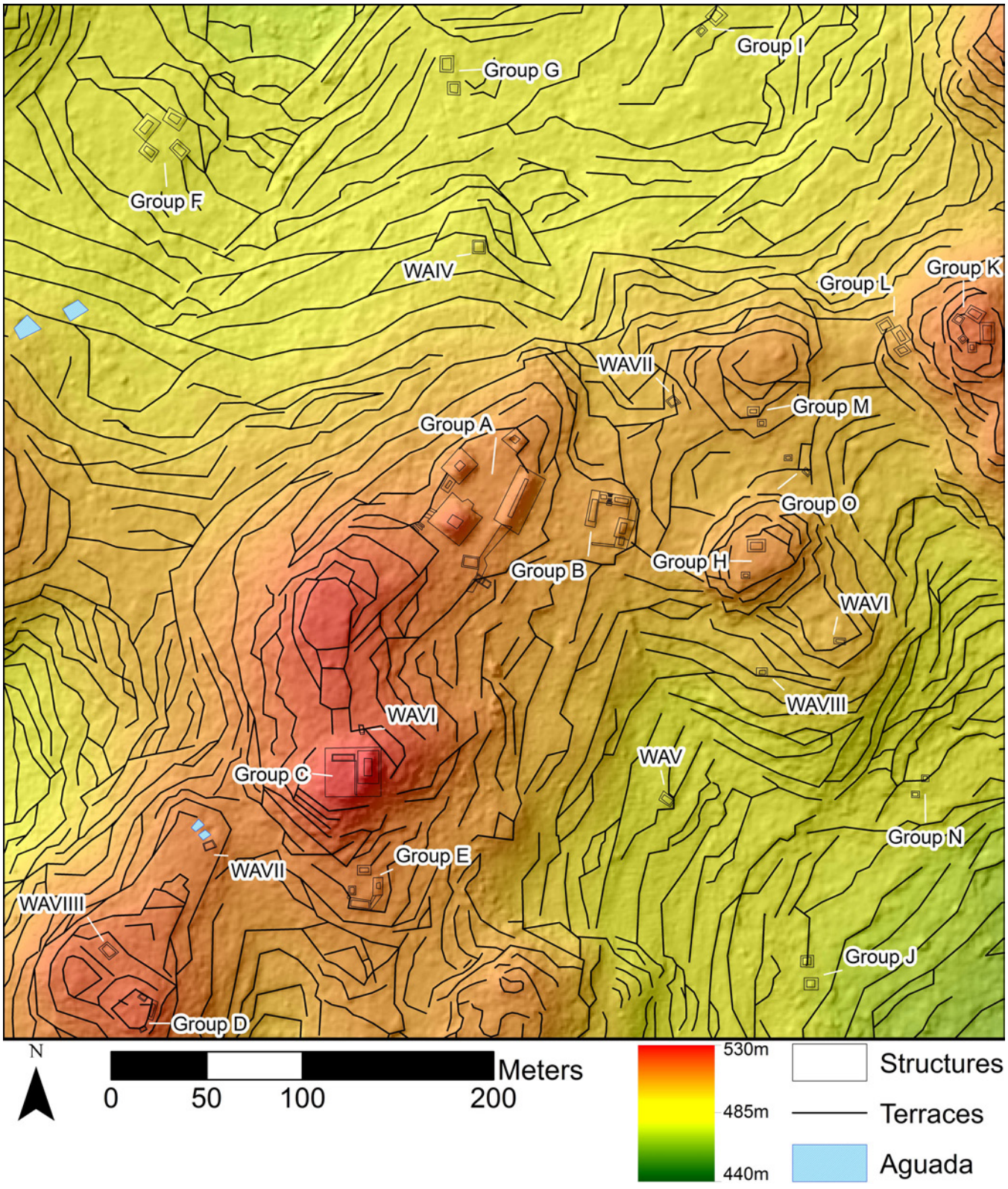


FIGURE 2. The minor center Waybil depicting settlement groups (Groups A–P) and solitary structures (WA I–VIII) as well as agricultural terraces.

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The DEM of the Waybil survey was created by converting the lidar point-cloud into a multi-point feature, using only ground return points. The IDW interpolator technique was used to create a raster image, setting the number of neighboring points examined to 12, with a weight of two (Supplemental Figure 2a). Horizontal resolution was set to 1 m. Although greater resolution of .5 m or even .25 m was possible, we determined that this produced too much noise for accurate hydrological analysis. Vertical accuracy of the DEM is approximately 5–30 cm (Chase et al. 2011; Chase, Chase, Awe, Weishampel, Iannone, Moyes, Yaeger, Brown, et al. 2014). We found that the best way to visually present the agricultural terraces and settlement was to overlay the DEM with a raster image depicting slope (Supplemental Figure 2b).

To address the role agricultural terraces played in the production of the hydrological systems, we constructed a second comparative DEM with the majority of agricultural terraces removed from the landscape. We created this surface model using the same IDW interpolation method to create the surface model and Arc Hydro processes to calculate the flow accumulation and delineate catchments (see below). Prior to hydrological analysis, we used the ArcGIS Focal Statistic tool (ESRI 2014) to remove the agricultural terraces from the interpolated raster image. Focal Statistics operates by calculating the sum elevation value of a specified neighborhood of cells surrounding each interpolated point, as well as adding the value of the processing cells. Identified neighborhoods have the ability to overlap based on the proximity of the cells being calculated. To remove the majority of the agricultural terraces, while maintaining accuracy within the topography, we used a circle neighborhood with a radius of 10 m. Only minimum elevation values from the neighboring cells were calculated. This approach created a smoother surface model from the original interpolated points. It is important to note that while the majority of the terraces, especially walls with smaller elevation changes, were removed, some terrace contours remained. In order to manipulate the surface model sufficiently to remove the taller terraces we would have had to significantly modify the elevation of the natural topography, thus these were ultimately left in place. Further, some aggressive elevation changes represent natural bedrock formations. For example, the southeastern portion of the survey zone that exhibits cross-channel terraces was subjected to excavations revealing a relatively small terrace walls built atop step shaped bedrock. Thus, by using surveyed and excavated terraces for comparison, we decided on what scale to use the focal statistics tool. As a result, while the terrace-removed DEM has extracted the majority of the terraces, it may not be completely representative of natural topography, which has been buried under centuries of human occupation and manipulation.

Arc Hydro: Drainage, and Catchments

To reconstruct the drainage networks and catchments of the Waybil landscape, we used Arc Hydro (Arc Hydro 2.0), a geospatial relational database management system (RDBMS) designed to present and support models created from geospatial and temporal information for hydrography and hydrology data (Maidment 2002; Shamsi 2008:165). These reconstructions require the manipulation of the DEM and use of tools such as Flow Accumulation and Catchment Delineation.

DEM Manipulation. Arc Hydro results are dependent on the quality of the data input, in our case a lidar dataset and high resolution DEM. Often a DEM is accompanied by other primary datasets from water resource studies that collected hydrological information, usually data of a higher resolution and independent of the DEM. This is not the case in our study. We used the DEM to compute potential hydrological functions, and thus depended on the quality of resolution to be transferred into the results. This dependency required that we complete a number of analytical steps to reach our objective.

