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Taking the high ground: A model for lowland Maya settlement patterns

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ABSTRACT

Settlement research in the Maya lowlands has struggled to reconcile its goals to model a tropical forest civilization in ecological terms with the logistical constraints imposed by the forest itself. In this paper, we argue that the methodological challenges facing settlement research in this tropical lowland setting limited researchers' confidence in the representativeness of their data, nudging the discipline toward community-scale analysis and away from quantitative macro-scale settlement pattern research. As a result, many basic facts of human geography have remained unsettled. These challenges can now be overcome thanks to advances in remote sensing. Here, we use lidar-derived settlement and topographic data from the Corona-Achiotal region of northwestern Guatemala to develop a settlement suitability model that reveals patterns in the distribution of archaeological remains vis-à-vis landforms. Applying this model to a much larger published settlement dataset, we demonstrate how it is not only widely applicable in the interior Maya Lowlands, but also capable of identifying historical contingencies in the distribution of settlement, namely the crowding of less-suitable areas of the landscape, linked to urban densification.

1. Introduction

Reviewing what was then the young and burgeoning field of archaeological settlement pattern research, Trigger (1967, 1968) noted the emergence of two major paradigms. The first focused on the size and distribution of whole sites, *macro-settlement patterns*, as techno-social adaptations to the environment. The second approach concentrated on patterning within individual settlements, *micro-settlement patterns*, as reflections of socio-political organization. This dichotomy was echoed by Sanders (1967) who distinguished between "zonal" and "community" settlement patterns and by de Montmollin's (1988a, 1988b) classification of bottom-up and top-down analyses. Though scholarship never drew a hard line between these approaches in practice (Earle and Kolb 2010; Johnson and Earle 1987; Marcus 1973, 1993; Wright 1977, 1994), the distinction proposed by these early synthesizers helps make sense of the literature. For instance, research employing ideal distribution models (Jazwa and Jazwa 2017; Prufer et al. 2017; Weitzel and Codding 2020) inherits the generalizing ecological tendencies of macro-settlement pattern research, while interest in communities, neighborhoods, and urbanism (Arnauld 2012; Canuto and Fash 2004; Hutson et al. 2008; Isendahl and Smith 2013; Kurjack and Garza, 1981; Lemonnier 2012; Pyburn 1989; Robin 2012; Sabloff 1996; Smith 2011; Smith and Novic 2012; Smith et al., 2021; Tourtellot and Sabloff 1994; Yaeger 2003) hews to community-scale approaches.

In this paper, we argue that Lowland Maya archaeology's macro-scale research efforts have been beset by the methodological challenges of conducting the necessary fieldwork. These limitations established a scalar ceiling on settlement data that led the discipline to rally around community-scale analysis. Seeking to refresh the discipline's macro-settlement pattern analysis, this study leverages lidar-derived settlement and topographic data to propose a spatially-explicit *settlement suitability model* for the interior central Maya Lowlands, an area of some 60,000 km^2 (Fig. 1). We argue that this model provides a common yardstick for Lowland Maya settlement pattern research that enables well-controlled interregional comparisons and the recognition of historical contingencies in settlement growth.

This paper proceeds in three sections. First, we track how settlement pattern research in the Maya Lowlands favored either community-scale analysis or culture-ecology approaches that, while rigorous, were applicable only to small study areas except in qualitative and descriptive terms. This historical overview explains why some recurring questions—such as the distinctions between Maya cities and rural communities (Hutson 2016; Smith et al., 2021), or about regional variability in settlement patterning (Dunning et al. 1998; Dunning and Beach 2011)—

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remain unsettled. Furthermore, this section clarifies how airborne lidar's contribution to the discipline is not just a matter of data precision, but a matter of *analytical scale*. The second section presents the results of our own lidar-assisted settlement research in the Corona-Achiotal region of northwestern Guatemala. We bridge community-scale and macro-scale settlement analyses by introducing our settlement suitability model, which provides a clearly specified and generalizable assessment of how settlement was distributed across the Corona-Achiotal landscape. In the third and final section, to gauge regional variability in settlement patterning, we apply the suitability model to the 2100 km^2 settlement sample recently published by the Pacunam Lidar Initiative (PLI) research consortium. We demonstrate that settlement throughout the interior central lowlands strongly favors the same landforms as in the Corona-Achiotal study area—meaning that the suitability model is robust and generalizable across the entire region, despite local physiographic diversity—and that marginal landforms were more heavily settled in urbanized landscapes.

1.1. Geographic setting

In this paper, we focus on a region we loosely call the interior of the central Maya Lowlands. This is a karst environment with locally rugged terrain but limited absolute elevation change (Dunning et al. 1998). One consequence of this region's geology is relatively poor drainage in flat and low-lying areas, especially the flat-bottomed karst depressions (poljes) known locally as *bajos*. Although karst processes are responsible for landforms throughout the Yucatan Peninsula, bajos are characteristic of this interior region, where the combination of tectonic, geochemical, and climatic conditions has favored the development of seasonal wetlands in low-lying terrain (Dunning et al. 2019:3). Interdigitated with these bajos are upland areas with productive but shallow, erosible soils that support high-canopy forests. These edaphic conditions have given rise to distinct vegetation communities in bajo and upland environments and along ecotones, producing a dense ecological mosaic (Lundell 1937). It was in the mosaic environment of the interior central Maya Lowlands that archaeology set out, beginning nearly a century ago, to understand how ancient settlement was disposed across the landscape.

