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ARTICLE

Beyond Visualization: Remote Sensing Applications in Prehispanic Settlements to Understand Ancient Anthropogenic Land Use and Occupation in the Sierra Nevada de Santa Marta, Colombia

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Abstract
Archaeology is increasingly employing remote sensing techniques such as airborne lidar (light detection and ranging), terrestrial laser scanning (TLS), and photogrammetry in tropical environments where dense vegetation hinders to a great extent the ability to understand the scope of ancient landscape modification. These technologies have enabled archaeologists to develop sophisticated analyses that overturn traditional misconceptions of tropical ecologies and the human groups that have inhabited them in the long term. This article presents new data on the Sierra Nevada de Santa Marta in northern Colombia that reveals the extent to which its ancient societies transformed this landscape, which is frequently thought of as pristine. By recursively integrating remote sensing and archaeology, this study contributes to interdisciplinary scholarship examining ancient land use and occupation in densely forested contexts.

Resumen
La arqueología está utilizando crecientemente técnicas de teledetección tales como láser aéreo y terrestre y fotogrametría en ambientes tropicales donde la densa vegetación dificulta la posibilidad de entender la magnitud de modificaciones antiguas del paisaje. Estas tecnologías ha permitido a los arqueólogos implementar análisis sofisticados para revaluar ideas tradicionales de las ecologías y los grupos humanos que han habitado estas regiones en el largo plazo. Este artículo presenta nuevos datos de la Sierra Nevada de Santa Marta, en el norte de Colombia, que revelan hasta que grado las sociedades prehispánicas transformaron este paisaje, usualmente interpretado como prístino. A través de la integración de datos de sensores remotos y arqueologógicos, este artículo contribuye a las investigaciones interdisciplinarias que examinan el uso y ocupación prehispánica en contextos de vegetación muy densa.

Keywords: ancient land use and occupation; Sierra Nevada de Santa Marta; airborne lidar; TLS; photogrammetry

Palabras Clave: uso y ocupación del espacio en la antigüedad; Sierra Nevada de Santa Marta; lidar; TLS; fotogrametría

In the past two decades, archaeology has reframed its view of the relationship between densely forested ecosystems and the development of complex societies. Underneath the thick canopy of the Amazon, Cambodia, and Belize, archaeologists are increasingly finding evidence of intensive landscape transformation via extensive ancient settlement systems (Chase et al. 2014; Evans et al. 2007; Heckenberger et al. 2008). These findings are leading scholars to question long-held views of these regions as being void of sociopolitical complexity (e.g., Meggers 1954; Steward 1946, 1948; Willey 1966) and to acknowledge that their ancient societies developed ways of life as sophisticated as urbanism and political forms as complex as states and empires (see Chase and Chase 2017; Evans et al. 2013; Fletcher 2012). The steady growth and progressive accessibility of remote sensing techniques such as airborne lidar (light detection and ranging), terrestrial laser scanning (TLS), and photogrammetry have been crucial for this reappraisal. They have provided the tools to overcome dense vegetation that hindered understanding of the extent of ancient landscape modification (Chase et al. 2011; Evans et al. 2013; Ford and Horn 2019; Prufer et al. 2015; Rosenswig et al. 2013; Saunaluoma et al. 2019).

Before these techniques were available, a handful of archaeologists had found some evidence of sociopolitical complexity in tropical forests, on the basis of which they proposed alternative models acknowledging ancient sociopolitical complexity and sophisticated landscape modification in tropical forests (e.g., Coe 1957; Lathrap 1970). Nonetheless, the absence of extensive data and the lack of tools to collect it impeded the wide acceptance of such models. The Amazon, Mayan Mesoamerica, and Cambodia, where airborne lidar has been widely applied, illustrate these theoretical and methodological changes (see Chase et al. 2011; Evans et al. 2013; Prufer et al. 2015). However, in contexts where lidar and other remote sensing techniques were not readily available, the traditional misconceptions of tropical ecologies and the human groups that inhabited them continue to hinder the development of alternative models, reducing archaeological and cultural heritage research to monumental site centers, much to the detriment of regional land use and occupation studies. This is the case of the Sierra Nevada de Santa Marta (SNSM), Colombia, where research has focused on two archaeological sites, Teyuna-Ciudad Perdida and Pueblito; despite the data yielded by previous regional surveys, sociopolitical development and spatial organization theories have been limited to these sites.

In this article we present an unprecedented view of the Sierra Nevada de Santa Marta that reveals the extent to which its ancient societies engineered this landscape before the European invasion. We use airborne lidar and integrate TLS and photogrammetry in two analogous archaeological sites to model the prospective location of settlements and cultivable areas underneath the dense canopy, revealing a sprawling anthropogenic ancient landscape in which sites often interpreted as regional centers become part of borderless settlement systems that intensively transformed this region of northern Colombia. The study sites, Teyuna-Ciudad Perdida and Congo-Ciudad Antigua, are two of more than 250 ancient settlements identified in the SNSM that belonged to independent polities that shared sociocultural traits (Cadavid and Herrera 1985; Reichel-Dolmatoff 1951; Figure 1). The architecture and archaeological evidence of both sites show observable similarities and differences. They constitute two of the most remarkable architectural remains of Colombia's prehispanic heritage.

Tropical Environments and Sociopolitical Complexity

The groundbreaking work of archaeologists worldwide is changing our view of tropical environments as having been pristine forests inhabited by so-called primitive societies to built landscapes that are the product of long-term processes in which Indigenous groups developed complex sociopolitical forms and sophisticated economies that intensively transformed these environments (e.g., Chase and Chase 2017; Fletcher 2009, 2012; Heckenberger et al. 2008; Hutson 2015). Previous theories saw in the environmental conditions of tropical forests obstacles to the development of intensive agriculture, state-level political organization, urbanization, and other elements of sociopolitical complexity. For example, the theory of environmental limitation argues that the environmental unsuitability of the Amazonian soils—deemed as profoundly weathered and poor in nutrients—largely hindered the development of large-scale economies capable of yielding the agricultural surplus required to trigger civilization (Meggers 1954). Similarly, the dense vegetation in Belize and Guatemala not only reduced the ability to thoroughly assess the extent and density of Maya land use and occupation but also fed the long-standing misconception that tropical forests are significant obstacles to civilization (Chase and Chase 2017).

Archaeologists have proposed alternative models that recognize the economic and sociopolitical sophistication of the ancient societies that peopled tropical environments. For the Amazon rainforest, Donald Lathrap's (1970, 1973) cardiac model suggested that the floodplains of Amazonia and northern South America constituted the core of the Americas' civilization. Subsequentially a long-term

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Figure 1. (A) Congo-Ciudad Antigua (photograph by Eduardo Mazuera, 2018); (B) Teyuna-Ciudad Perdida (photograph by Eduardo Mazuera, 2015); (C) location of Teyuna-Ciudad Perdida and Congo-Ciudad Antigua. (Color online)

historical-ecological research agenda has demonstrated that, rather than there being a primeval forest unsuitable for civilization, Indigenous communities profoundly transformed and built the Amazonia environment through sophisticated practices that produced *terras pretas*, intricate networks of settlements with awe-inspiring infrastructure with an urban character; sustainable agroforestry systems that did not depend on exclusive staples; and complex stateless polities (Balée 1995; Denevan 2001; Neves et al. 2003). In addition, data from research at epicenters like Caracol (e.g., Jaeger 1991) and Tikal (e.g., Puleston 1983; Sabloff 2003), along with regional settlement pattern studies, led some scholars to theorize that the Maya developed urbanism and competing regional polities (Chase and Chase 2017; Haviland 1970). However, the absence of extensive data and the infeasibility of full-coverage regional surveys because of cost and time prevented these models from becoming widely accepted.