Imperfections, often present within DEMs, needed to be accounted for. This required a sink fill (Pit Removal) to remove surface depressions, known as sink or pits, which are usually present in the DEM. Surface depressions can be the result of data errors created during the surface modeling, or can be real topographic features that are the result of both natural and anthropogenic processes (Deursen 1995:47; Jenson and Domingue 1988:1593–1594; Wang and Liu 2006:195). They are defined in GIS modeling as local minimums without a downslope flow path, composed of a single or group of cells of the same elevation and surrounded by cells of a higher elevation (Conolly and Lake 2006:257; Wang and Liu 2006:195). Sinks in a DEM reconstruction can be detrimental to hydrological modeling, causing modeled water flows to terminate or accumulate until the sink is filled, prior to reaching the edge of the study area. Several analytical procedures can be used to condition the DEM by applying smoothing filters to raise the sink or lower the surrounding neighboring cells, making the DEM depressionless (Conolly and Lake 2006:257; Deursen 1995:47; Olivera et al. 2002:71). These procedures have developed from earlier approaches (see Band 1986; Jenson and Domingue 1988; Marks et al. 1984; Morris and Heerdegen 1988) to more complicated algorithms that take into account specific sizes based on area, depth, and volume (see Deursen 1995). Arc Hydro provides several tools to address sinks, including Sink Prescreening, Sink Evaluation, Sink Selection, and Fill Sink. These tools allow the user to develop a sink criterion, evaluate potential sinks, deselect true sinks, and finally fill the sinks. We used excavation and survey data to evaluate whether sinks were true features and to fill the remaining 1,127 false sinks identified across the Waybil survey zone (Supplemental Figure 3a-b).

Drainage Analysis. The modified DEM was next used to analyze the Waybil drainage system. Drainage is the flow process of water direction as it moves from its origin point in the landscape to its final resting location. This is a function of topography, which directs the flow of water, and elevation, which determines the wetness of land surfaces (Olivera et al. 2002:56). Simply stated, ridges of higher elevation will have drier soils then the low flats of valley bottoms. We began by identifying the Flow Direction (FDR) that describes the direction in which water will flow out from one cell to another (Jenson and Domingue 1988:1594). In ArcGIS, this is a slope operation, defined by elevation decreased per unit of travel distance. ArcGIS uses an eight-direction pour point model in which the program examines surrounding cells, comprising eight possibilities, and describes water movement from one cell to another based on steepest descent (Jenson 1985:304–305; Olivera et al. 2002:69). The steepest descent is calculated by elevation change between cells divided by distance to cell centers (see Greenlee 1987; Jenson 1985; Jenson and Domingue 1988). This method produces

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a number of conditions in which assigning flow direction is not necessarily straightforward, but can be overcome through the sink filling processes or with a lookup table such as a spreadsheet describing elevations and most likely direction (see Greenlee 1987; Jenson and Domingue 1988). We used the simplest technique available to determine this process, allowing the flow of water into a single cell (Olivera et al. 2002:69) and creating an integer raster that encodes cells with a single value between 1 and 128, using divisions of 2, representative of cardinal directions (Supplemental Figure 4; Jenson and Domingue 1988:1594; Olivera et al. 2002:69).

The final result is a model of Flow Accumulation (FAC), which describes individual cells based on the number of different cells that drain into it (Jenson and Domingue 1988:1594–1595; O'Callaghan and Mark 1984:326; Olivera et al. 2002:72). The raster output of ArcGIS assigns each cell the accumulated value of all the cells that flow into it (Figure 3). The cells that exhibit a high accumulation level are areas where water may accumulate and can be used to identify stream channels. The cells with low accumulation levels are likely areas of high elevation such as ridges (Jenson and Domingue 1988:1596).

Catchment Analysis. Watersheds or catchments are regions, often basin shaped, in which all the water drains to a common terminus. The final analysis of the Waybil terraces involved digitizing the watersheds and catchments found across the landscape. Arc Hydro differentiates between watersheds and catchments based on whether the delineation is automatically derived from drainage characteristics (catchment), or manually manipulated with a secondary data source of hydrological information (watershed; Olivera et al. 2002:60). Catchments in this sense are a precursor to the manual manipulation that creates watersheds. Without additional hydrological information, our study focused on catchments. The Waybil catchments were digitized in Arc Hydro by extracting data from both the FDR and FAC to construct Stream Definition and Stream Segmentation. These two functions utilize FAC by identifying cells that meet and supersede a threshold of accumulation as streams, ultimately creating a network of streams. The constructed stream network is then divided into segments/links with junctions separating the segments. Segments are assigned a numeric order determined by their location in the stream network, increasing from one based on the number of networked tributaries (see Strahler 1964). There are several methods to assign values (see Tarboton et al. 1991). With this analysis in hand, the catchments can be delimitated. The boundary of a catchment is referred to as a drainage divide. The drainage divide begins at a pour point, the locus where all the accumulated water drains from a specific catchment, and encompassed all the cells that flow in the direction of this point (Olivera et al. 2002:57–58, 74). This places each stream network, within the specified threshold of accumulation, in its own catchment.

The delineation of catchments is strongly influenced by the resolution available in both FDR and FAC, and, as with DEM, ultimately the lidar resolution. However, lidar has been proven to provide more information than is required, or even useful, for some hydrological analyses (Jones et al. 2008:4149). The high-resolution lidar available for Waybil presented such a situation, with the data resolution outrunning the level of analysis. The recommended FAC threshold of 1 percent created 98 catchments across Waybil (Supplemental Figure 4). While these minutiae have important implications for analyzing the hydrological process, we found a less detailed analysis more beneficial for understanding agricultural terrace systems. Using a FAC threshold of 2 percent, we were able to create more generalizing catchments, grouping many of the smaller ones (Figure 4). An alternative solution would have been to reduce the number of lidar point-returns used in creating the DEM by adjusting their classification. This approach was avoided because of the unevenness of point-return distribution and a desire to maintain all the subtle impacts that agricultural terraces have on the elevation and slope modeling.

RESULTS

Identifying Agricultural Terraces Characteristics at Waybil

Agricultural terraces are prolific throughout the Waybil survey zone, converting the majority of the landscape into planting surfaces. Traditional survey and lidar digitization have identified 589 terraces. Terraces are primarily composed of contour and cross-channel types. Contour terraces are found along the gentle slopes in the northern and southeast portions of the survey zone. These function to disperse water parallel across the hillsides, while reducing slope to create level planting surfaces. Cross-channel terraces, found in the constricted topography in the southwest and eastern portions of the survey zone, capture the sediment and water that flows down these narrow valley bottoms, creating deep planting surfaces. The number and distribution of terrace walls at Waybil indicate a significant investment in the modification and management of the landscape through a geointensive agricultural strategy.

Excavations of these agricultural features have revealed several courses of dry-laid, limestone boulders that create a retaining wall (riser) with a level planting surface (tread) of varying widths behind it (Kunen 2001:327, 339; Thompson 1939:229; Turner 1974:119). Retaining walls were constructed in both single and double wall construction techniques (Figure 5; see Beach et al. 2008; Chase and Chase 1998:69; Dunning and Beach 1994:59; Healy et al. 1983:404; Kunen 2001:327, 339; Turner 1983:77–84). Terrace walls are anchored directly to the bedrock, occasionally utilizing its step-like nature. Planting surfaces reveal a single anthropogenic soil horizon attesting to an expedient construction process, where soils were stripped to the bedrock before wall construction and refilled after wall completion (Chase and Chase 1998:70; Hansen et al. 2002:283; Healy et al. 1983; Kunen 2001:339; Robin 2015:44).

Excavations also identify both wall and bed characteristics that would have facilitated water retention and dispersal. Evidence is revealed by the construction of a cobble layer underneath the planting surface and upslope of the terrace wall (Figure 6). The lower matrix potential of the finer aggregate of the planting surface retains water in the planting surface during periods of low precipitation, while the higher matrix potential of the cobbles in the construction fill facilitate drainage when saturated (Brady and Weil 2007:197, 201; Brooks 1998:132; Denevan 2001:179; Treacy 1989:80; Treacy and Denevan 1994:105).