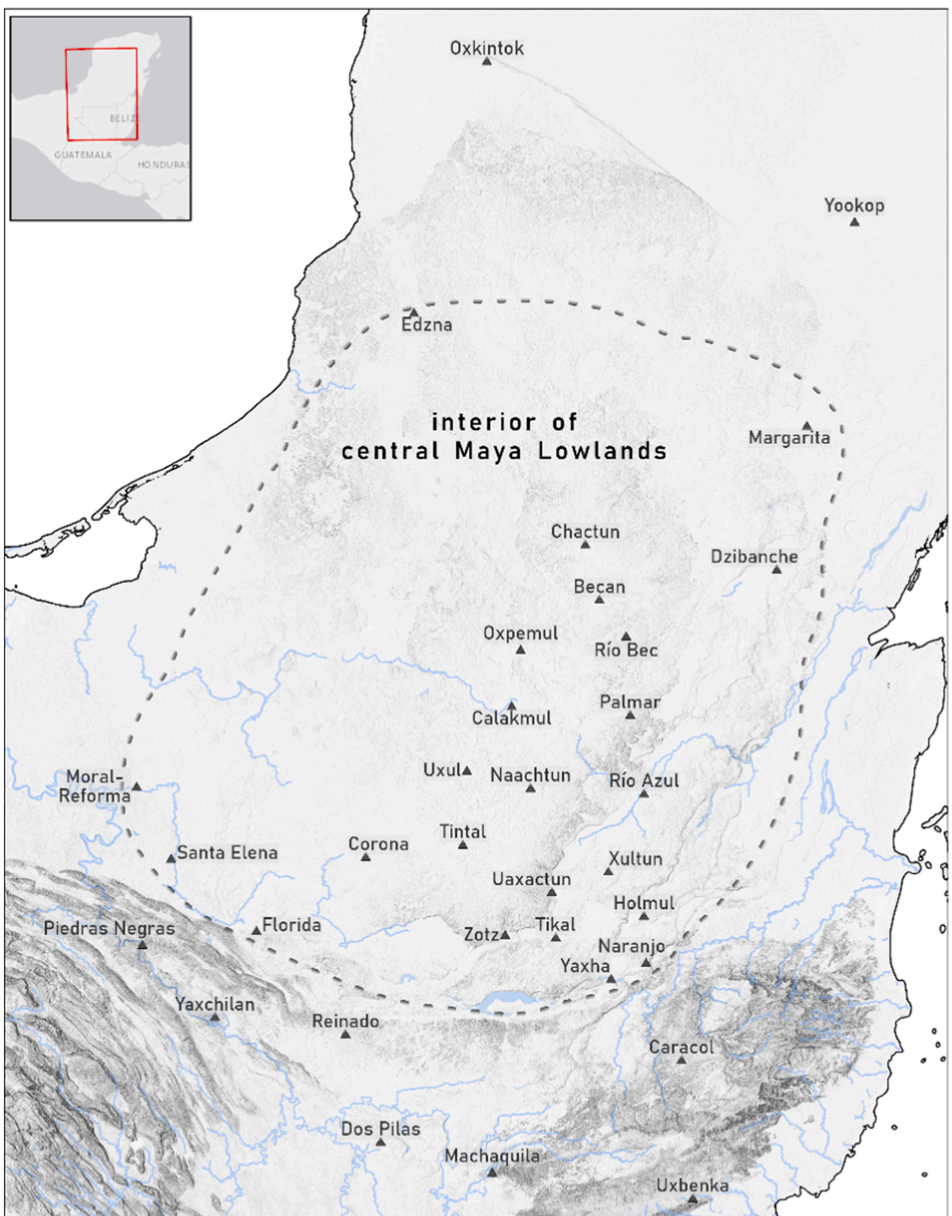

Fig. 1. Interior of central Maya Lowlands.

2. Lowland Maya settlement studies: The rise of the community scale

In 1925, Sylvanus Morley stated: “it is not improbable that the southern Maya Lowlands was one of the most densely populated areas of its size in the world during the first five centuries of the Christian era” (1925:63). Since Morley’s declaration, scholarly interest in Lowland Maya society has striven to determine the size, pattern, and distribution of Lowland Maya settlement. The earliest methodologically rigorous settlement study in the Maya Lowlands (Ashmore and Willey 1981:9) was undertaken by the Carnegie Institute of Washington’s research of Uaxactun in the 1920s. O.G. Ricketson designated a cruciform area of ca. 2 km^2 for survey (1937:15) that had a twofold result: the development of the first empirically based population estimate for the Lowland Maya as well as, and perhaps more importantly, the first macro-settlement pattern model for the area. Ricketson (1937:9) claimed:

> No Maya constructions (with one exception to be noted later) are found in *bajo*. Though house-mounds are scattered throughout the area, they always occur on high ground, while ruins of a more pretentious nature usually crown the tops of hills. It is therefore logical to assume that at the time of the ancient Maya’s occupancy of this region the present areas of *bajo* were considered unsuited for human habitation.

Following up on this novel survey methodology, Wauchope (1934) analyzed several structures located in the Uaxactun survey strips and confirmed their function as ancient residences.

Thanks to this earliest research, two fundamental aspects of Maya settlement became clear. First, most of the “mounds” surrounding larger architectural complexes were indeed ancient residences. Second, these residences were distributed across the landscape in patterned, predictable ways. However, the effort to locate and document them was hampered by “the extreme difficulty and slowness of ground travel and the inability of the explorer, because of the density of the vegetation, to gain a comprehensive idea of the topography of the region he is working…” (Ricketson Jr. and Kidder 1930:204). Nevertheless, settlement patterning, as a reflection of ancient Maya logistical and cultural preferences, became integral to the study of ancient populations, subsistence strategies, and urbanization.

From these initial forays, the study of “settlement patterns” aimed to address questions of demography, agricultural intensity, and urbanism by focusing on settlement typology and spatial patterning (Thompson 1939), the premise being that “the manner in which people have arranged themselves over and built upon the surfaces of the earth must inevitably tell us something about the societies and cultures of which they were a part” (Willey 2005:2). After Willey’s celebrated Belize River Valley survey in the mid-1950s, settlement research gained explicit marching-orders: “Until we have more real knowledge of Maya settlement, the archaeologist will be in no position to attack the problems of demography or of prehistoric agricultural techniques and productiveness… [such questions] will remain insoluble until we can pin down the facts of habitation” (Willey 1956:114). Following suit, Bullard’s (1960, 1964) survey in eastern Peten resulted in the formalization of the “domestic house ruin” as a fundamental unit of ancient Maya settlement (Ashmore 2007:49). Bullard (1960) further proposed a typology based on the *scale* (e.g., house ruins, minor and major ceremonial centers), *function* (e.g., quarries, flint-working sites), *grouping* (e.g., clusters, zones, districts), and a *distribution* of settlement that was “conditioned principally by the occurrence of sufficiently large tracts of well-drained relatively level terrain within a kilometer or so of a water source” (365).

Although Bullard addressed all of Trigger’s analytical scales by developing terminology for individual buildings, community organization, and regional patterns, his interpretations focused on Trigger’s micro-scale. Willey’s Belize Valley research also emphasized the micro-scale, borrowing the term “community pattern” introduced by Chang (1958) to define his approach. Community-scale settlement pattern studies thus flourished as multiple efforts focused on developing settlement models and typologies (Coe 1961; Haviland 1966; Puleston 1973, 1983, 2015; Vogt 1968; Willey et al. 1965). This research aimed to recognize “hierarchies in Maya settlement clustering and to suggest they were indices of successively more inclusive scales of social aggregation and integration” (Ashmore 2007:49; see Willey and Bullard 1965; Willey et al. 1965). Field projects at Tikal by the University of Pennsylvania and Dzibilchaltun by Tulane University’s Middle American Research Institute also focused on household activities, social organization, and community settlement patterns (Andrews 1965a, 1965b; Andrews and Andrews 1980; Becker 1971; Haviland 1965, 1968, 1969, 1970; Kurjack 1974). As research increasingly drew inferences about larger sociopolitical structures, the mid-1960s saw Mayanists reviving “with vigor, the controversy over the Maya lowland ‘city.’ Did the true city exist, with all its sociopolitical and socioeconomic implications for the interpretation of ancient Maya society?” (Ashmore and Willey 1981:14). With scholarship calling for an amplification of settlement research to better address these particular questions (see Haviland 1966), scholars further concentrated on household and community scales of analysis.