Airborne lidar has contributed to change this situation by enhancing the detection of archaeological features, including ancient settlements (Canuto et al. 2018; Hagan and Brown 2019; Thompson 2020), agricultural features (Ebert et al. 2016; McCoy et al. 2011), ancient roads networks (Friedman et al. 2017), and other anthropogenic landscape modifications (Hesse 2010; Prufer and Thompson 2016; Štular et al. 2012; Verhagen 2012). This has enabled recent scholarship to overturn traditional accounts of urbanism, agricultural intensification, and political organization in several parts of the world (Chase and Chase 2017; Evans et al. 2013). The results of airborne lidar-derived analyses in the Maya Lowlands (Chase et al. 2014) and Angkor Wat (Evans et al. 2007) strongly suggest that these areas developed a form of low-density agricultural urbanism grounded on the practice of agriculture within urban confines that produced sprawling settlements that completely transformed regional landscapes (Fletcher 2009, 2012). Furthermore, archaeologists used TLS in their research to improve the documentation of archaeological sites and features (Garrison et al. 2016; Rodríguez-Gonzálvez et al. 2017). This enabled several types of analyses, such as highly detailed stratigraphic interpretations in geoarchaeology (Tapete et al. 2017) and systematic architectural surveys (Arav et al. 2015; Weber and Powis 2014), that provide richer data than unaided visual observations. Although the application of TLS is in the beginning of the transition from visualization to more sophisticated analytical endeavors, there is little doubt of its potential, and scholars are increasingly discussing how to incorporate it into archaeological praxis in strategic ways (Galeazzi 2016; Gonzalez et al. 2017; Grimaud and Cassen 2019; Hagan and Brown 2019; Lerma et al. 2010; Richards-Rissetto 2017). In fact, researchers such as Tapete and colleagues (2017) have recently highlighted the relevance and possibilities of integrating diverse lines of evidence, including geological, airborne lidar, and TLS data, to bring together regional and local scales in understandings of past human land use, occupation, and landscape modification.

Archaeology in the Sierra Nevada de Santa Marta

Before European contact, the Indigenous populations inhabiting the Sierra Nevada de Santa Marta (AD 100–1600), commonly grouped by scholars under the general ethnonym *Tairona*, intensively transformed the northern and western slopes of this coastal mountain range located in northern Colombia that rises from sea level to 5,775 m asl and encompasses a vast diversity of ecosystems. These modifications included the building of large stone masonry settlements interconnected by extensive networks of flagstone pathways and the production of an agricultural landscape over the broken topography of the massif (Cadavid and Herrera 1985; Giraldo 2010; Groot de Maecha 1985; Herrera 1984, 1985; Serje 1987, 1984; Soto 1988). Most ancient settlements were built from the seashore up to 1,000 m asl, somewhat fewer up to 2,000 m asl, and very few above that altitude (Herrera 1984, 1985). Many settlements are located on ridgelines and adjoining slopes between rivers, allowing access to clean running water from a defensive and visually dominant position (Giraldo 2010; Serje 1987). Other villages were established alongside riverbanks on relatively flat areas, bays and inlets, flat coastal areas, and deeper canyon locations with more accessible transit roads for exchange and communication (Giraldo 2010).

Archaeologists have hypothesized that the construction of these settlements started in the lowlands of the massif from AD 200 to 1100, during the Neguanje period, and developed later in the upper slopes from AD 1100 to 1600, during the Tairona period, in response to population growth and environmental crisis (Oyuela-Caycedo 1985, 1987:221, 1998; Langebaek 2005). However, recent research in Teyuna-Ciudad Perdida shows that the construction of settlements in the upper ranges started as early as AD 400 in the Neguanje period (Giraldo 2010). Although there is consensus that these two periods characterize the chronology of the SNSM, scholars have reported variations from site to site that suggest very localized trajectories, rather than homogeneous horizons across all settlements.

Curved stone masonry walls filled with rammed earth were used in both periods to build terraces on which circular-cut and dressed stone foundations were emplaced. Dwellings, temples, public structures, and storage buildings made from wood and palm thatching were then built and sequentially rebuilt on these stone and rammed earth foundations. Perishable construction materials disappeared, leaving the stone foundations. These constructions constitute great feats of engineering given the difficult terrain and the transportation of massive stone elements. Additionally, the complex system of stone-paved paths, stairs, walls, and rainwater drainages is evidence of advanced building abilities amid the rugged topography, tropical rainforests, and high pluviosity of the SNSM (Soto 1988).

Until recently, scholars had primarily considered these stone masonry settlements to be an adaptive strategy to the massif's environmental conditions that produced no major alterations to its ecosystems (Groot de Maecha 1985; Herrera 1984, 1985; Serje 1984, 1987). For instance, Ana María Groot de Maecha (1985) regarded stone architecture as evidence of an almost nonintrusive construction technique that allowed for population growth within a fragile ecosystem without negative impacts. In the same vein, Luisa Fernanda Herrera's (1985) palynological data suggested a relatively rapid forest regeneration after the abandonment of sites like Teyuna-Ciudad Perdida in the sixteenth century. That Tairona settlements were quickly covered by vegetation and forest was interpreted as a clear indicator of a modest ecological footprint. Although these accounts productively concentrated on environmental management and sustainability, they did not explore the extent to which Tairona settlements and agriculture transformed the massif in the long term, enabling certain ecological successions and sociopolitical processes that would not have occurred without this intensive and extensive landscape engineering. Furthermore, the data that were analyzed correspond almost exclusively to extensive research conducted at Teyuna-Ciudad Perdida and Pueblito, two archaeological sites located on the northern slopes of the SNSM (Cadavid and Herrera 1985; Giraldo 2010; Herrera 1985;

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Reichel-Dolmatoff 1954a, 1954b; Serje 1987, 1984; Soto 1988). Despite the intensive occupation inferred from the historical and archaeological reports, the data currently available are insufficient to understand the scope of land use and occupation of the SNSM. For example, extensive pedestrian surveys confirmed the existence of more than 250 Tairona settlements in its northern and northwestern slopes (Bahn et al. 1974; Cadavid and Herrera 1985; Wynn 1975). However, their descriptions only provide preliminary information, and most of these archaeological sites have not been revisited because of their difficult access and remote locations.

Newer research has questioned these approaches by foregrounding the study of local occupation and construction sequences to understand the constitution of power and economic specialization and their role in the emergence of urbanism (Dever 2007; Giraldo 2010; Langebaek 2005). For instance, Santiago Giraldo (2010) examined how the Tairona produced a political landscape that materialized power in ways typically overlooked by archaeologists. In contrast to previous interpretations, he found that the construction of Teyuna-Ciudad Perdida and Pueblito, located in completely different ecological settings (rainforest and dry tropical forest) and altitudes, began simultaneously during the Neguanje period. Their inhabitants built the same open architecture of rammed earth terraces and stone masonry walls interconnected by intricate networks of stone pathways that privileged uninterrupted movement over enclosure and exclusion. Still, in the absence of enclosures, these pathways effectively controlled how people moved, subtly favoring and restricting access to certain areas (Giraldo 2010). This approach proposes that ancient landscape production of the SNSM resulted from a complex entanglement of variables: the constitution and institutionalization of diverse sociopolitical forms, the integration of agriculture and urbanism to the emergence of these polities, and the production of a relatively standardized aesthetics in terms of architecture and material culture among such ecological diversity. Although this scholarship sheds new light on how the ancient population of the SNSM built a political urban landscape, it is limited to a handful of archaeological sites and, as a result, does not account for broader patterns or interconnections. In this article, we address this limitation by assessing whether and how different lidar approaches can unveil the extent of prehispanic land use and occupation in the SNSM.

Airborne Lidar: Teyuna-Ciudad Perdida and the Upper Buritaca River Basin

Airborne lidar data allow us to estimate the extent to which the Tairona people transformed the Upper Buritaca zone (northern SNSM) through the construction of settlements and agriculture fields. Based on the archaeological knowledge from this massif, we established four variables—*slope*, *relief*, *shape*, and *size*—to detect prospective areas of land use and occupation. Our results yield a broader, cross-watershed understanding of the ancient human environmental modification in this region of northern South America that challenges previous interpretations rendering it as a primeval and mostly untouched landscape (e.g., Aja Eslava 2010; Cardoso 1987; Soto 1988).

Materials and Methods

In March 2019, the National Geographic Society subcontracted with cinematography producer Aerial Filmworks to conduct lidar scanning throughout an area of approximately 671 ha located in the Upper Buritaca River basin, encompassing the archaeological site of Teyuna-Ciudad Perdida and sites G-1, G-2, B-201, B-202, and B-203 (Supplemental Text 1). Raw data were handed over to the local Pro Sierra Nevada de Santa Marta Foundation and the Colombian Institute of Anthropology and History for further research. This article's lead author Daniel Rodríguez Osorio conducted a pilot ground-truthing field season in 2019 to assess the accuracy of a preliminary pixel-based unsupervised classification that he derived from the airborne lidar dataset.