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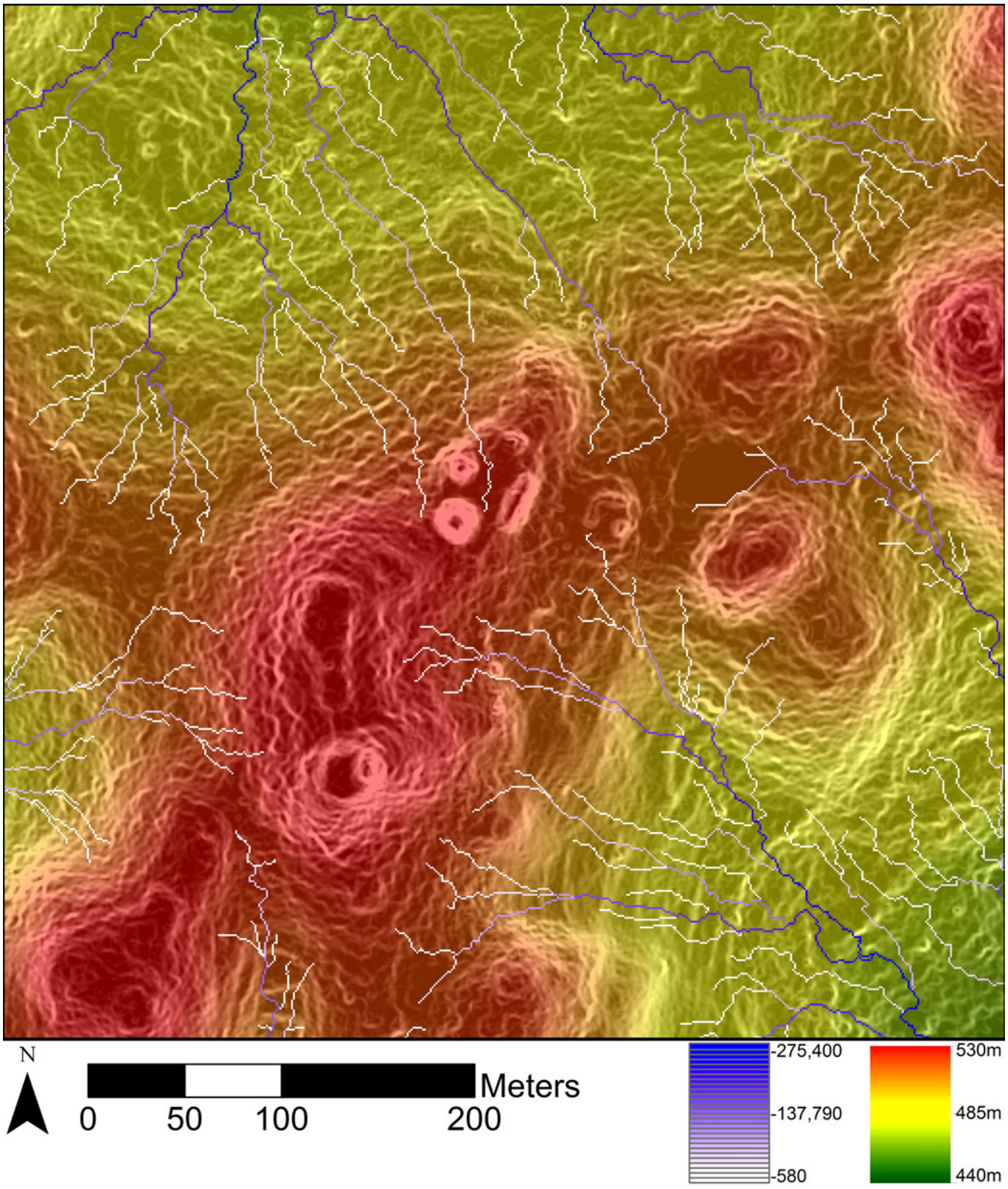


FIGURE 3. Flow Accumulation (FAC) across the Waybil survey zone.

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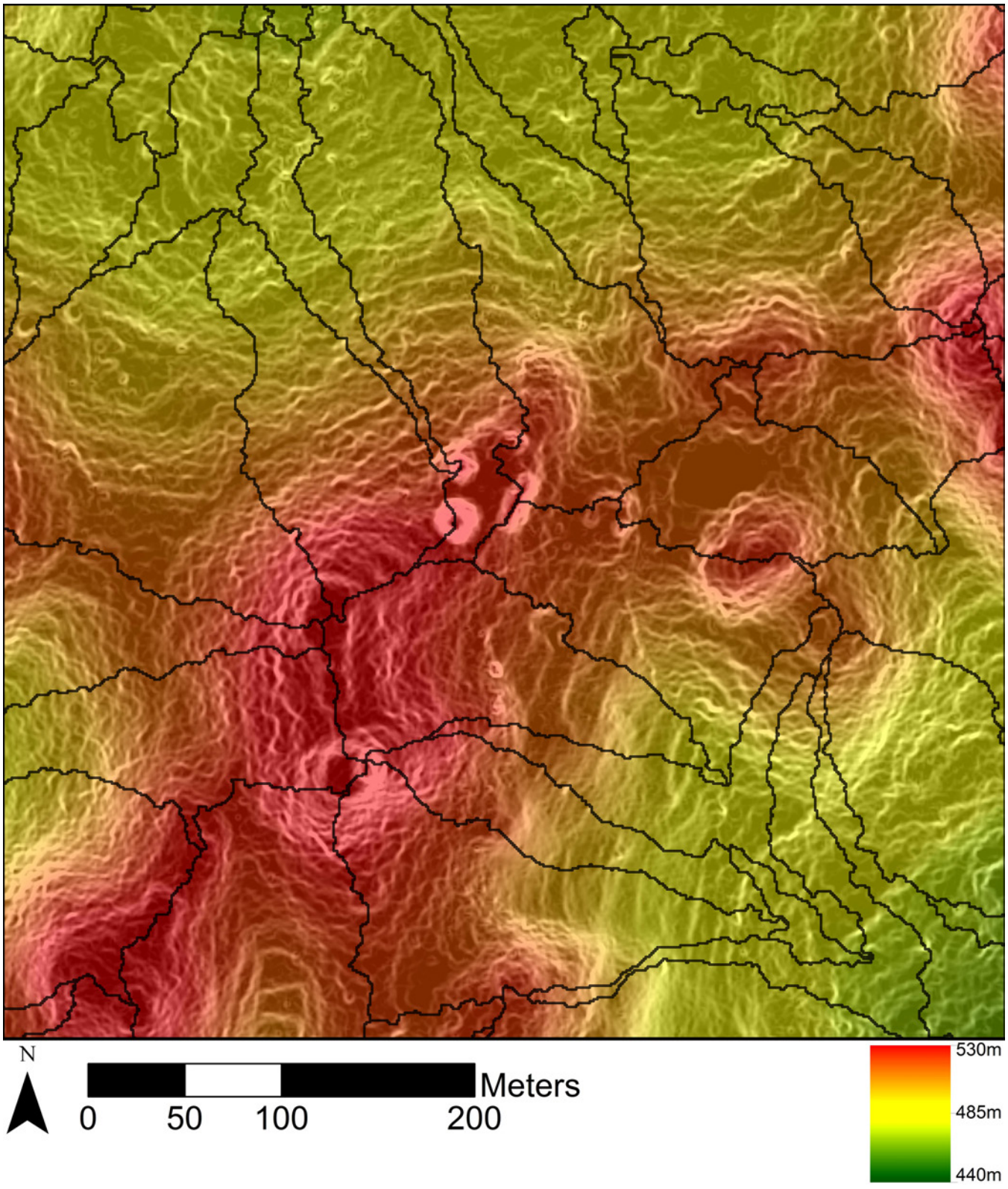


FIGURE 4. Catchment delineation across the Waybil survey zone, using 2 percent Flow Accumulation threshold.