In the wake of efforts at Tikal, Belize, and northern Yucatan, Mayanists increasingly appreciated the need to overcome “site bias” by expanding the scale of analysis (Willey and Smith 1969:33). Thus, larger-scale approaches such as inter-site and regional surveys expanded beyond the immediate orbit of a single site, especially with an eye toward determining how regional or hinterland populations were integrated politically and economically with cities and political seats (see Adams 1981; Ashmore 1981a, 1981b; Fash 1983a, 1983b; Ford 1986; Hammond 1975; Harrison 1981; Kurjack 1981; Leventhal 1979, 1981; Puleston 1973, 1974, 1983, 2015; Rice 1976; Sharer 1978; Tourtellot 1970, 1988b, 1988c). However, difficulties in accessibility and visibility limited the regional scope of field research; so much so, that at the beginning of 1990s, after nearly four decades of intensive settlement pattern research, the sum total of the interior central lowlands that had been fully surveyed and mapped was only ca. 130 km^2 (~0.2% of the area in question) with no individual project contributing more than ca. 30 km^2 (Fig. 2). Research was thus obliged to limit macro-settlement analyses to areas that could be sufficiently sampled (Fedick 1988; Ford et al. 2009; Puleston 2015; Rice 1976), and only the most ambitious of these efforts—such as Ford and Fedick’s (1990) comparison of landforms and settlement density across three extensively-sampled subregions—came close to the scale implied by the “zonal” settlement analysis advocated by the more ardent proponents of *macro-settlement* patterns (see 1962, 1963).

Instead, the majority of Maya settlement studies directed attention to vibrant and sophisticated analyses of activity areas, households, communities, and neighborhoods, as well as a practice-oriented approach to landscapes (e.g., Arnauld et al. 2012; Ashmore 2004; Ashmore and Wilk 1988; Canuto and Yaeger 2000; Dunning 1992; Iannone and Connell 2003; Lohse and Valdez 2004; Robin 2013). In extensively-deforested areas outside of the interior central lowlands *per se*, researchers were able to conduct broader full-coverage surveys, expanding Willey’s community pattern and assessing the internal organization of entire polities (e.g., de Montmollin 1989, 1995; Liendo Stuardo et al. 2011; Webster et al. 2000). These combined efforts gave rise to important insights regarding social organization, socio-economic complexity, and rural–urban integration that modeled Maya society as a complex intercalation of multiple socio-political units based on diverse organizing principles such as kinship, community, or economic specialization. In this way, scholarship addressed Willey’s (1956:111) “problem of ceremonial-center-dwelling-site relationships” by a half-century application and elaboration of his community-scale settlement analysis.

Culture ecology approaches, meanwhile, struggled to achieve a holistic model of Lowland Maya settlement patterns as they were confounded by the realities of fieldwork: “mapping efforts[…] generally covered only a limited sample of any single site and rarely

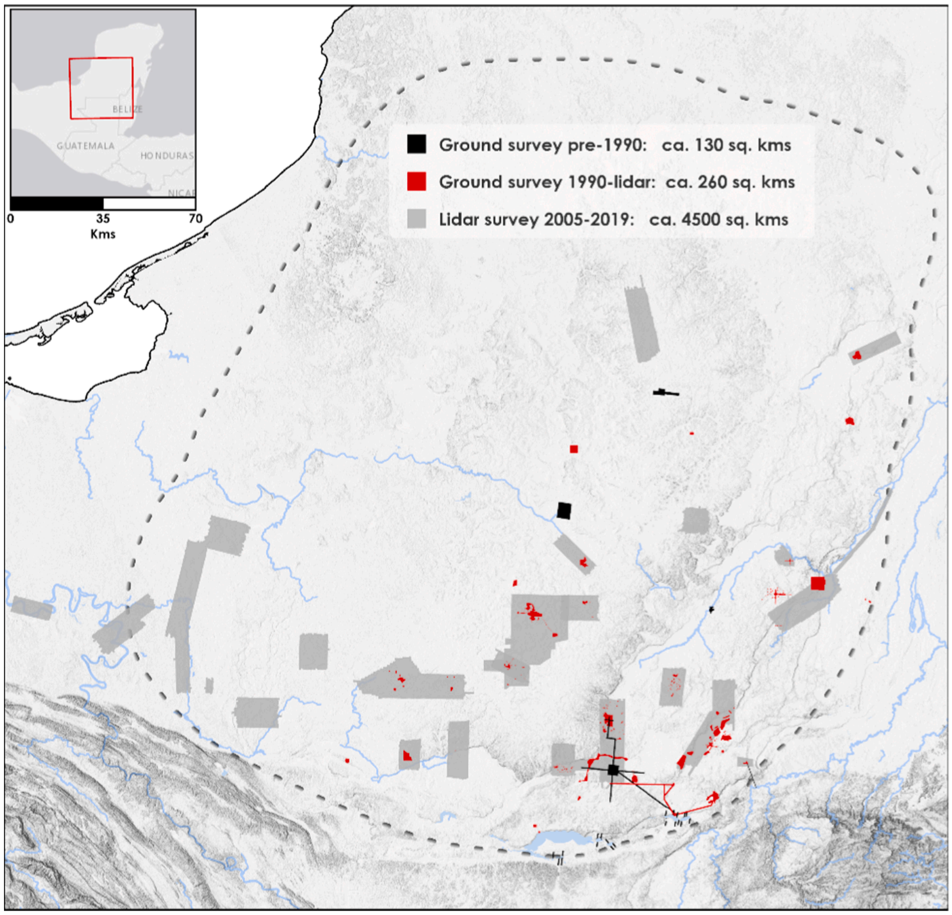

Fig. 2. Ground and lidar surveys in the "bajo zone"

contextualized settlement in terms of its overall landscape" (Chase et al. 2012:12917). Parsons' survey (1972:141) of the state of regional, zonal, or macro-scale settlement research named only two efforts in the Maya lowlands, Willey et al. (1965) and Bullard (1960), that had concerned themselves with this broader scale. Three decades later, Sabloff and Ashmore only extolled these same efforts from the Maya area when reviewing the importance of macroregional analysis in settlement archaeology (2001:19). In some sense, this scale of analysis in the Maya area had rested with Bullard's (1960:365) claim:

> In broad view, settlement fringing lakes and *bajos* and where aguadas and water sources are common often seems to be virtually continuous. Actually, the seeming continuum is divided into large and small segments by breaks in the terrain and the availability of suitable building sites. Preferred locations were the comparatively level, well-drained, hill and ridge tops at medium elevations, with houses also found on level spurs on hill slopes, the tops of semi-isolated knolls, level areas at the foot of escarpments, and similar places. Where the ground surface has a slight undulation, the houses typically occupy the high points. Areas of steep slopes and rugged terrain were either not settled or very lightly so. *Bajos* and other areas of swamp or poor drainage were not inhabited, although houses may be found at their very edges. In sum, the distribution of settlement appears conditioned principally by the occurrence of sufficiently large tracts of well-drained relatively level terrain within a kilometer or so of a water source.