Next, Rodríguez Osorio undertook two stages of processing. The first corresponded to the classification of the lidar point clouds dataset into two discrete classes: ground and vegetation (Supplemental Text 1). LAStools software suite version 180911 and ArcGIS PRO 2.5 were used for processing and developing a workflow that followed parameters equivalent to those established by researchers such as Evans and colleagues (2013), Lasaponara and colleagues (2011), Isenburg (2013), Verhagen (2012), and Prufer and colleagues (2015). The parameters were set to the specific conditions of the

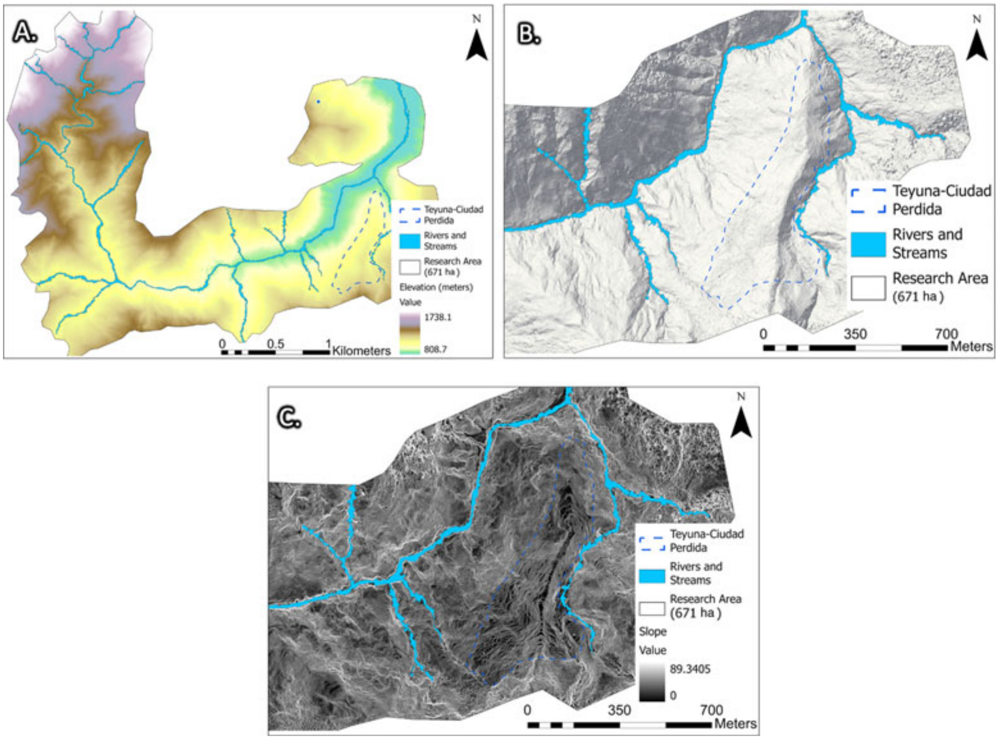

Figure 2. Products derived from airborne lidar dataset. (A) DTM (30 cm); (B) hillshade raster derived from DTM (30 cm); (C) slope gradient model derived from DTM (30 cm). (Color online)

steep topography and dense canopy of the Upper Buritaca area, yielding a classification that accurately discriminated bare earth from vegetation. Then the bare earth point cloud—with an average density of 25 points/m^2—was extracted and processed into a 30 cm resolution DTM, from which hillshade and slope gradient models were produced using ArcGIS Pro. Figure 2 illustrates how the DTM and hillshade models accurately render the topography of the research area, suggesting that the slope gradient model is best suited for visualizing archaeological features in the Upper Buritaca area.

In the second stage of processing, through object-based image analysis (OBIA), one unsupervised and two supervised classifications were produced to detect prospective prehispanic anthropogenic areas. OBIA is an approach that clusters pixels into discrete objects based on spectral, textural, or contextual similarity, allowing the incorporation of many variables into classification exercises (Drăgut and Blaschke 2006). This analysis entails a segmentation stage that uses predefined parameters derived from real-world knowledge that are used to create objects that are then classified (Gao et al. 2006). It offers the potential to deal with some of the shortcomings identified in pixel-based classification approaches, such as the difficulty of including topological relationships in classifications and the production of speckle noise by high local spatial heterogeneity between neighboring pixels in fine spatial resolution imagery (Dorren et al. 2003; Drăgut and Blaschke 2006; Herrera-Fernandez et al. 2004).

OBIA is a relatively new technique within archaeology that has yielded versatile surface cover classifications enabling the automated identification of archaeological features. However, as Verhagen (2012) notes, to become a fully applicable methodology, the categories used by archaeologists need to inform the classes and object images that constitute such classifications. To conduct the OBIA classifications presented here, we build on Verhagen (2012) by translating fieldwork knowledge of the SNSM into four variables (slope, relief, shape, and size) akin to Ecognition 9.4 processing parameters. This dimensionality-reduction exercise allowed us to prioritize the kind of information with analytical significance for estimating the extent and density of prehispanic land use and occupation.

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Yet, we did not seek to reduce the trajectories of ancient land use and occupation to these four variables, because that would overlook other important aspects essential to understanding these processes and specific practices that leave completely different footprints in the landscape, which are undetectable through lidar. Moreover, despite how diagnostic these variables are, the dense vegetation cover and its long-term growth and regrowth dynamics lessen the possibility of a clean identification of archaeological sites. As Figure 3 illustrates, the pedogenetic processes in the Upper Buritaca area resulted in sediments ranging from at least 40–100 cm that cover archaeological features. In some cases, these sediments can turn 0°< 10° flat areas into slightly steeper slopes ranging from 10° to 20° (see the section on methods in Supplemental Text 1 for a comprehensive description of these variables).

We tested three algorithms on Ecognition 9.4 to produce the classifications described later. First, we conducted an unsupervised classification using a threshold-based algorithm that focused on the slope gradient and for which we established two classes, 0°< 25° for prospective ancient anthropogenic areas and 25°< 90° for nonanthropogenic areas. Then we conducted two supervised classifications using the classification and regression trees (CART) and random forest (RF) algorithms; these are two decision tree (DT) algorithms increasingly used for land cover classification because of their ability to identify and reduce meaningful variables from complex datasets (Phiri et al. 2020). To produce discrete classes, a CART algorithm builds a single decision tree using a defined array of predictor and response variables, which makes it particularly sensitive to outliers (Breiman et al. 1984). In contrast, an RF algorithm is an ensemble of decision trees based on random samples of data that yield several predictions that are then combined to define the classes of a classification (Bonaccorso 2018). To apply these classifier algorithms, we created a training sample using data from Teyuna-Ciudad Perdida and other known archaeological sites on the scanned areas—G-1, G-2, B-201, B-202, and B-203—to train the CART and RF algorithms and produce the supervised classifications.

Next, we undertook a nonsystematic and nonrepresentative accuracy assessment that used data from a pilot ground-truthing season that Rodríguez Osorio conducted (Figure 3). For this preliminary assessment, he produced a manual pixel-based classification obtained from a slope gradient model derived from the dataset that the National Geographic Society generously provided. This slope gradient model was reclassified into three classes—0°< 11°, 11°< 25°, and 25°< 90°—to identify the areas of interest, as shown in Figure 4. These classes were defined based on the data collected in previous pedestrian surveys (Cadavid and Herrera 1985; Giraldo 2010; Herrera 1985; Rodríguez Osorio 2017) and colonial documents (Reichel-Dolmatoff 1951; Simón 1981). The first class (0°< 11°) corresponds to relatively flat areas where prehispanic settlements are expected, the second class (11°< 25°) corresponds to cultivable areas located in the peripheries of the settlements, and the third class (25°< 90°) corresponds to steep topography where these practices would not have been viable. Because of time and budget limitations, we visited only 10 of 50 areas, confirming that they correspond to archaeological sites, as Figure 4 illustrates. Those areas were georeferenced and then used to assess the three OBIA classifications.

Results

The classifications produced using the threshold-based, CART, and RF algorithms (Figure 5) yield a novel view of the Upper Buritaca river basin's ancient land use and occupation: it depicts Teyuna-Ciudad Perdida as part of an intricate settlement system. The classifications started to reveal potential anthropogenic areas in the surroundings of Teyuna-Ciudad Perdida; their extent and location had been ignored because of the overwhelming dense canopy covering them. This view integrates Teyuna-Ciudad Perdida and the prospective anthropogenic areas into a settlement system that needs further study to determine whether it corresponded to the single regional center of Teyuna-Ciudad Perdida or a compound of interconnected settlements.