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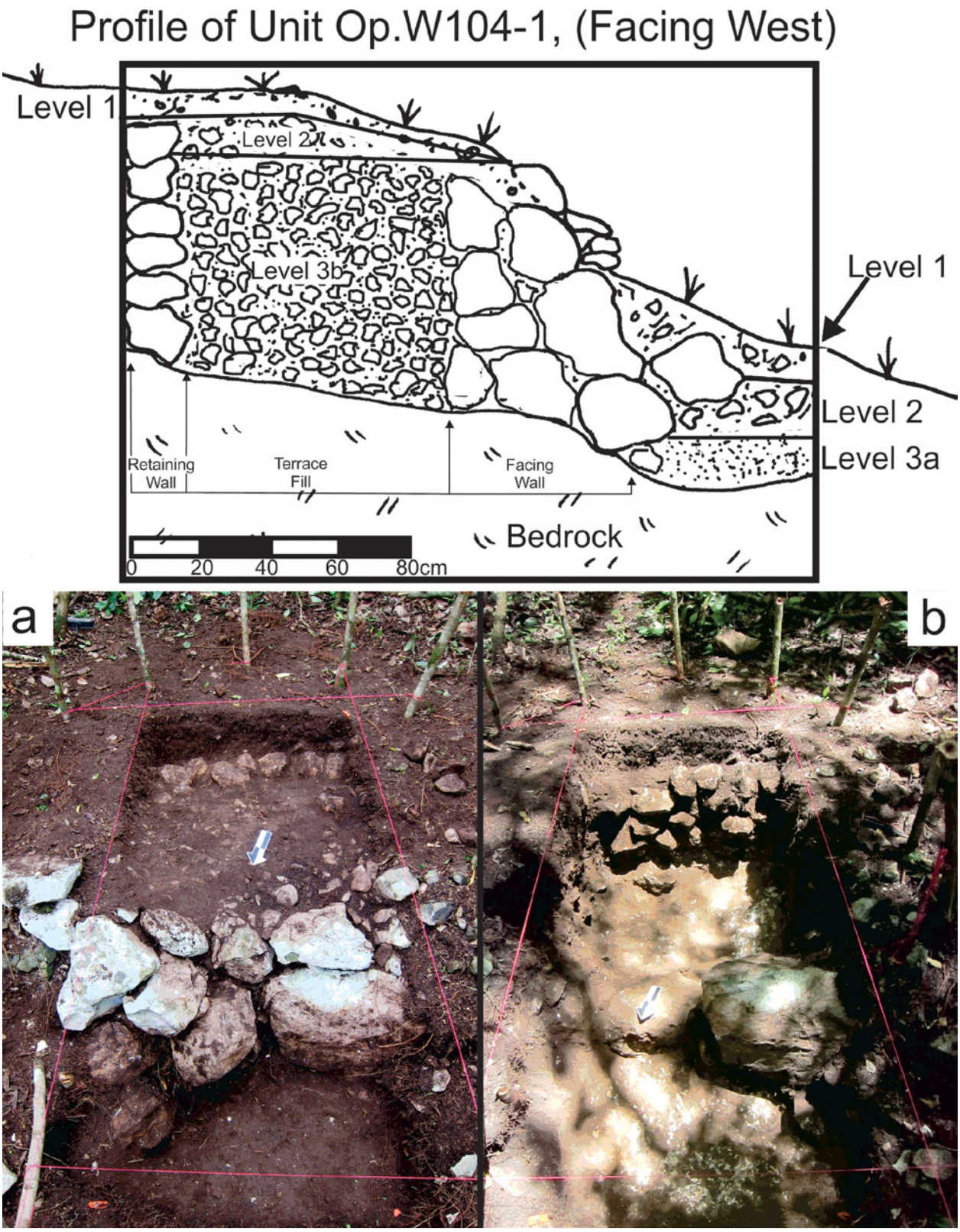


FIGURE 5. Terrace excavation depicting double wall construction: (a) Terrace facing wall; (b) terrace retaining wall.

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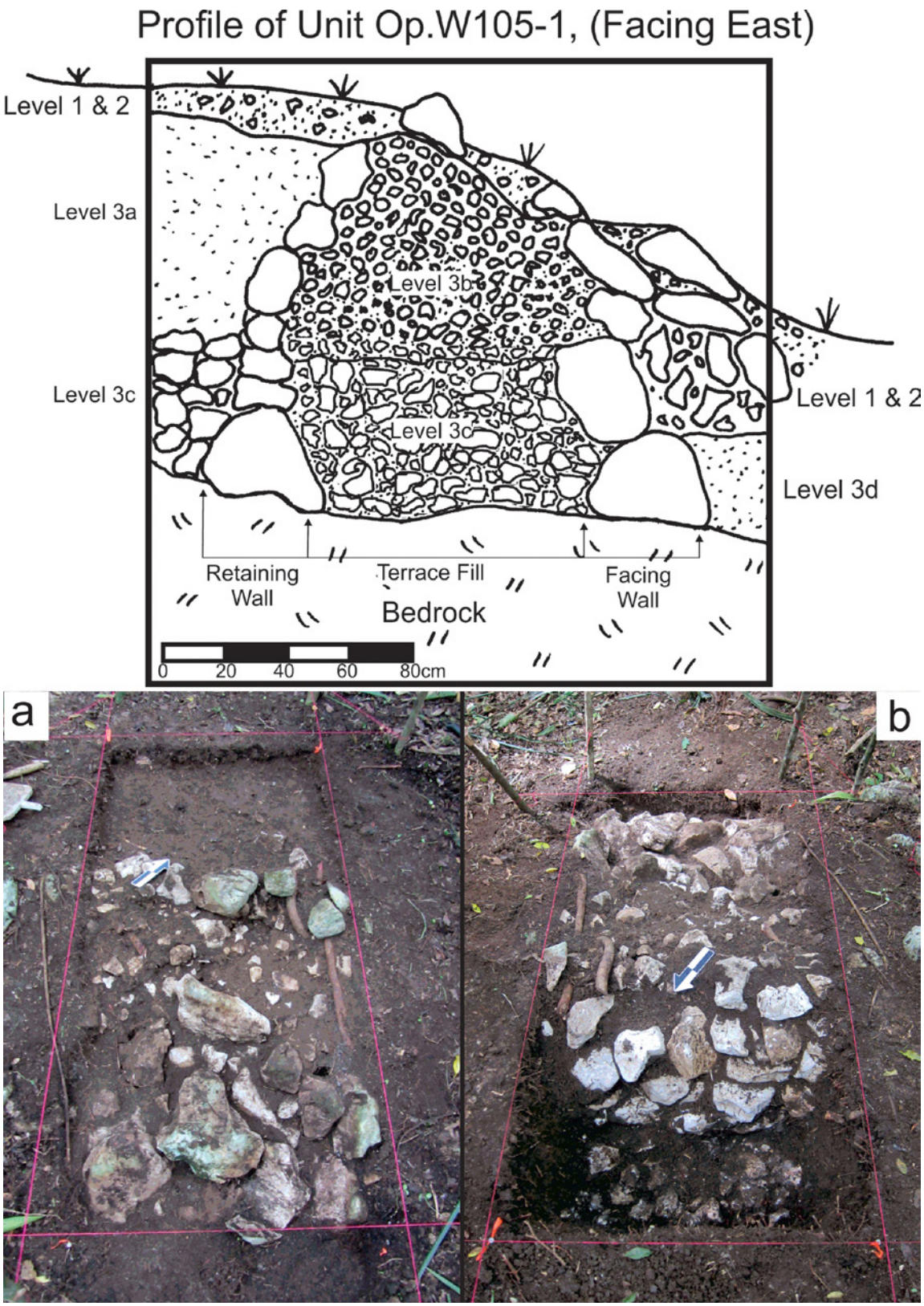


FIGURE 6. Terrace excavation depicting terrace wall and cobble construction fill under planting surface: (a) terrace facing wall; (b) cobble construction fill underneath planting surface behind terrace, facing downhill.