While this remarkably insightful synopsis was consistent with Ricketson's observations decades earlier, subsequent attempts to refine, quantify, and test the applicability of this paradigmatic description of ancient Maya settlement's disposition on the landscape were immured by the scalar limitations of empirical observation and data recovery.

Indeed, concerns about the size and spatial biases of the settlement sample became common in synthetic statements about Maya settlement patterns during the 1980s and 90s. Rice and Puleston (1981:155) noted that as a function of "these biases result[ing] both from logistical considerations—such as time, money, and manpower—and from the methodological orientations of archaeologists […] assessments of environmental impact on settlement dynamics, resource utilization, interregional commerce, and sociopolitical evolution are still at best conjecture." Nine years later, Turner (1990:312) explicitly warned against extending the findings of limited survey coverage to the entire Maya Lowlands, noting that the Maya settlement sample was so heavily biased toward cities and their immediate hinterlands that any extrapolations would result in "astronomical" estimates of structure density and population. Sanders advanced the same argument, writing that "The major problem, […] is the very small size of the sample areas, varying from a few scores of square kilometers up to a few hundred. We need to know much more about […] the 'intersite' areas in order to attempt a reconstruction of the entire Maya Lowlands" (1993:788). As the larger scale analyses undertaken in highland Mexico (see Blanton 1978; Parsons 1971; Sanders 1965; Sanders et al. 1979; Spores 1969) remained unmatched in the Maya lowlands (Chase et al. 2012:12917), by the 1990s Mayanists had at least implicitly aligned behind the notion that their survey research had not accumulated a sufficiently large sample to sustain a rigorous, quantitative macro-scale analysis.

2.1. The promise and perils of remote sensing

Given these challenges, Mayanists looked to remote sensing to bring their projects to scale. While generally described as a single area of research (e.g. Parcak 2009), remote sensing offers two potential uses for archaeologists that do not necessarily overlap. First, remote sensing has always held out the potential for *direct discovery*, i.e., the identification of real, specific features of archaeological interest through remote means (Garrison 2020; Kvamme 2005:28-29; Parcak 2009). Less tantalizingly, remote sensing data allow researchers to correlate well-controlled archaeological datasets with other remotely-sensed variables such as forest type or elevation, and then model the archaeological phenomenon of interest across space based on this correlation (Howey and Brouwer Burg 2017; Howey et al. 2020).

The possibility of remotely identifying features occluded by ground-level hindrances was the goal of the first application of remote sensing to Maya studies: a simple "overflight" survey by Ricketson and Kidder (see Kidder 1930; Ricketson Jr. and Kidder 1930:204). This effort induced pure giddiness: "one can learn to recognize the sort of terrain the Maya were accustomed to pick for their temples and what varieties of trees flourish on the soil best fitted for their system of agriculture" (Ricketson Jr. and Kidder 1930:204-5). Nevertheless, settlement research at Tikal (Puleston 2015:23) found aerial photography useful to confirm elevation contours and identify larger "satellite" sites, but not for the detailed survey of residential structures (Puleston 1973:68-70). Even in more deforested areas, such as in the Copan region, aerial photography proved most useful in defining survey zones and situating sites on the landscape rather than finding them *per se* (Webster 1985). As a tool for direct discovery, aerial photography was most successful in northern Yucatán, where extensive clearing together with lower and more open natural vegetation made the detection of large numbers of sites possible (Andrews and Robles Castellanos 2004; Andrews and Andrews 1980; Covarrubias Reyna and Burgos Villanueva 2016; Kurjack 1974; Ringle and Andrews 1990). It even permitted a degree of quantitative macro-settlement pattern analysis for the region (Brown and Witschey 2003; Winemiller 2007).

As archaeology adopted more explicitly probabilistic approaches to settlement survey throughout the 1970s, disappointment with aerial photography's direct-discovery potential was replaced by the realization that it could help develop fine-grained overviews of the environment at scales much larger than those of any field survey. Rice's (1976) study of the Yaxha-Sacnab basins, carried out as part of an ambitious multidisciplinary "historical ecology" project (and representing the first use of that term, see Balée 2006), exemplified this approach. Using aerial photos, Rice and colleagues classified the landscape into four topographically conditioned vegetation types (tall upland forest, tall forest on moist slopes, swamp forest, and swamp thicket), and correlated these with archaeological remains mapped in survey transects. This correlation then informed broader interpretations about culture-ecological patterns and population dynamics in the region that had been sampled by the survey. Puleston's research in the hinterlands of Tikal took a similar approach, analyzing settlement density in terms of the vegetation communities with which ancient buildings co-occurred (Puleston 1973: Chapter 7), estimating the total number of ancient buildings in Tikal National Park (576 km^2) by extrapolating from his own survey data using vegetation maps derived from aerial photos (Puleston 1973:229-230).

Both aerial photography and Synthetic Aperture Radar (SAR) were employed during the 1970s and 80s to directly identify agricultural modifications in wetlands (Dahlin 1979; Harrison 1977, 1990; Puleston 1977; Siemens 1982; Siemens and Puleston 1972; Turner II 1978), but not without controversy. Adams et al. (1981) used SAR to suggest the existence of extensive canal systems throughout Maya lowland bajos (Adams 1980; Adams et al. 1981; Adams et al. 1990). These conclusions were largely incorrect as the ubiquitous linear features in the images were shown to be either artifacts of data processing or the natural products of shrink-swell cycles in bajo clays (Garrison 2020:255-257; Pope and Dahlin 1989, 1993; Pope et al. 1996). The experience with SAR would have lasting impacts on the discipline: undermining confidence in remote sensing's usefulness as well as fueling an intense preoccupation with ground-truthing that has extended well beyond the identification of wetland agricultural features (Dunning et al. 2020a; Ford and Horn 2018; Sabloff 2019).

An early success in the use of remote sensing for direct discovery of *settlement* remains (as opposed to agriculture) in the forested parts of the Maya lowlands involved the discovery of *bajo communities*. NASA's Thomas Sever combined moderate-resolution digital elevation models with multispectral images of the overlying vegetation to identify small islands of elevated terrain located within the large bajos scattered throughout the Maya lowlands. (Sever 1995, 1998, 1999, 2000; Sever and Irwin 2003). Once investigated in the field, these islands proved to contain settlement, suggesting that the ancient Maya settled them to make use of the surrounding wetlands for agriculture or resource extraction (Culbert et al. 1996; Culbert et al. 1997; Grazioso et al., 2001; Kunen et al. 2000; Sever and Irwin 2003). Nuancing the blanket observation that settlement avoided bajos, Sever and Irwin (2003: 118) observed that "almost every rise in elevation that reaches above the level of seasonal inundation contains an archaeological site."