A visual comparison of the classifications produced using the algorithms with the classification produced in 2019 confirms that those produced by using OBIA outperformed the manual pixel-based classification (Figure 5). Furthermore, this comparison also strongly suggests the high degree of accuracy of these three classifications because the ground-truthing information collected in 2019 was not incorporated as training data for the classifiers used in this article but only for assessment. We extended this comparison by using the Jaccard Similarity Index, which measures the similarity and diversity between

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Figure 3. Stone terraces covered by trees and sediments from organic decomposition identified during ground-truthing season (2019). Photographs by Daniel Rodríguez Osorio, 2019. (Color online)

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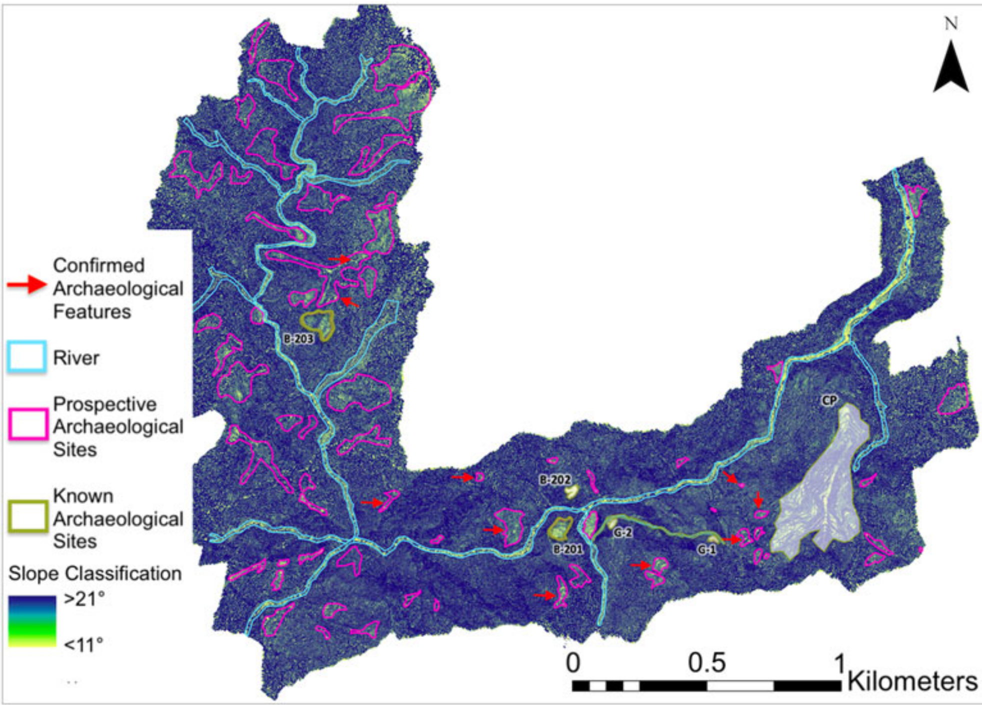

Figure 4. Manual pixel-based classification examining the slope. (Color online)

finite sample sets by dividing their intersection by the union of those sample sets. We obtained a similarity index of 74.9% between the classifications yielded using the CART and RF algorithms, which contrasts with less than 13% of similarity between those two and the threshold-based algorithm. This difference was due to the parameters used to set up the algorithms. The threshold-based algorithm only considered the slope gradient, regarding areas with angles 0°< 25° as prospective prehispanic land use and occupation areas, and those with angles 25°< 90° as areas with rugged topography where settlements and croplands would not have been viable. In contrast, the CART and RF algorithms examined values derived from parameters such as *mean*, *Max. diff.*, *area*, *length/width*, *compactness*, and *density*. Moreover, whereas those two algorithms extracted the foregoing indexes and statistics data from a training sample of areas for the two targeted classes, the threshold-based algorithm yielded an unsupervised classification that only examined the slope gradient.

Figure 5 illustrates that the threshold-based algorithm accurately identified the stone terraces of Teyuna-Ciudad Perdida, suggesting that it is well suited to classify these archaeological features as prospective areas of ancient use and occupation. Moreover, it classified as anthropogenic the areas confirmed to be archaeological features during the 2019 pilot ground-truthing season, supporting the previous observation. However, this classification seems to overlook that pedogenetic processes in the research area produced sediments that cover archaeological features, which created steeper surfaces that would have been flat in prehispanic times, thereby increasing the possibility of misclassification. Furthermore, examining only the slope gradient fails to take into account that prehispanic land use and occupation were not limited exclusively to relatively flat areas and did not only yield such kinds of landscape transformation. For instance, the threshold-based algorithm seems to largely ignore the agricultural fields that must have sustained the ancient population of the Upper Buritaca. It yields a conservative estimate for prehispanic land use and occupation—covering only 14.55 ha of the 671 ha (the research area)—that fails to accurately represent the extent of ancient settlements and agriculture at the Upper Buritaca, such as Teyuna-Ciudad Perdida that alone encompassed at least 33 ha (Giraldo 2010).

CART and RF algorithms yielded more comprehensive estimates of 96 ha and 112 ha, respectively, which seems to better represent prehispanic land use and occupation (Figure 5). Both algorithms

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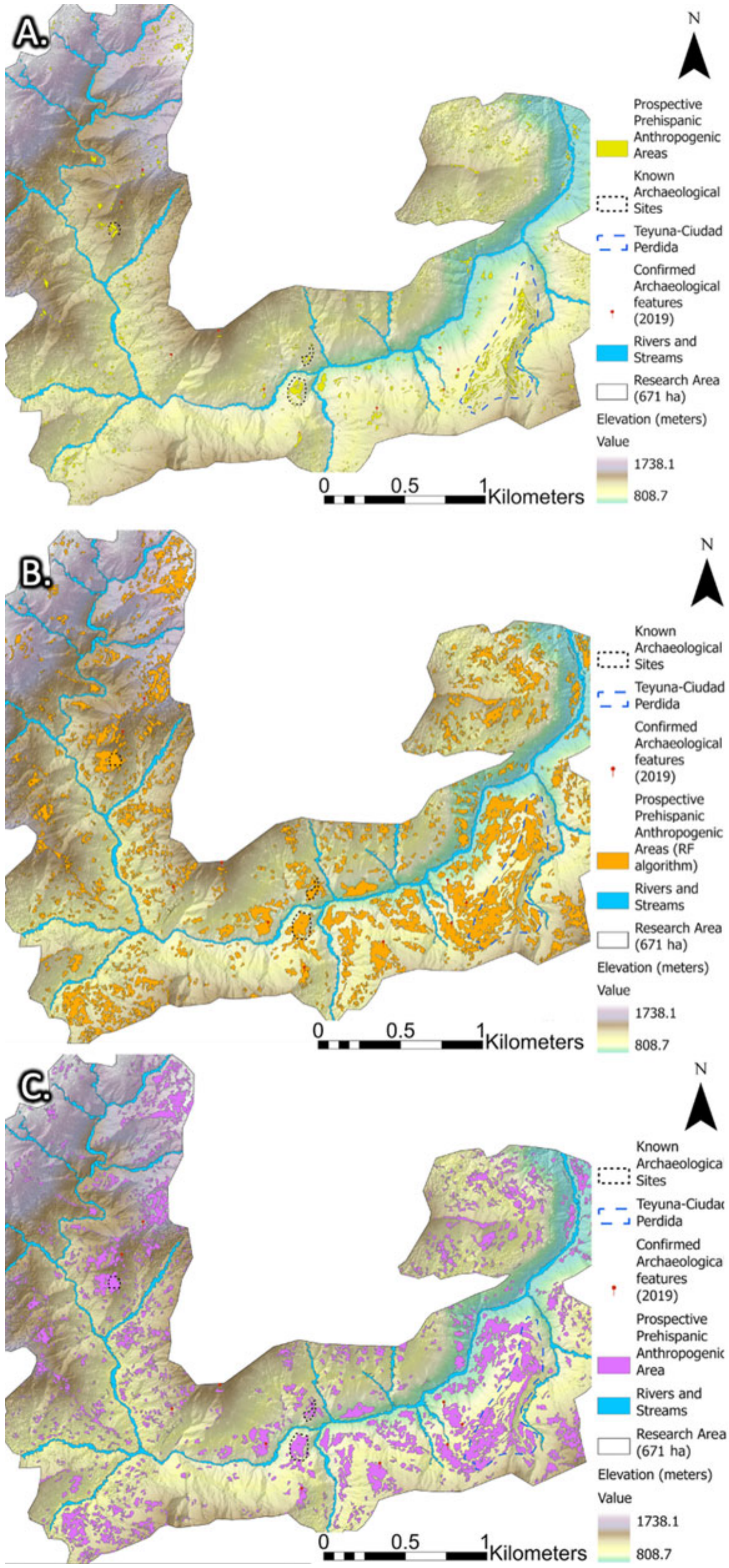