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Defining the Impact of Terrace Construction on Drainage and Catchment

Understanding drainage patterns across the agroecosystem constructed by the ancient Maya provides an in-depth understanding of how agricultural terraces interact with the flow of water and movement of sediments across the landscape. The hydrological analysis of both the terraced DEM and terraced-removed DEM has identified drainage catchments across the survey zone and FAC values for each 1-m-x-1-m cell that comprised the DEMs.

Drainage analysis delineated 45 catchments across the terraced DEM with a mean surface area of 6,205 m². The terrace-removed DEM exhibited 44 catchments with a mean surface area of 6,346 m². The density distribution of these values reveals that the terraced DEM has a higher percentage of catchments with a surface area between 0–5,000 m², while the terrace-removed DEM has a spike between 5,000–10,000 m² (Figure 7). However, the terraced DEM also exhibits a higher percentage of catchments in the range of 20,000–25,000 m². Visually, the terraced landscape creates wider, shorter catchments while the terrace-removed topography produces narrower, elongated catchments. The FAC values were exported from the raster image and examined in terms of both the mean and density. The results from the FAC analysis revealed that the terraced DEM has a mean FAC value of 189, while the terrace-removed DEM has a mean FAC value of 285. To confirm and highlight these trends, a smaller area of the survey zone was sampled. This area was selected on the basis that it was subjected to theodolite survey as well as an excavation that presented a uniform sloped nature to the underlying bedrock. Mean FAC values of 288 for the terraced DEM and 232 for the terrace-removed DEM were produced when analyzed (Figure 8). These conflicting numbers were explored by examining the FAC density distribution. Results indicated a higher percentage of lower FAC valued cells and ultimately a few of the highest FAC cells within the terraced DEM. The terrace-removed DEM presents a more even distribution of FAC, reducing in density as the FAC increases. This same trend is present in the sampled area, although several of the extreme values, likely outliers, were removed (Figure 9). This is confirmed by the visual analysis of the steam networks. The terraced DEM presents much broader accumulation, and more evenly dispersed networks, while the terrace-removed DEM exhibits narrower, less dispersed accumulation networks. This is especially clear in the broad sloping hillsides found in the north of the survey zone.

DISCUSSION

This research demonstrates the potential that a lidar dataset coupled with the hydrological mapping program Arc Hydro holds for the investigation of ancient Maya hydrology, particularly the impact of geointensive agricultural systems on the drainage catchments and movement of water and sediments across the managed landscape.

Our method of analysis was dependent on the resolution of the surface model. The lidar dataset provided the necessary control points to interpolate a high-resolution DEM. However, throughout the process, we made several decisions based on the survey and excavations conducted at Waybil. Ground-truthing confirmed the accuracy and features present in the surface model. As a result, we determined that IDW interpolation best revealed the anthropogenic qualities at Waybil. Producing and confirming this level of resolution was imperative for hydrological post-processing.

Crucial to interpreting the relationship between the agricultural terraces and the hydrological processes is determining whether the drainage catchments and flow accumulation identified are a result of the agricultural terraces. To address this issue, we compared the catchments and FAC of the terraced DEM and terrace-removed DEM. This revealed minimal difference in terms of the number of catchments, while a significant difference was identified in the surface area. The clear differences in percentage of catchments between 0–10,000 m² indicate that the agricultural terraces are affecting the drainage networks. However, the most dramatic differences are found in the visual assessment of catchment shape. To confirm these differences, we examine the FAC. The density distribution of the FAC of both the terraced DEM and terrace-removed DEM suggests an important divergence. The higher percentage of low-level FAC in the terraced DEM indicates that the agricultural terraces are decreasing the medium-level FAC across the landscape, resulting in a more even, lower FAC across the field systems. This trend was highlighted and confirmed in the analysis of the smaller sample area. The wider collection of FAC attests to the infrequent, yet highest, FAC values in the terraced DEM. The analysis of the drainage catchment and FAC in both the terraced DEM and non-terraced DEM clearly indicates that the agricultural terraces are manipulating the hydrological processes.

Clear association between FAC, areas prone to soil erosion and excess water, and the placement of agricultural terraces supports the argument that terraces combat erosion while accumulating sediment, as well as conserving and evenly dispersing water (Figure 10). The majority of agricultural terraces are found perpendicular to the stream networks in areas of higher FAC, while functioning in two different manners. First, the cross-channel terraces bisect paths of higher FAC, functioning to slow the movement of sediment in those areas prone to erosion, while maximizing the size of the planting surfaces with acquired sediments. These terraces are also capitalizing on the capture and dispersal of water. Second, the contour terraces, while bisecting paths of higher FAC, are also functioning to disperse these values, increasing the number of stream segments in the network and lowering the FAC. This process diffuses the sediment and water flow associated with a high FAC laterally across the landscape.

On a broader scale of analysis, interpretations can be drawn for the terraced field systems. Although the visual assessment of the catchment areas is a qualitative assessment, results suggest that the intentional function of the agricultural terraces was to disperse water and sediment over a broad area, rather than directing these to specific field systems or away from the fields (to protect against flooding, for example). This is supported by evidence of terrace walls transcending catchment areas (Figure 11). If a larger threshold were specified for the stream networks that created the catchment, a broader trend might appear; this requires a larger scale of analysis and thus a larger survey zone. The current trend suggests that terrace construction was

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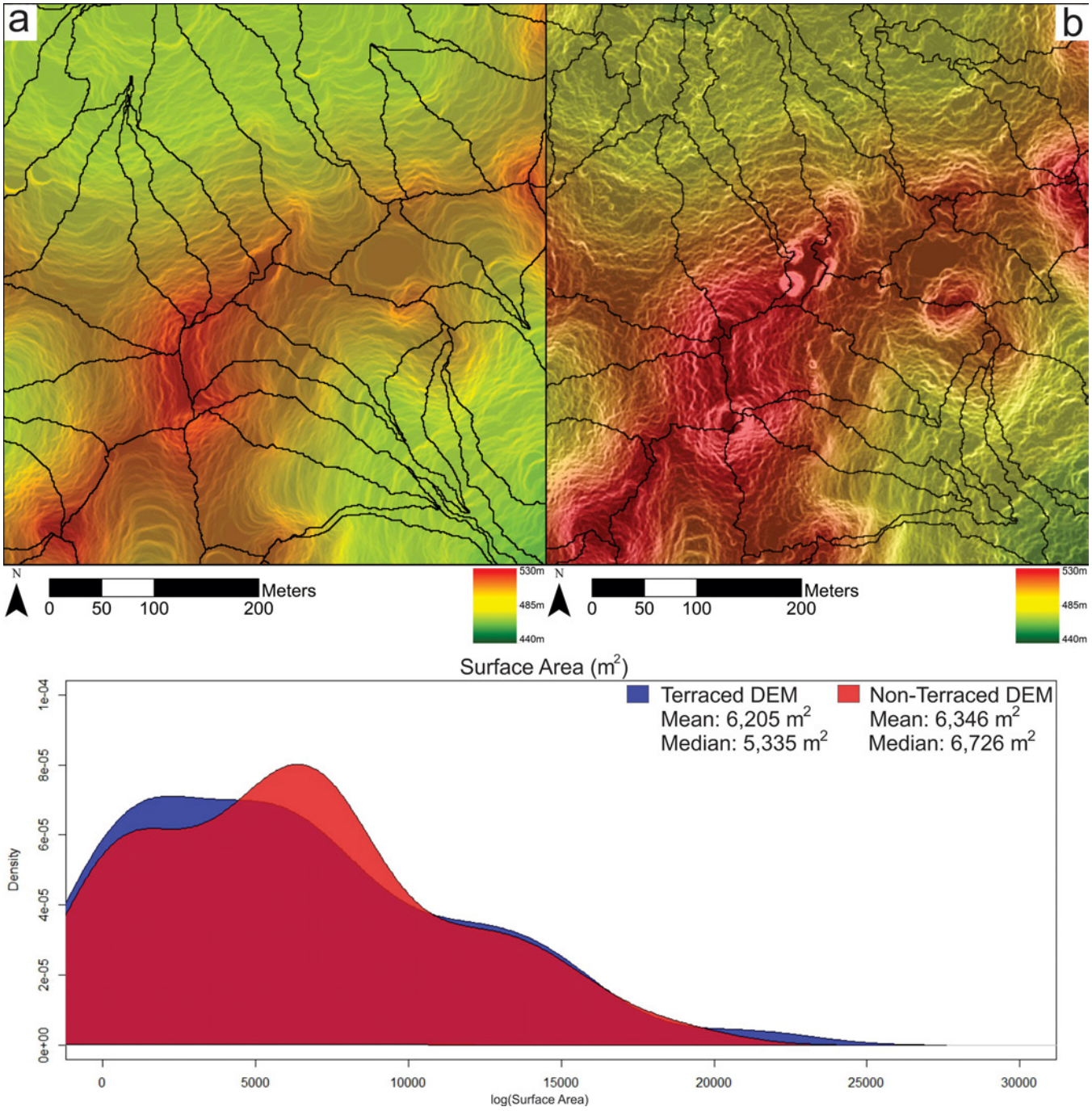