With the advent of very high-resolution satellite imagery, new efforts were dedicated to the direct discovery of settlement. Saturno et al. (2006, 2007) observed that multispectral signatures of vegetation correlated directly to the presence of ancient architecture—a link that had been suggested and explored as early as the Tikal project (see Puleston 1973:70). They suggested that some component of ancient Maya architecture—perhaps decomposing lime plaster—stressed the overlying vegetation such that its multispectral signature was separable from that of surrounding vegetation. Follow-up research noted that this "settlement signature" was either invisible or unreliable in much of the Maya lowlands, concluding that the correlation was a function of physiographic and seasonal factors limited to the area of the initial study (Garrison et al. 2008).

Surveys in Campeche (Šprajc 2008) and Quintana Roo (Guderjan and Krause 2011; Guderjan et al. 2016; López Camacho 2010; López Camacho et al. 2016; Tsukamoto 2005) as well as broader Maya area efforts (Witschey and Brown 2010, 2014) made use of satellite imagery and aerial photography to aid in the identification of new sites and the geolocation of poorly-known sites, as well as in the continued detection of wetland agricultural features (Dunning et al., 2020b). These efforts largely relied on the identification of open water or hydrophytic vegetation to distinguish features of interest—ancient reservoirs as proxies for large sites, rectilinear patterns of grass and scrub as indicators of wetland fields—from a backdrop of forest. The insights provided by remotely-sensed data highlighted a fundamental epistemological problem: it was possible to identify *some* sites in *some* regions through remote sensing, but it was never possible to establish how representative that knowledge was of facts beneath the canopy. The sites so identified remained isolated points against a backdrop of near-total uncertainty that only challenging, scale-limited pedestrian survey could fill in. Thus, inasmuch as direct identification of settlement remained limited (Kurjack et al. 2004), the possibility of macro-scale analyses remained out-of-reach.

2.2. Remote sensing and modeling: Toward regional settlement pattern

As a greater diversity of remote sensing data became available and as the tools to analyze those data became more powerful and accessible, some researchers adopted spatial modeling techniques to interpolate settlement patterns at larger scales. Fedick (1994, 1995) calculated settlement density by soil class within a 5 km^2 transect sample, then modelled the distribution of settlement across a 1,000 km^2 area of western Belize using 1:50,000 scale soil maps (Wright et al. 1959:8). Two decades later, Garrison used unsupervised clustering on multispectral imagery and compared this with his own pedestrian survey data to determine that Lowland Maya "settlement features displayed strong correlations with certain microenvironments that might be isolated in a classification" (2010:218). Based on the frequency of these vegetation classes and the density of mapped settlement within a 2.5 km^2 sample, Garrison extrapolated a population estimate for a 25 km^2 region between San Bartolo and Xultun (Garrison 2007:197-200, 2010:225–227). Griffin's (2012) study in the same region, while not concerned with settlement *per se*, used a classification of forest types in Landsat 7 imagery to characterize the agricultural potential of a large area (~2,800 km^2) to suggest upper limits for ancient population estimates.

Extending Fedick's efforts, Ford undertook the most ambitious example of probabilistic modeling of settlement in Maya studies thus far (Ford et al. 2011; Ford et al. 2009; Ford and Nigh 2015). Using decades of survey data in the vicinity of El Pilar as training data, her team determined the relative importance of several regional data sets—soil fertility, drainage, topography, and hydrological features—to settlement distribution. Based on these weights, Ford and colleagues developed a model that calculated the probability of settlement within a large 1300 km^2 area of the upper Belize River region. They concluded that "four geographic and environmental factors predict 82 percent of the Maya sites in the high-probability areas. Furthermore, fully 96 percent of the settlement, a vast majority, can be predicted for less than 60 percent" (2009:514) of the study area. In later studies (Ford et al. 2011; Ford and Nigh 2015), they refined their analysis and extrapolated a population estimate for a yet-larger region. Carleton et al. (2012), also working in Belize, used a distinct modelling approach but with a similar goal of identifying areas with high probability of containing archaeological sites—and in their case, were able to validate the model several years later using the results of an airborne lidar survey (Carleton et al. 2017).

While spatial analysis became more technical and sophisticated, these approaches still derived from methods used by Rice and Puleston in the 1970 s: mapping settlement in detail within a sample of a given survey universe, then using the correlation between mapped features and remote sensing data to make well-founded statements that extended to the entire region. *Even so*, the reality of small samples meant that the regions considered by these rigorous and bold analyses seldom met the scales that could be mapped in full in less challenging environments, such as the 3,100 km^2 mapped in the Basin of Mexico (Gorenflo 2015). Consequently, the considerable body of research that sought to specify ecological variables for settlement analysis (e.g., Fedick 1995; Garrison 2010; Murtha 2002, 2015; Thompson and Prufer 2021) used local variables toward local ends, making regional comparison difficult. Attempts to find a generalizable model for Maya settlement location were ultimately hemmed in by regional variation in the proxies they sought to employ (Garrison et al. 2008).

So, while it had been long clear that most Maya settlement favored upland areas, we could not determine if "most" meant 70% or 98%, or whether that proportion varied meaningfully between regions. Into the 2010s the basic problem Ricketson and Bullard considered—the rules and patterns that describe how Maya settlement was distributed on the landscape—could still only be answered in qualitative terms beyond the scale of local case studies: without a common culture-ecological yardstick, macro-settlement analysis could be quantitative or generalizable, but not both. Writing on the eve of Mesoamerica's "geospatial revolution", Ford noted that Mayanists had managed to specify that "environmental factors played a role in Maya site location, but the spatial implications of these arguments have not been fully pursued" (Ford et al. 2009:497).

2.3. Lidar and the return of direct discovery

The application of lidar in the Maya lowlands, beginning with the pioneering survey at Caracol in the Vaca Plateau of Belize (Chase et al. 2011a; Chase et al. 2011b), initiated a sea change in settlement research: "With LiDAR coverage of the Mesoamerican landscape, interpretations of spatial organization no longer need to be based on a small survey sample of an undefined larger universe or require extensive on-the-ground penetration of forest canopy" (Chase et al. 2012:12919). Mayanists were thus presented with a direct-discovery tool that held promise where earlier technologies had faltered.

A raft of studies, site-based (Acuña and Chiriboga 2019; Chase and Weishampel 2016; Ford 2014; Garrison et al. 2019; Inomata et al. 2018; Prufer et al. 2015), regional (Canuto et al., 2018a; Chase et al., 2014a,b; Golden et al., 2016; Schroder et al., 2020; Stanton et al., 2020), methodological (Cap et al. 2018; Hutson 2015; Inomata et al. 2017; Reese-Taylor et al. 2016; Yaeger et al. 2016), and theoretical (Chase and Chase 2017a; Chase et al. 2012; Michelet and Nondédéo 2018), have shown how this technology has inundated the discipline with data of unprecedented precision and detail. Notwithstanding occasional claims to the contrary (Ford and Horn 2018; Horn and Ford 2019), there has been a sober and sustained reckoning with the technology's capabilities and limitations as a direct-discovery tool (Ebert et al. 2016; Hutson et al. 2016; Inomata et al. 2017; Magnoni et al. 2016; Reese-Taylor et al. 2016).