Figure 5. Prehispanic land use and occupation in the Upper Buritaca area. (A) Classification produced using a threshold-based algorithm; (B) classification produced using a random forest algorithm; (C) classification produced using a CART algorithm. (Color online)

accurately classified as anthropogenic those areas that the pilot ground-truthing season confirmed to be archaeological features, as well as identifying the masonry architecture of Teyuna-Ciudad Perdida. This strongly suggests that algorithms like CART and RF that consider a core of parameters—in this case, mean, Max. diff., area, length/width, compactness, and density—are best suited to model the extent of prehispanic settlement and agriculture at the Upper Buritaca. Like colonial descriptions and data from different archaeological surveys at the SNSM, these two algorithms show a sprawling anthropogenic ancient landscape that was not limited to Teyuna-Ciudad Perdida and its immediate area but had a broader and more extensive interconnected settlement system, with this site as its probable regional center.

Photogrammetry and TLS: Congo-Ciudad Antigua

We shift away from the watershed scale to examine how photogrammetry and TLS can be recursively used together to produce site-scale classifications that deepen our understanding of the ways in which ancient land use and occupation shaped the SNSM. These tools enable analyses as detailed as individual stone-level architectural surveys and individual tree-specimen forest or floristic inventories (e.g., Noordermeer et al. 2019; Rahlf et al. 2017). They also shed light on creative ways of integrating photogrammetry and TLS to undertake analyses that can be compared to classifications produced using airborne lidar. Photogrammetry is a transformative practice in the development of contemporary archaeology, enabling accurate documentation of archaeological sites with unprecedented quality at a relatively low cost (Jeong et al. 2018). Furthermore, we build on recent discussions in archaeology regarding the role of TLS in the discipline not only as a tool for producing outstanding visualization of archaeological sites and features but also as a milieu for optimizing systematic analyses that otherwise would be very time-consuming and expensive (Arav et al. 2015; Weber and Powis 2014).

In June 2019, we used photogrammetry and TLS at the archaeological site of Congo-Ciudad Antigua, located on the western side of the SNSM. The application of these technologies builds on a previous total station topographic survey that was conducted in July 2018 and yielded the first map of the site, providing an initial understanding of its extent (Mazuera 2019). As at Teyuna-Ciudad Perdida, both data collection processes faced an intricate series of logistical challenges caused by the topographical conditions and dense tropical forest of an ecologically rich and varied landscape.

Photogrammetry Materials and Methods

We used two UAVs—a DJI Mavic Pro and a DJI Phantom 4—to take aerial photographs (Supplemental Text 2) and processed these photographs to generate orthophotos and a 3D point cloud made up of 398,996,553 points. We then classified these points to differentiate ground, low vegetation, high vegetation, building, and stone path surface, using the Pix4DMapper automatic classification algorithm because of its suitability in forested areas. In Congo-Ciudad Antigua the percentage of point cloud classification obtained was 0.35% ground, 0.31% low vegetation, 97.7% high vegetation, 1.1% building, and 0.45% stone path surface. Thus, high vegetation between 627 and 1,015 m asl is prominent (Figure 6).

The classified point cloud was the input for processing in Autodesk REVIT, which contributed to the parameterization of architectural plans, sections, elevations, and aerial views of parts of the model. Explorations with this software resulted in a two-dimensional representation of the site at an architectural scale. Figure 7 illustrates slopes and specific spaces as a remarkably complex stair, as well as the level differences of the terrace's low and high points and the stone arrangements of the retaining walls. We refined the automatic classification by undertaking a supervised classification using ArcMap, for which we used training samples. With the maximum likelihood classification tool, the orthomosaic was classified taking the supervisory points as references. Figure 7 shows the resulting raster that discriminates stone masonry (black) from vegetation areas (orange). The raster was then vectorized to obtain a layer with the geometric attributes of the features.

TLS Materials and Methods

Using a FARO Focus M 70 unit, we took 86 sequential scans of Congo-Ciudad Antigua to produce the first set of three-dimensional models and other derived products that allowed us to conduct the

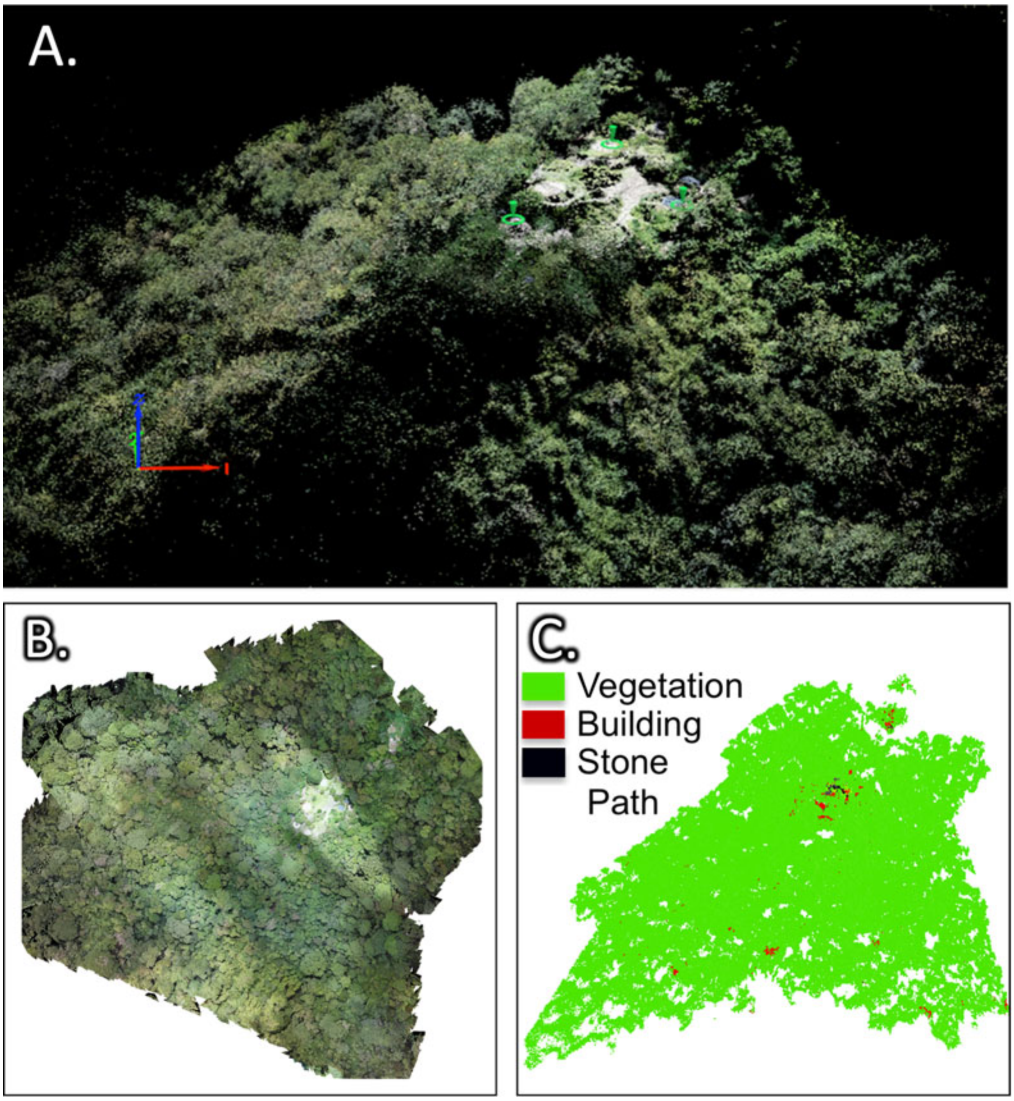

Figure 6. Point cloud Congo-Ciudad Antigua. (A) General photogrammetry; (B) general orthomosaic of the photogrammetry; (C) point cloud classification. (Color online)

analyses described here. Because of the extension of Congo-Ciudad Antigua, its complex topography, and the limitations of the fieldwork, the scans we recorded did not cover the entire archaeological site. Instead, the scans encompassed an approximate extension of 15,000 m^2 that covered the central area, its adjacent trails and stairs connecting it to the northern part of the site, and several sectors where the slope gradient allowed us to undertake TLS. We used the settings that the FARO (2021) Focus M 70 user manual recommends for outdoor and HDR scans: resolution 1/4, quality 4X, color on, sensors on, and HDR on.