FIGURE 7. Surface area: (a) terrace-removed DEM depicting catchments; (b) terraced DEM depicting catchments; (c) density distribution of surface area of terrace-removed DEM and terraced DEM.

not organized around catchments, at our scale of analysis, and that terraces represent a degree of manipulation to ensure that water could be more laterally shared between catchments, or accumulated in larger catchments. The stream networks created by higher density of low FAC values and a lower density of high FAC values in the terraced DEM present a pattern of wider horizontal accumulation and a directed lateral dispersal of water and sediment. Results suggest: (1) agricultural terraces are more evenly distributing the FAC of sediment and water across field systems; (2) the terraced landscape presents a larger, collectively accumulated FAC, terminating in a few places; (3) the lower FAC on terraced field systems reduces saturation and pressures exerted on the terrace walls in wet seasons, while increasing the even distribution of water during the dry season.

Combined, the drainage catchments and FAC suggest that the agricultural terraces found so prolifically across the Waybil survey area do not support a model of large-scale manipulation

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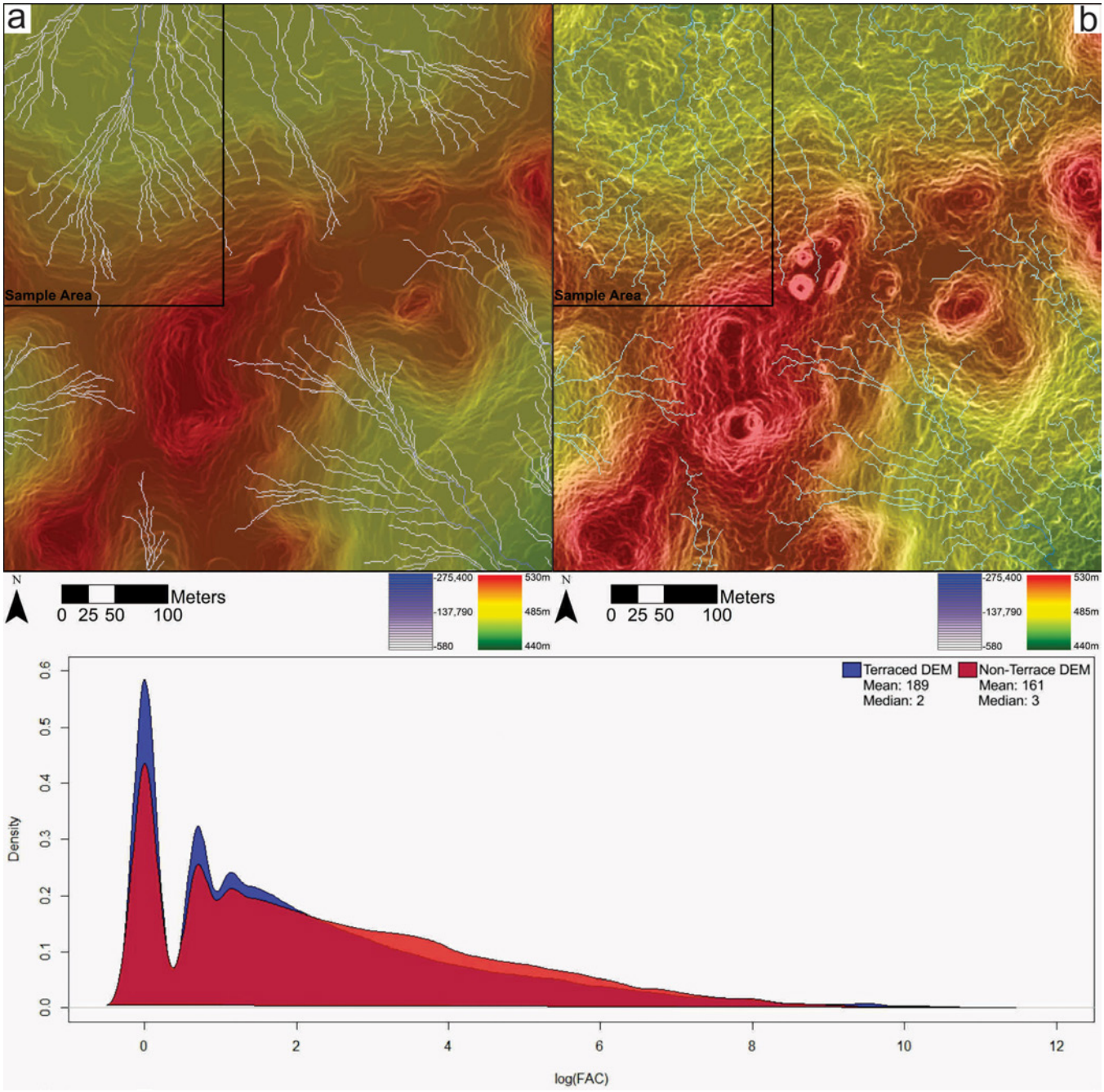


FIGURE 8. Flow Accumulation (FAC): (a) terrace-removed DEM depicting FAC; (b) terraced DEM depicting FAC; (c) FAC density distribution for terrace-removed DEM and terraced DEM.

of the local hydrological process that would have resulted in drastic catchment changes. Rather, the terraces acted in a more nuanced fashion to complement the natural topography while broadening the distribution of key resources.

Future Work

Demonstrating the results of flow accumulation and Catchment analysis, we have presented just a few of the possible lines of investigation that are possible using lidar generated hydrological models. Three potential lines of future inquiry include multi-scalar approaches, groundwater mapping, and time-series analysis. Exploring a multi-scale approach can address how the trends identified in this study extrapolate over a much larger area. Incorporating geometrical statistics in a catchment analysis would be very beneficial here. This scale of analysis requires significant ground-truthing of agricultural and water management features. However, the ever-increasing collection of lidar datasets is providing the basis for such interpretations (Wienhold 2013). The exploration of groundwater is a vital component for fully understanding hydrology. This involves mapping sub-