Nevertheless, lidar-based settlement analyses have largely focused on individual cities and their hinterlands (for exceptions see Canuto et al., 2018a; Chase et al., 2014b; Schroder et al., 2020). They are also, without exception, direct-discovery undertakings geared toward the identification and analysis of specific archaeological features, be they buildings (Canuto et al. 2018a; Inomata et al. 2018; Reese-Taylor et al. 2016), terraces (Chase and Weishampel 2016; Macrae and Iannone 2016), wetland fields (Beach et al. 2019), or reservoirs (Brewer et al. 2017; Chase 2016; Chase and Cesaretti 2019).

Thus, to advance macro-settlement analysis, we take a slightly different tack in this study. We leverage the direct-discovery potential of lidar with its ability to provide high-resolution terrain models to investigate the distribution of (extensively field-validated) settlement across topographic landforms. Based on lidar data from the Corona-Achiotal region in northwestern Petén, Guatemala, the resultant settlement-landform patterns form the basis of our *settlement suitability model* that we subsequently apply to a broader region with the aim of elucidating macro-settlement patterns of the ancient Lowland Maya.

3. Landforms and settlement in the Corona-Achiotal region

In 2016, the Pacunam Lidar Initiative (PLI) undertook a 2144 km^2 lidar survey in northern Guatemala (see Canuto et al. 2018a: for details on PLI)—five times what all full-coverage survey in the region had covered up to that point. As a member of the PLI's research consortium, the La Corona Archaeological Project (PRALC) was provided a 431 km^2 block of lidar data located in the western edge of the Yucatan Peninsula's central karstic uplands (Fig. 3). Even for Peten, the terrain of this survey block is exceedingly flat, descending westwardly in a series of broad terraces and low (5–30 m) scarps toward the marshy lowlands located in Laguna del Tigre National Park and the Tabasco coastal plain beyond.

3.1. Identification and validation of features

Analysis of these lidar data followed protocols established by the PLI consortium involving heads-up digitization of a defined set of archaeological features that included, among others, structures, agricultural infrastructure, defensive works, and causeways. "Structures" were defined as human constructions supporting a roofed area, whether perishable or masonry. In topographic terms, for a feature to be classified as a structure, it had to be (a) convex, (b) at least 3 m long and 2 m wide, and (c) marked by a break in elevation on at least three sides. Beyond these criteria, digitizers relied on field-based knowledge of local settlement characteristics to determine if a feature meeting the criteria was likely to be anthropogenic (a building[1]), natural (e.g., rock outcrop), or a data artifact (e.g., bushy vegetation misclassified as

[1] We use the words "structure," "building," and "mound" interchangeably here.

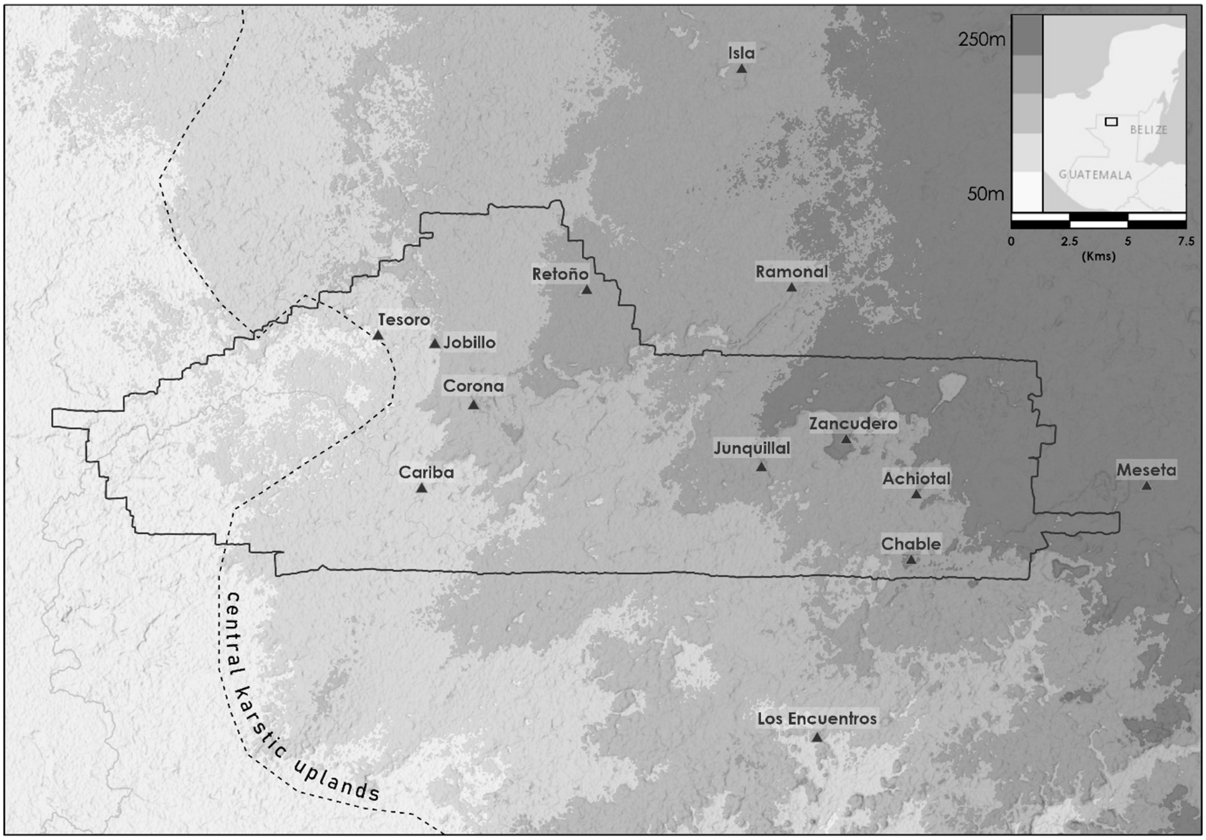

Fig. 3. Corona-Achiotal lidar block and nearby archaeological sites (dashed line: western edge of central karstic uplands).

ground).