We processed the collected data with Scene software. For the preliminary registration of point clouds, we grouped 15 adjoining shots, which formed six sector groups (e.g., roads or terrace areas), and then we stitched them together. The differences in levels and the abundant vegetation hindered the alignment and registration of the scans, making it necessary to use different strategies to enhance this process. For example, in some areas we used automatic registrations because of their high overlap rate; in other areas, the use of spherical targets allowed is to accurately stitch together the scans. This process yielded a general model comprising the terrace and trail areas (Figure 8).

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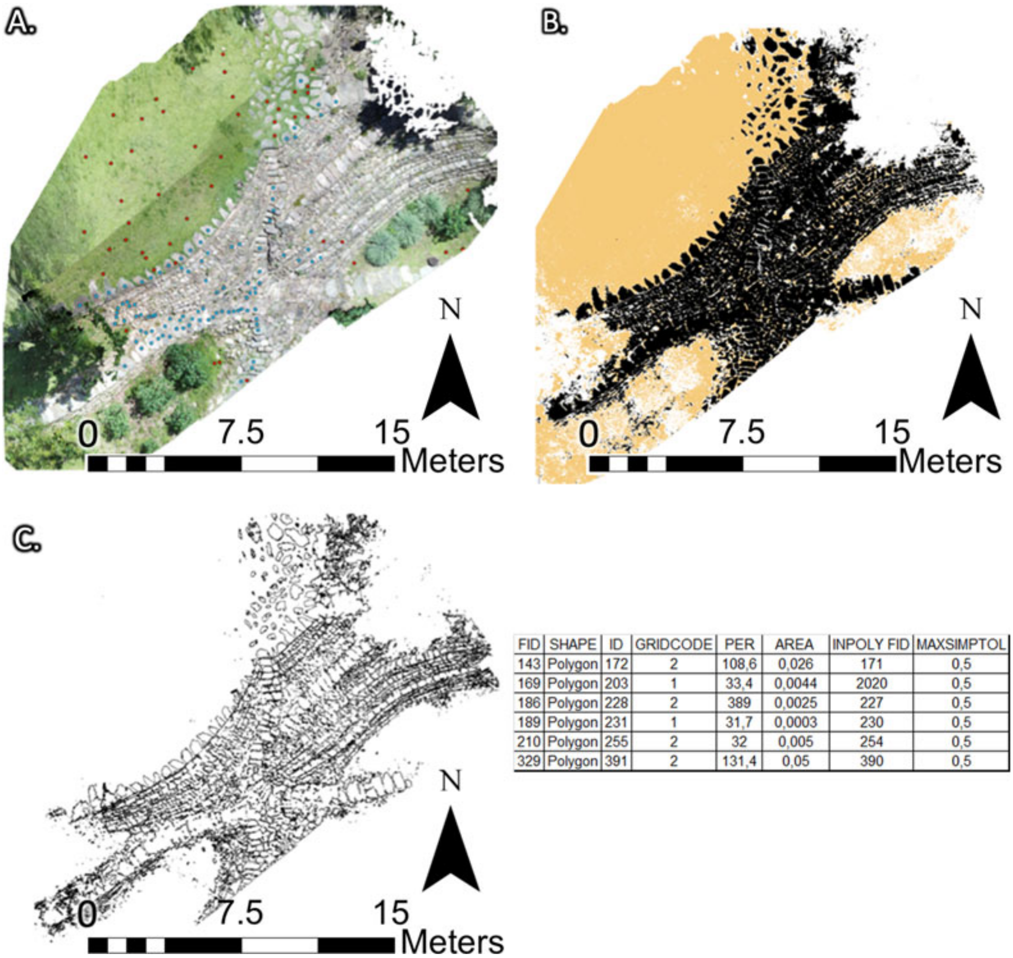

FID	SHAPE	ID	GRIDCODE	PER	AREA	INPOLY FID	MAXSIMPTOL
143	Polygon	172	2	108,6	0,026	171	0,5
169	Polygon	203	1	33,4	0,0044	2020	0,5
186	Polygon	228	2	389	0,0025	227	0,5
189	Polygon	231	1	31,7	0,0003	230	0,5
210	Polygon	255	2	32	0,005	254	0,5
329	Polygon	391	2	131,4	0,05	390	0,5

Figure 7. (A) Orthomosaic and training samples, differentiating stone masonry from vegetation, for a supervised classification; (B) supervised classification results; (C) vectorization of Congo-Ciudad Antigua stone masonry using ArcGIS. (Color online)

Overall, the degree of definition of the lidar scanned landscape is higher than that of the general point cloud obtained from photogrammetry, producing a detailed topographic reconstruction that reached areas below the tree canopy.

The next processing stage was the extraction of the topographic profile and the DTM production. For this purpose, we used the plug-in cloth simulation filter (CSF), a tool that segregates points that correspond to the terrain. We applied this plug-in to groups of 15 scans and assessed the optimal resolution for the segregation. Once these values were determined, we extrapolated the algorithm to the general model. The point clouds were classified into "ground points" and "out-of-ground points," obtaining a precise segmentation of the settlement that significantly contributed to the accuracy of the rendering of the archaeological site and enhanced the visualization of its stone masonry architecture (Supplemental Figure 1).

Photogrammetry and TLS Results

Here we present the results of an array of analyses that illustrate the possibilities and limitations of working with individual variables to assess the extent of ancient land use and occupation at the site scale. We also show the suitability of integrating variables such as morphology, slope, color, area, and perimeter to enable a better understanding of how the ancient societies of the SNSM modified

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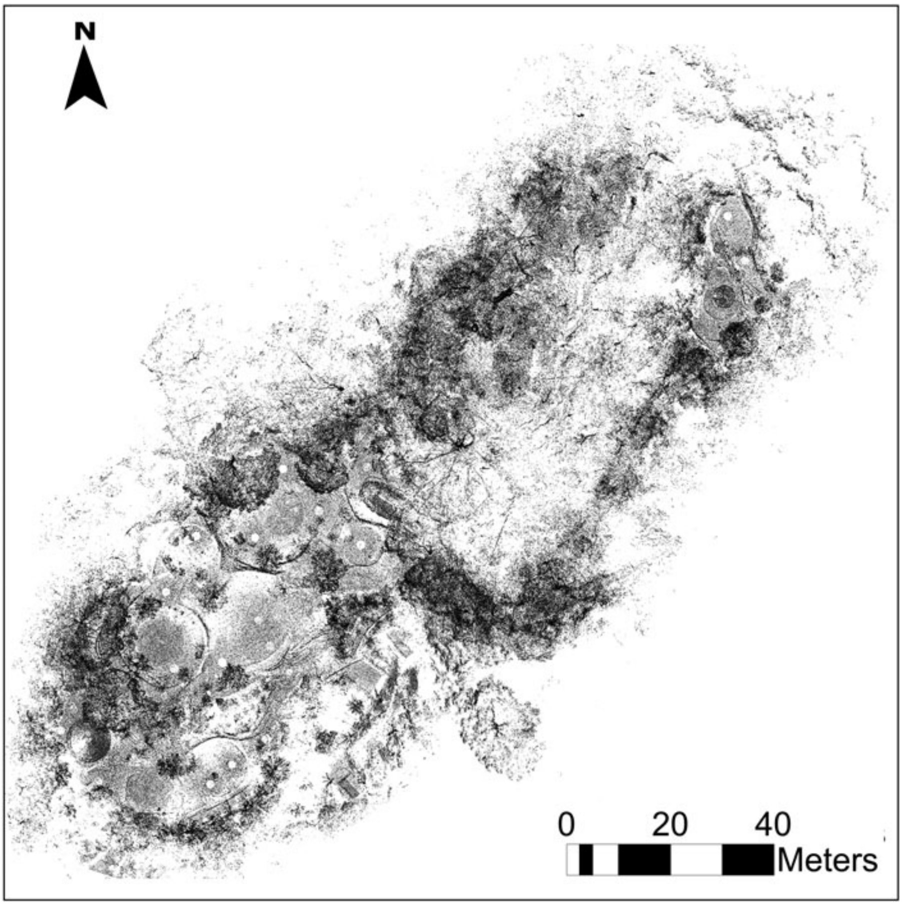

Figure 8. General model of Congo-Ciudad Antigua based on TLS (image produced using Scene).

this mountain range. In this case, information redundancy enables a conceptual transition in our understanding of whether and how this massif resulted from the long-term legacies of the construction of prehispanic settlements and croplands.