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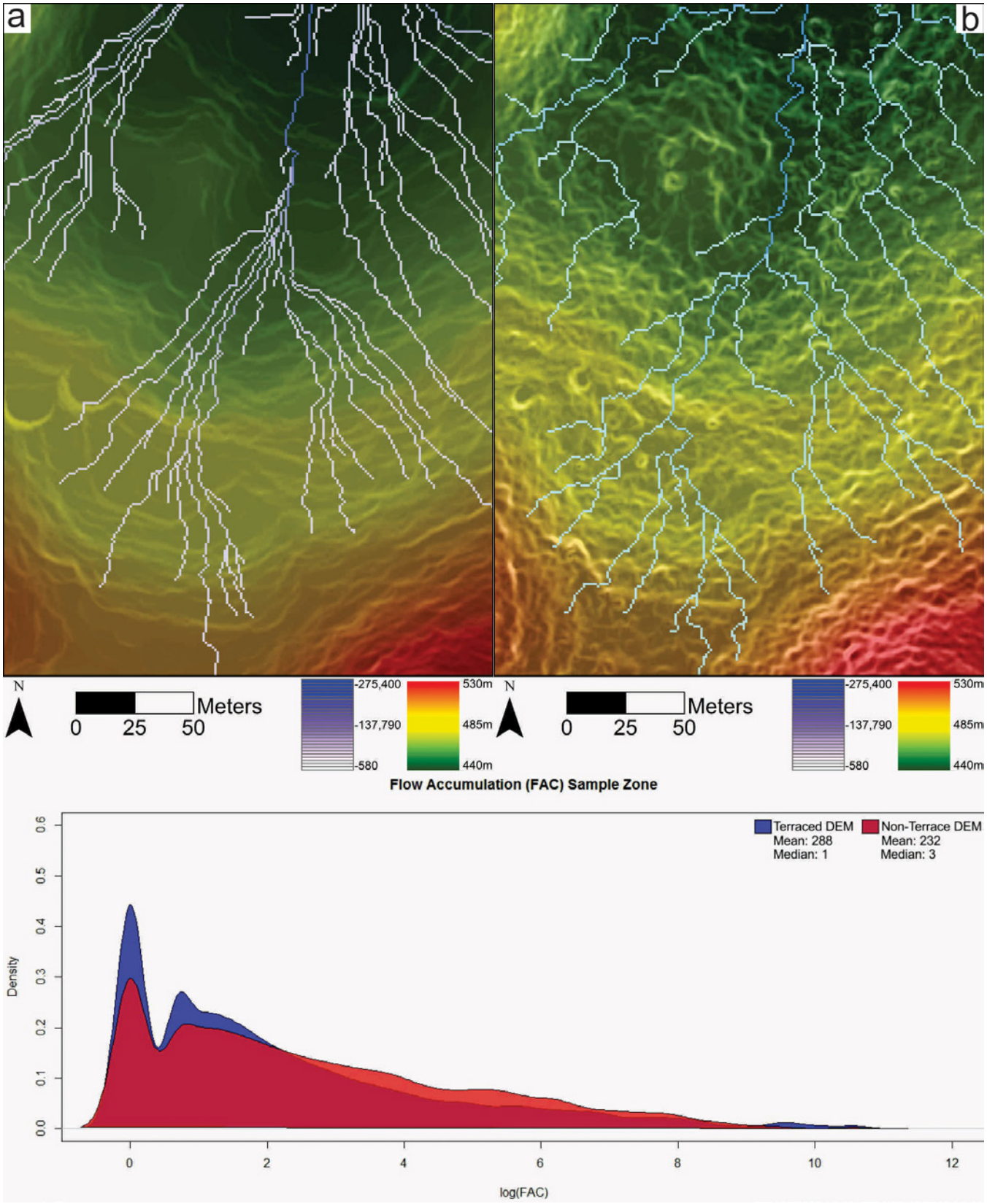


FIGURE 9. Flow Accumulation (FAC) in sample zone: (a) terrace-removed DEM depicting FAC in sample zone; (b) terraced DEM depicting FAC in sample zone; (c) FAC density distribution for terrace-removed DEM and terraced DEM in sample zone.

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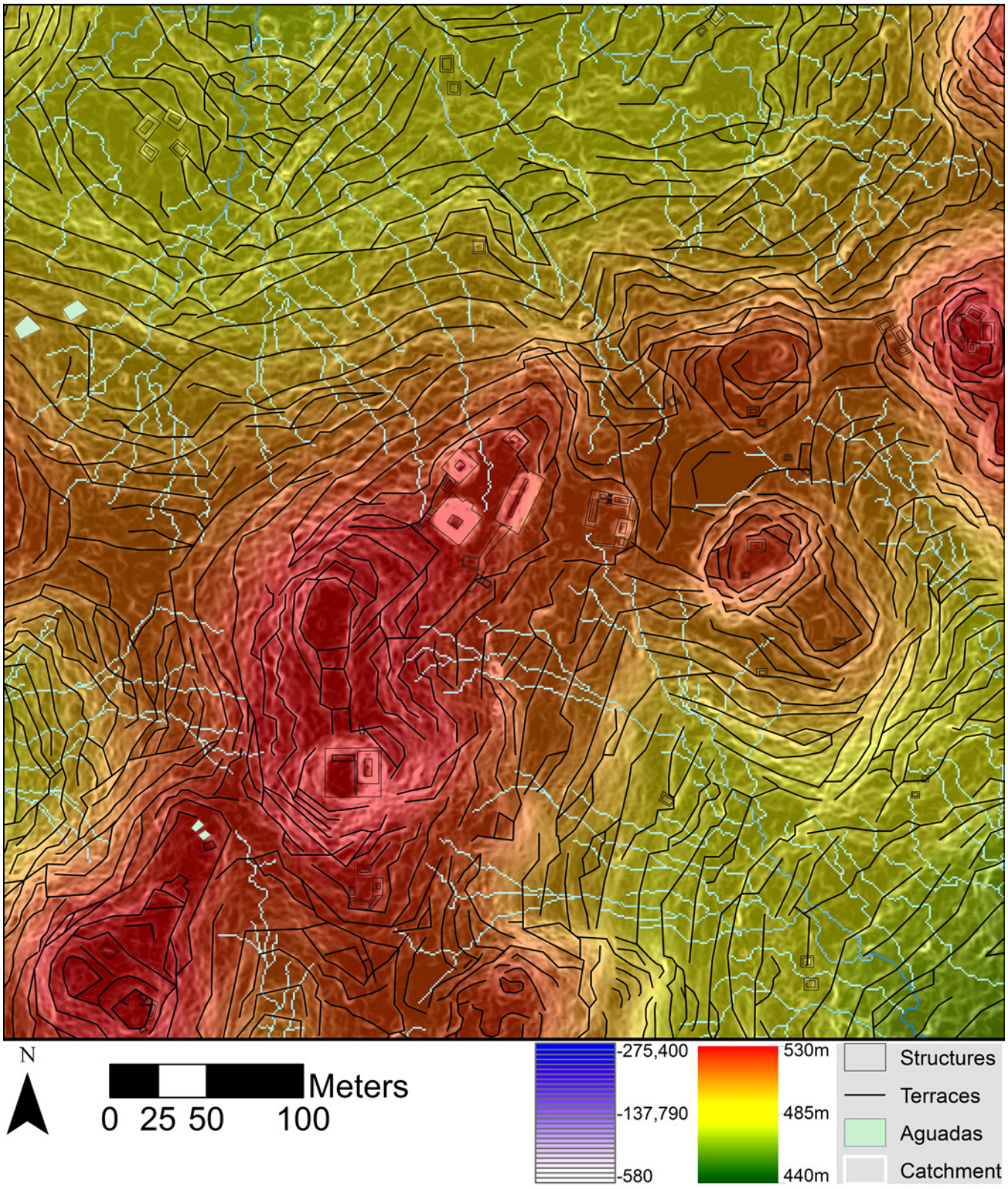


FIGURE 10. Flow Accumulation with digitized agricultural terraces and structures in the Waybil survey zone.