For the Corona-Achiotal region (Fig. 4), heads-up digitizing was conducted by three individuals over a period of three years during which time in-field verification efforts iteratively improved dataset accuracy (Canuto and Auld-Thomas 2020; Chatelain 2020). As of this writing, we have identified 3831 features as archaeological structures, nearly a quarter (942 features) of which have been confirmed through pedestrian survey. Begun in 2017, field validation has involved full-coverage pedestrian survey of 75 500 m^2 survey quadrats (thus far, 35 completed; 40 partially completed), totaling 12.71 km^2. Within these quadrat areas, structures were recorded as true positives, false positives, or false negatives.[2] This procedure has demonstrated excellent overall fidelity between the visual identification of structures in lidar data and what we have encountered in the field. Using a confusion matrix, we summarize our accuracy assessment using three indices: *precision* (user accuracy; i.e., how many of the buildings identified digitally were verified in the field), *recall* (producer accuracy; i.e., how many buildings identified in the field were also identified digitally), and the *F1-score* (composite measure of accuracy). Our verification efforts (Table 1) resulted in a high *precision* of 0.906 (i.e., 703/776), our *recall* was an acceptable 0.746 (i.e., 703/942), resulting in a good *F1-score* of 0.818 (the harmonic mean of 0.906 and 0.746). Further details on our calculations are summarized in Canuto and Auld-Thomas (2020).

Part of our field methodology was to identify two different types of "false negatives": those that could not be seen in the lidar data and those that proved visible upon re-inspection of the lidar data. The former were considered "unidentifiable false negatives" (n = 151), while the latter were identified as "unidentified but visible" (n = 88). For the purposes of basic data validation, this distinction was not relevant; nevertheless, when we added the "unidentified but visible" (n = 88) features to our "true positives" (n = 703) features, we thus controlled for our digitizing bias and more precisely assessed the fidelity of our lidar data. In so doing (Table 2), our *precision* increased to 0.916 (i.e., 791/864), our *recall* to 0.840 (i.e., 791/942), and our *F1-score* to 0.876. These numbers tell us our lidar data are exceptionally accurate.

In tandem, these two ways of assessing the accuracy of our digitization suggest that, as a function of both our lidar data's fidelity (high) and our digitizing bias (conservative), ground validation would result in a ca. 10–20% net increase in the number of structures determined by digitization alone (e.g., 776/864 digital structures vs. 942 field-verified structures). Thus, we are confident that our current tally of 3831 structures represents no less than ca. 85% of the total number of structures in the Corona-Achiotal region.

3.2. Community-scale settlement patterns in the Corona-Achiotal block

These digitization methods and on-going field validation efforts have resulted in a structure tally suggesting the Corona-Achiotal region was characterized by a low overall settlement density of ca. 9 strs/km^2. However, settlement is not evenly distributed across the region. There are several nodes of clustering, each centered around a known monumental site: namely, La Corona, Tesoro, Achiotal, and Chable. These clusters, measuring about 500–600 ha each, contain some 40% of the region's settlement; in the landscape surrounding these clusters, most of the remaining settlement is distributed in dozens of 10–50 ha clusters of

[2] "True negative" is virtually impossible to meaningfully calculate in applications such as archaeological survey, where the goal is to identify features of interest against a continuous backdrop of "non-features."

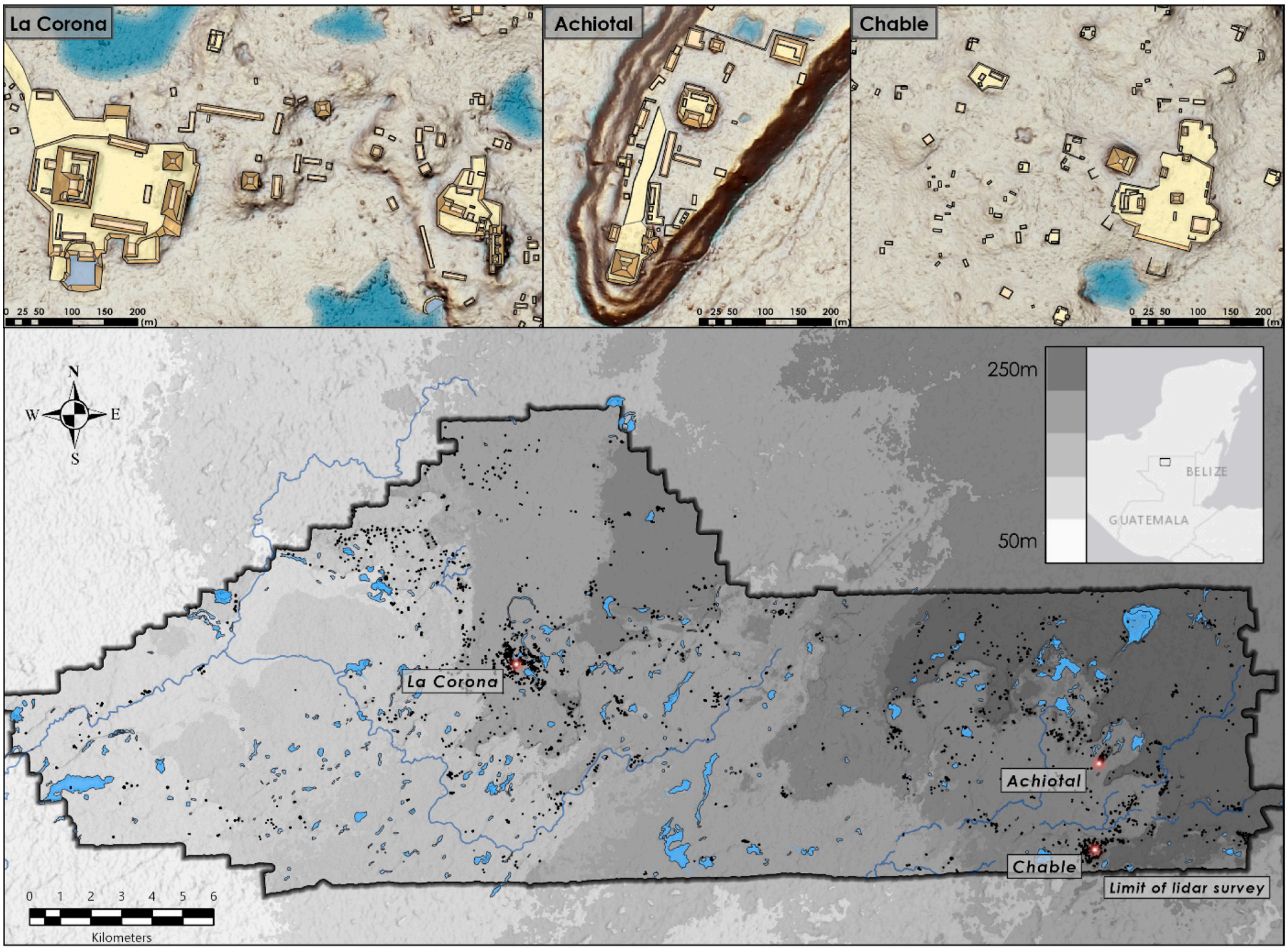

Fig. 4. Settlement in the Corona-Achiotal region (structures as black dots).

Table 1
Field validation Confusion Matrix: assessment of PRALC digitization as of 2019. Numbers represent structures.

		Lidar-based identification	
Field validation		Positive	Negative
	Positive	703 *(true positive)*	239 *(false negative)*
	Negative	73 *(false positive)*	NA

Table 2
Field validation Confusion Matrix: assessment of PRALC's lidar fidelity. Numbers represent structures.