The photogrammetric model of Congo-Ciudad Antigua enabled analyses at the architectural and micro-basin scales, by which it was possible to differentiate, define, and measure stones that correspond to masonry architecture and green areas corresponding to vegetation through RGB segmentation. Moreover, the vectorization of the classification results allowed us to obtain data on geometric attributes, such as the perimeter and area of each of the elements of the archaeological structures (Figure 7). Although this is a first approximation, the archaeological potential of these processes is of great relevance because 2D data can be systematized to methodically segregate, measure, and categorize complex and diverse areas. They enable the postprocessing of drone imagery to complement the large organizational deployment needed to carry out these analyses during fieldwork.

From the 216,973 m^2 documented with the drone photogrammetry, the binary classification between masonry architecture and vegetation areas yielded only 2,080 m^2 of exposed stone areas, approximately 1% of the total site. This corresponded to the surfaces visible only in cleared, nonforested areas encompassing the central sector, some terraces located in the northern part of the site, and certain stone paved paths interconnecting them (Figure 9). Moreover, an RGB orthophotograph classification using TLS data (similar to the foregoing binary classification) revealed 2,211 m^2 of stone areas, which are mainly the terraces at 870, 874, 924 and 927 m asl, plus the stone retaining walls, stairs, and paths leading to the upper part of the settlement. The 130 m^2 increase in stone areas (Table 1), which in comparison to the photogrammetric classification may not seem significant, offers

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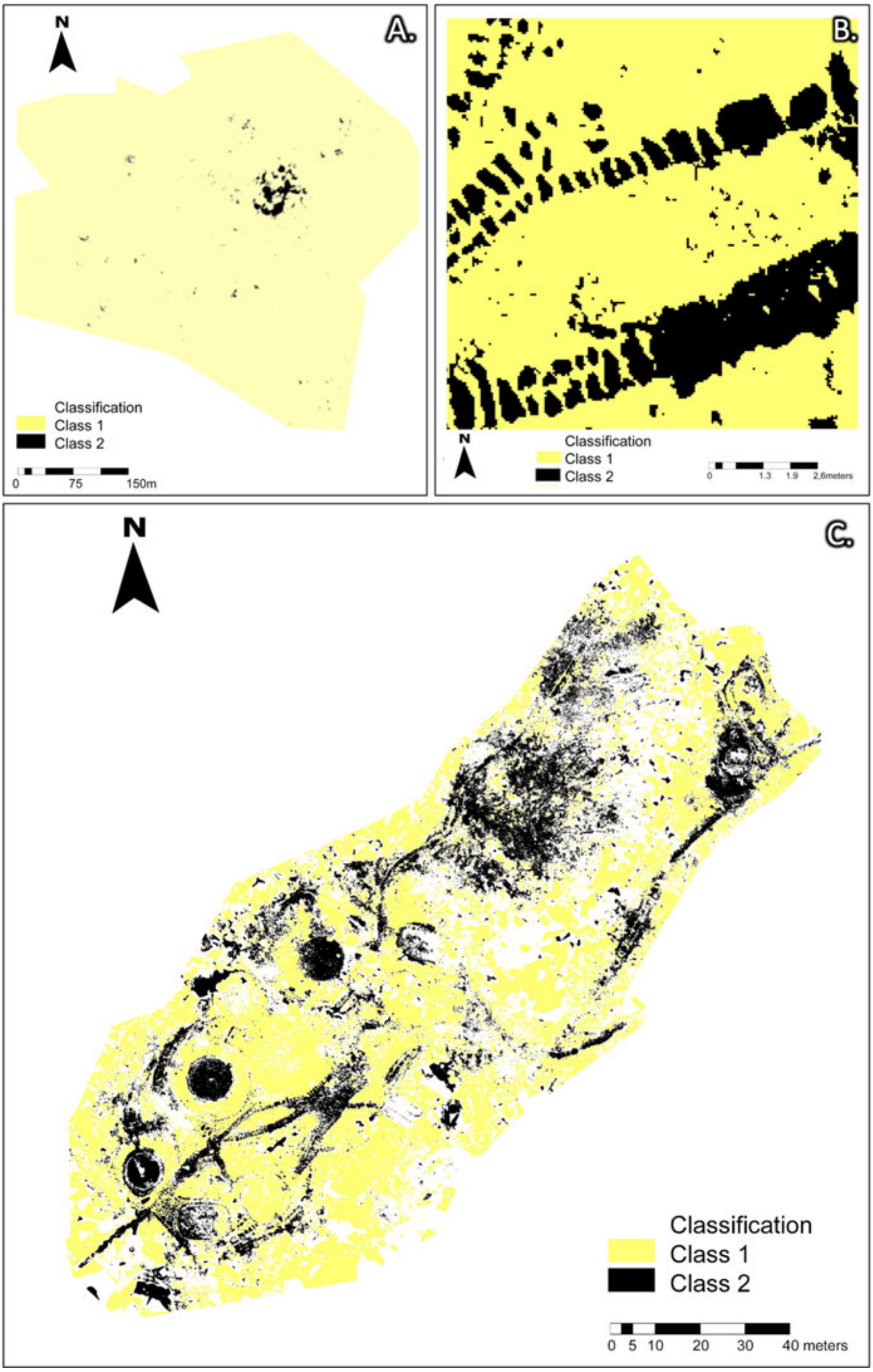

Figure 9. (A) Photogrammetry supervised classification (images constructed using ArcMap); (B) TLS supervised classification; (C) raster vectorization of the TLS classification. (Color online)

the possibility of increasing the accuracy of the analysis by enabling the extraction of geometric area and perimeter attributes of the polygons corresponding to stone masonry (Figure 9).

We conducted an additional classification using *slope* as a variable to expand the previous analysis. This classification took the values established for the 2019 Upper Buritaca area pixel-based

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Table 1. Comparison between Vegetation and Stone Areas Using Photogrammetry and Terrestrial Lidar.

Category	Photogrammetry Area (m^2) RGB Classification	Terrestrial Lidar Area (m^2) RGB Classification	Terrestrial Lidar Area (m^2) Slope Gradient Classification
Vegetation area/prospective nonanthropogenic	214,892	12,789	9,228
Masonry architecture/prospective prehispanic land use and occupation	2,081	2,211	5,772
Total area	216,973	15,000	15,000