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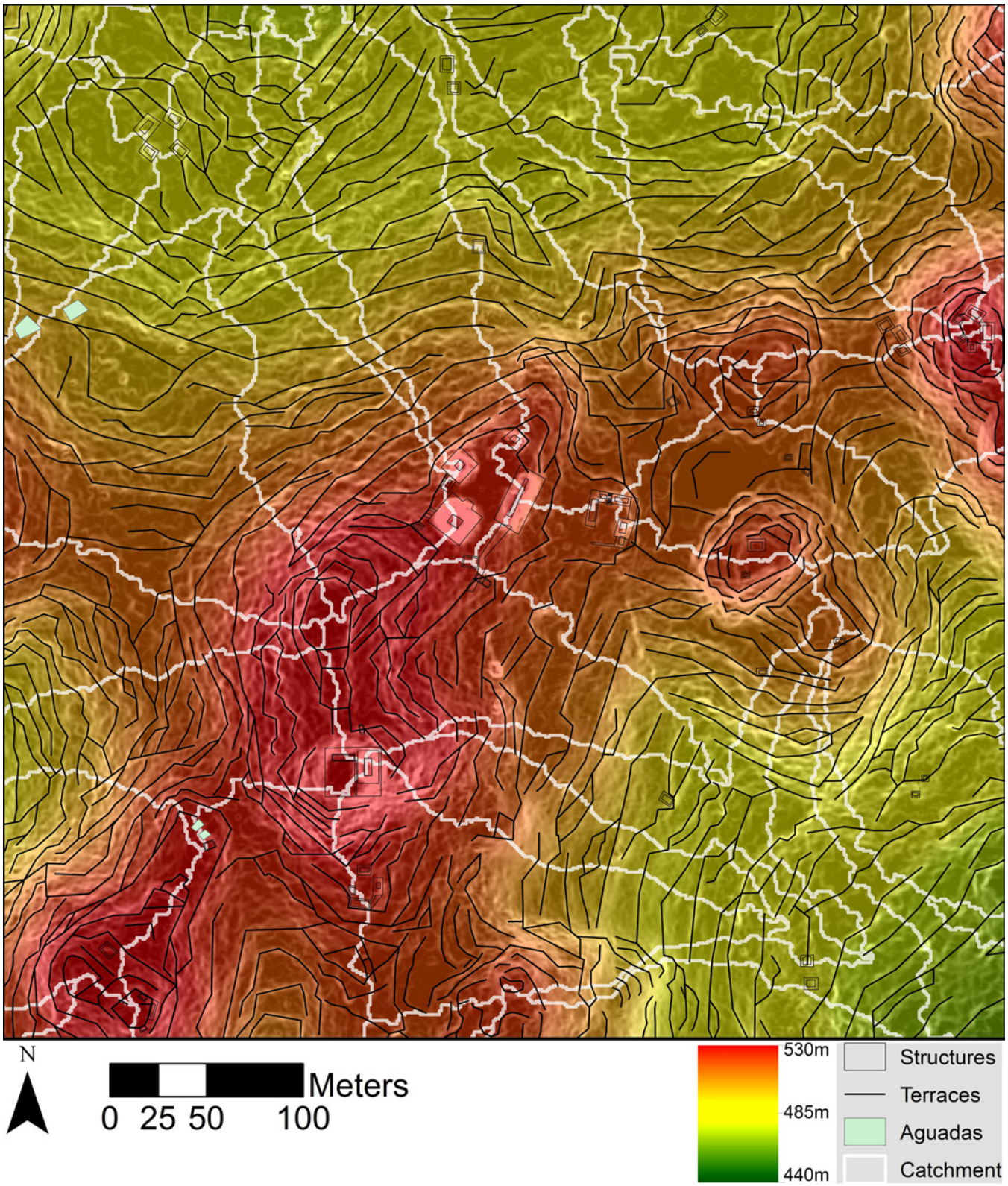


FIGURE 11. Catchment delineation, using 2 percent Flow Accumulation threshold, with digitized agricultural terraces and structures in the Waybil survey zone.

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surface water across the landscape (see Strassberg et al. 2011) and requires a systematic geological survey of the study area accompanied by comprehensive pedological analysis. The level of detailed investigation necessary for such analysis has been accumulating within the Maya area. Research in Northern Belize, the Peten region of Guatemala, and the Sierra regions and Usumacinta plains of western Guatemala and eastern Mexico holds the greatest potential for such investigations (see Beach 1998a, 1998b; Beach et al. 2006; Beach et al. 2008; Beach et al. 2009; Dunning and Beach 1994; Fernandez et al. 2005; Foias and Emery 2012; Johnson et al. 2007; Lentz et al. 2015; Liendo et al. 2014; Luzzadder-Beach et al. 2012). Understanding groundwater movement across relic field systems and surface permeability may assist in describing and quantifying construction techniques, such as terrace walls, or the incorporation of other subtle water management features. Finally, time-series analysis has the ability to model changes in both surface and groundwater over a specified time period. The recent advancements in highly accurate climatic data within Vaca Plateau make this a real possibility (see Brook and Akers 2010; Iannone, ed. 2014; Polk et al. 2007; Polk 2010; Reeder 2010; Webster 2000). With this technique, archaeologists will be able to assess changes in the drainage patterns throughout an agroecosystem and across a defined time frame, allowing them to assess the development, transformation, and even the demise of specific agricultural strategies (Macrae 2016). However, a strong chronological sequence for the agricultural features in question is required to conduct such analyses.

CONCLUSIONS

A large component of this article has been specifically aimed at examining the potential for using lidar data in detailed hydrological analysis. Lidar has proven to be a valuable tool for interpolating high-resolution DEMs necessary for accurately mapping flow accumulation and delineating hydrological catchments. The high number of point returns provides both the horizontal and vertical accuracy to produce surface models that capture the anthropogenic qualities in the landscape. The acquisition of such datasets facilitates several unique ways of investigating relic anthropogenic landscapes. In this study, we have demonstrated how the accuracy of a lidar dataset, coupled with traditional archaeological research, can be transmitted to a hydrological model. Using this level of resolution, we were able to identify the effect that agricultural terraces had on the hydrological processes at the ancient Maya minor center of Waybil. We analyzed both flow accumulations and drainage catchments to more fully understand the distribution and function of agricultural terraces in preventing soil erosion and water saturation while also facilitating sediment accumulation and water dispersal. This hydrological approach brings us a step closer to confirming and quantifying the role these features play in geointensive agricultural strategies. Our results confirm that the ancient Maya had a sophisticated understanding of hydrological processes. These initial observations also suggest great potential for future investigations using these analytical tools with different agricultural strategies both within and outside of the Maya area.

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Data Availability Statement

This article is based on data excavated and surveyed by SARP. The excavation and survey of Waybil were primarily supervised by Gyles Iannone, Scott Macrae, Pete Demarte, and Kendal Hills, whose site report chapters contain raw data and may be emailed by the first author upon request. The analysis and interpretation of the agricultural terraces rely on the ongoing Ph.D. dissertation by Scott Macrae; upon completion, the dissertation it will be available on Proquest with supplemental material published through Open Context (opencontext.org). Moreover, several papers presented at the Belizean Archaeology Symposium by the authors contain preliminary interpretations and are available in the conference proceedings. The greater agricultural study at Waybil will be available through the Florida Museum of Natural History (FLMNH) website (flmnh.ufl.edu/envarch) and ongoing research exhibits (http://www.flmnh.ufl.edu/exhibits/always-on-display/exploring-our-world/). The collection of the lidar data for western Belize in 2013 was a collaborative effort by the archaeologists working in western Belize with the Institute of Archaeology and was not issued a formal permit. In accord with the wishes of the Institute of Archaeology in the country of Belize, the lidar data reported in this article are not available to the general public in order to protect the country's archaeological resources from further looting. However, the LAS digital files are on file with the Institute of Archaeology in Belize and may be provided to qualified professional researchers for valid teaching and learning purposes on a limited basis. The person to contact in Belize with regard to these files is: Dr. John Morris, Director, Institute of Archaeology, Archaeology Museum & Research Centre, Culvert Road, Belmopan City, Belize; phone: 501-822-2227; email: research@nichbelize.org.

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