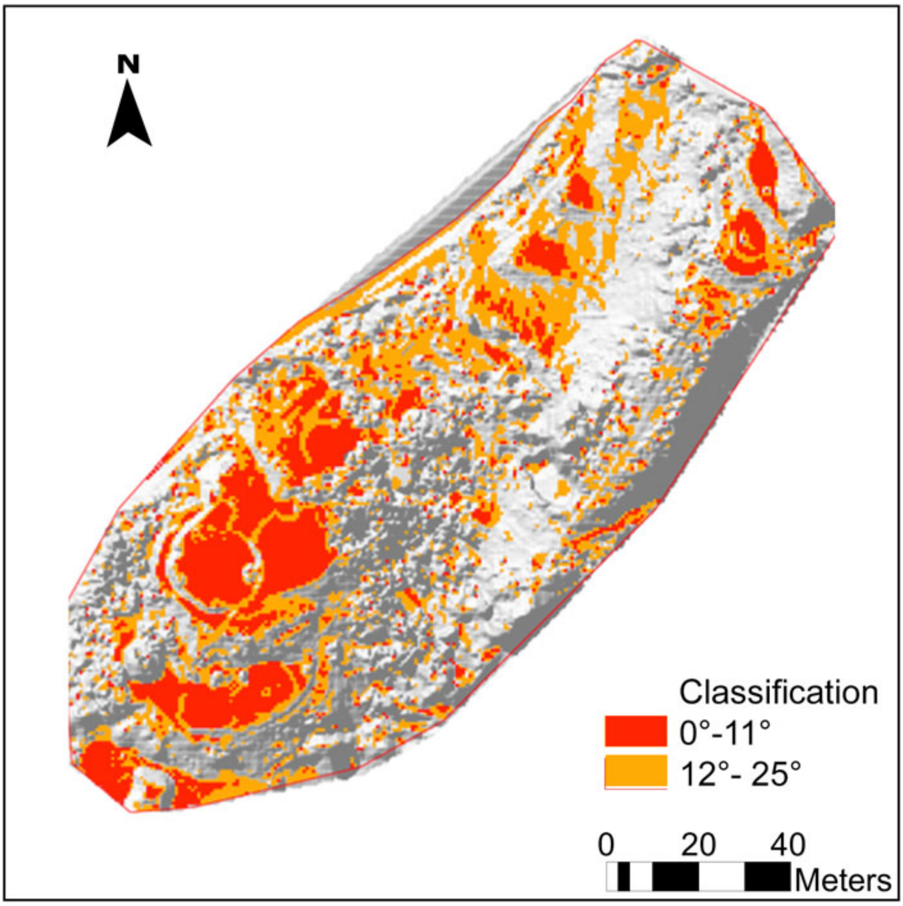

Figure 10. Congo-Ciudad Antigua slope classification. (Color online)

classification to define prospective prehispanic anthropogenic areas at the site scale. In Figure 10, the areas in red (0°< 11° slope) and in orange (11°< 25° slope) correspond to terraces and possible agricultural fields, respectively. This yielded a considerable increase compared to the previous classification for the prospective occupation and use area: of the total 15,000 m^2 scanned using TLS, 5,772 m^2 corresponded to areas between 0° and 25° (Table 1). Nevertheless, this classification failed to capture paths and stairs that have slopes greater than 26°. Furthermore, compared to the classification with the photogrammetry area (216,973 m^2), it did not indicate a significant increase in the total areas of prehispanic land use and occupation: they corresponded to just 2.7% of the total flight. This result was ultimately due to the orthophotograph area of the drone flight being 14 times larger than the TLS

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shot area. Therefore, for future research with further scanned areas, more thorough comparisons of prehispanic use and occupation areas could be made between photogrammetric techniques and TLS.

Discussion

The case studies presented here bring to light the intersection of remote sensing and archaeology in the study of ancient land use and occupation, which enables the interrogation of epistemological questions and categories that archaeologists create and engage with. For the Upper Buritaca area and Congo-Ciudad Antigua, we defined the category "prehispanic anthropogenic area" to quantify the extent of the ancient SNSM land use and occupation. We sought to avoid an exclusive emphasis on conspicuous landscape modifications created via masonry architecture with this category. However, this category is very broad, with the limitation of conflating two distinctive, yet closely related, kinds of practices: (1) settlement patterns or land occupation and (2) agriculture or land use. Thus, the category "prehispanic anthropogenic area" should be broken down into subclasses, giving space to economic activities such as agriculture, which also shaped the SNSM ecologies. We need to identify additional parameters through hybrid approaches that use targeted fieldwork observations that draw on and further test our results for those subclasses to be created. However, the data available for defining such parameters remain insufficient and limited to nonrepresentative phytolith or pollen samples collected in four archaeological sites—Teyuna-Ciudad Perdida, Pueblito, Estrella, and Anima—the latter two of which are located relatively close to the Upper Buritaca area (Giraldo 2010; Herrera 1985).

Conversely, the "stone masonry" class for the RGB classification produced for Congo-Ciudad Antigua aimed to fashion a highly detailed analysis that has the potential to systematically characterize prehispanic stonework. The use of TLS not only yields a classification that increases the accuracy and detail of the results achieved with the photogrammetry imagery but also provides the opportunity to conduct architectural analyses such as those recently undertaken in other regions of the Andes (Guengerich 2014; Kosiba and Bauer 2013), Mesoamerica (Garrison et al. 2016; Weber and Powis 2014), and the Near East (Arav et al. 2015). Given that TLS is time-consuming and costly in the rough terrain of the SNSM, however, its use for estimating land use and occupation at a more extensive scale may not be feasible.

Our analyses also raise an important question regarding how to assess algorithms or classifiers scholars use, in this case, to estimate the extent and density of ancient land use and occupation. Although further ground-truthing seasons will systematically assess the accuracy of the threshold-based, CART, and RF algorithms we used for the Upper Buritaca area, it is possible to discuss their suitability for identifying prospective prehispanic anthropogenic areas, based on what we already know about the Upper Buritaca area (i.e., fieldwork knowledge collected since 1976). For instance, the data collected through pilot ground-truthing strongly suggest that algorithms that consider a core of parameters, like CART and RF, are best suited to model the extent of prehispanic settlement and agriculture in the Upper Buritaca. Moreover, the results suggest that hybrid approaches, which integrate fieldwork knowledge and computing resources, offer an adequate methodology to study past anthropogenic landscape modifications in the research area. This promising scenario leaves us with the question of which is the best algorithm to use to examine the extent of prehispanic land use and occupation in the SNSM. Because the similarity index of the classification produced with CART and RF is relatively high but not sufficiently so as to deem an answer trivial, further ground-truthing seasons are needed to assess these algorithms' accuracy systematically. However, we agree with authors such as Prufer and colleagues (2015:3) that archaeologists need to be aware that digital models should not be taken as true proxies of the ground surface and the archaeological features on a landscape.

Conclusions

This study contributes to interdisciplinary scholarship examining ancient land use and occupation from a multiscalar perspective and recursively integrating remote sensing and archaeology (Bauer 2014; Chase et al. 2014; Evans et al. 2013; Kosiba and Hunter 2017; Prufer et al. 2015; Roman et al. 2017). Furthermore, it provides a novel view of long-term human-environmental interaction in the SNSM that strongly suggests that the ecologies constituting its north and northwestern slopes were shaped and reshaped by ancient societies between AD 100 and 1600. Drawing on the archaeological knowledge collected in the past four decades and using airborne lidar data, the preliminary results in the Upper Buritaca area suggest a relatively intensive land use and occupation. The estimates, which range from 96 to 112 ha of the 671 ha, appear to be comparable to "low-density agricultural urbanism" models (Fletcher 2009, 2012) such as those observed in Mesoamerica (Chase and Chase 2017) and Southeast Asia (Evans et al. 2007). Estimates for Congo-Ciudad Antigua accord with results from the Upper Buritaca area, where more than 5,000 m^2 of 15,000 m^2 correspond to prehispanic use and occupation. These findings allow us to better understand and quantify the wider settlement footprint within each watershed and the approximate area required to support habitation.

The prehispanic societies that lived on the SNSM for more than 1,500 years extensively transformed the landscape with a combination of more than 250 settlements, hundreds of stone paved paths that connected these sites, and extensive croplands. Until recently, most theoretical models of land use and occupation considered the ancient Tairona societies as populations concentrated in principal dwelling and ceremonial centers amidst a pristine and mainly untouched natural habitat. With this study, we shed a different light on this relationship within this complex landscape, moving to a concept of sprawling settlements over vast extensions of the massif, combined with abundant cultivable fields where different types of primary forest throughout a wide range of altitudes were profoundly altered. This novel approach can be an opportunity to rethink ancient urbanism in the SNSM and the categories of anthropogenic landscape modifications and, hence, imagine a different path taken toward social complexity.

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Data Availability Statement. The aerial lidar data presented in this article may be requested from the ICANH repositories. The TLS and photogrammetry dataset are available from the following link: https://drive.google.com/drive/folders/1qnTRLg-O-gS43Kltwqb-vSLF2RRsJ6sn?usp=sharing.

Competing Interests. The authors declare none.

Supplemental Material. For supplemental material accompanying this article, visit https://doi.org/10.1017/laq.2022.91.

Supplemental Figure 1. Longitudinal and transverse sections of models. (A) Point cloud of one of Congo-Ciudad Antigua trails; (B) topography model without the canopy; (C) staircase profile section connecting the central area with terraces on the north side; (D) central area section (images constructed using Autodesk Recap and Cloud Compare).

Supplemental Text 1. Materials and Methods: Airborne Lidar; Teyuna—Ciudad Perdida and the Upper Buritaca River Basin.

Supplemental Text 2. Materials and Methods: Photogrammetry and TLS: Congo-Ciudad Antigua.

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