		Lidar-based identification	
		Positive	Negative
Field validation	Positive	791 *(true positive & unid/vis)*	151 *(unid false negative)*
	Negative	73 *(false positive)*	NA

10 to 50 structures[3]. As a result of the uneven distribution, the settlement concentration climbs to as high as 275 strs/km^2 in the densest parts of this region[4] while there are large swaths devoid of settlement altogether. Furthermore, when calculated and expressed as a function of hectares[5], structure density increases to 18 strs/ha in a few select areas. It is important to note, however, that these pockets of elevated density are small (no larger than 10 ha in overall size) and mostly located within the core of the largest centers of the region.

Regarding settlement variability, ground-verified settlement was classified according to a basic settlement typology consisting of six site types: monumental core, formal plaza, patio cluster, patio, informal mound group, and isolated mound (Fig. 5). Our preliminary interpretations of what social groups these settlement types represent relies on a robust community-scale settlement studies literature in the Maya Lowlands (see Ashmore 1981b; Becker 1982, 2003; de Montmollin 1995; Fash 1983a; Haviland 1981, 1988; Pyburn 1990; Tourtellot and Sabloff 1994; Willey 1981). Monumental structures combined with formal plazas were scarce (6% of sites). These values suggest that the

[3] While the chronological sequence of this region's settlement remains outside the purview of this study, we note that the evidence suggests that these various "regional clusters" of settlement represent discrete non-contemporary occupations, ranging from the Late Preclassic to Terminal Classic periods. However, given that our concern here is to define a general settlement pattern, temporal development of this system represents a potential consequence rather than a parameter of the patterns we seek to elucidate and therefore will be considered elsewhere.

[4] ArcGIS Pro 2.6.1, Point Density, circle neighborhood, 564.19m radius.

[5] ArcGIS Pro 2.6.1, Point Density, circle neighborhood, 56.42m radius.

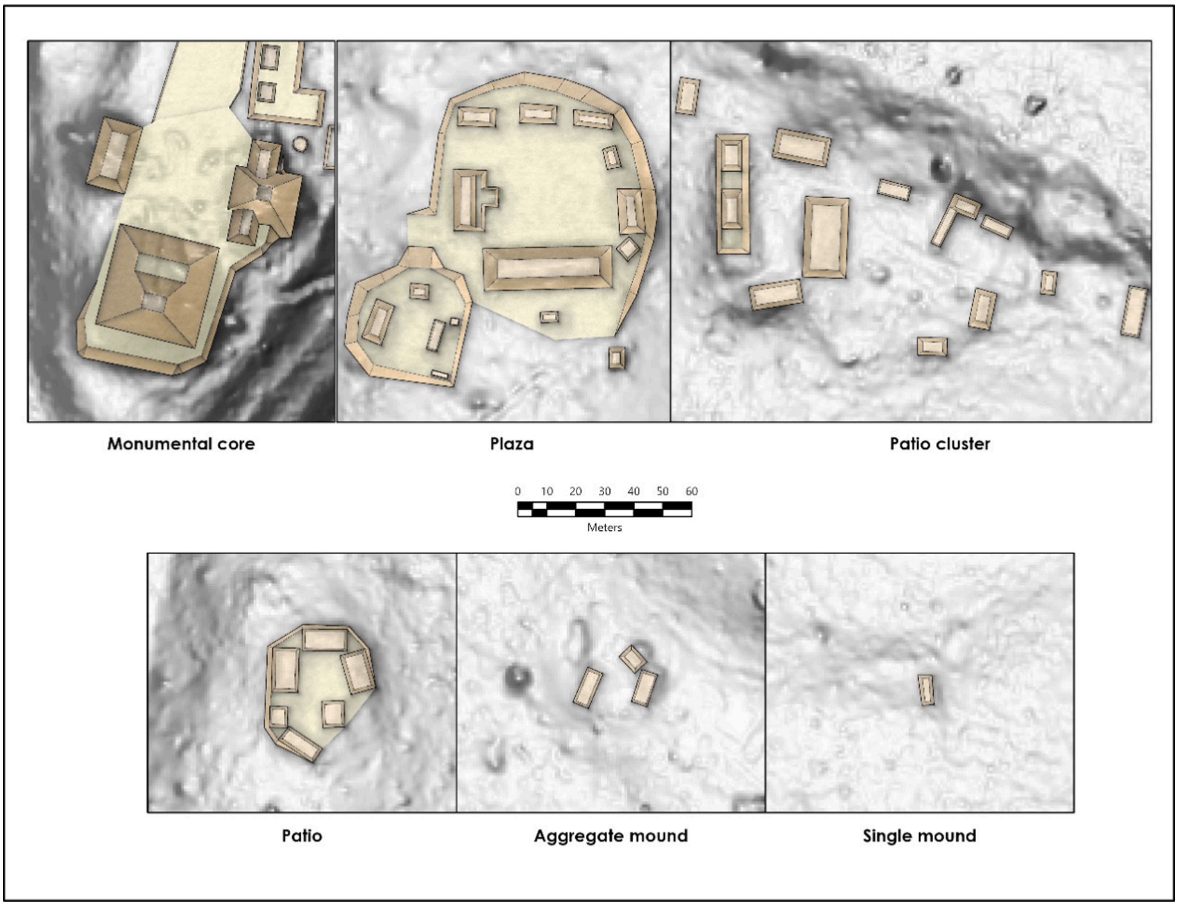

Fig. 5. PRALC settlement typology.

region's elite inhabitants were few, perhaps 5–10% of the overall population. There is a scattering of patio cluster sites, usually consisting of 5 to 24 residential structures arranged in contiguous patio groups. These scattered site types likely represented multi-generational extended family households of slightly higher status; they appear to compose less than 15% of the region's overall population. Most site types, however, were patio and aggregate mound groups (types III and II), each consisting of 3–6 structures. Their overwhelming majority suggests that most of the region's population was arranged in single family households (see Table 3).

From the Late Preclassic to Terminal Classic periods, the Corona-Achiotal region appears to have been settled by rural populations of farmers loosely distributed around the few monumental centers within the region. Only two such concentrations, La Corona and Chable, are sufficiently large and dense to potentially be considered urban, though these are still quite small compared to most Maya cities (Canuto et al. 2018a; Chase and Chase 2017b; Folan 1992; Haviland 1969; Hutson 2016; Hutson et al. 2008). Throughout the surrounding region, distended rural populations were likely organized in kin-based households clustered into communities of 30–160 people, likely representing small farming hamlets.

With the exception of La Corona itself (Canuto and Barrientos Q. 2011, 2013, 2020), the limited presence of socio-political centers combined with an overall low-density population suggest that this region's settlement represents a good example of Lowland Maya settlement patterning unencumbered by outsized historical, political, and economic forces. That is, it illustrates how ancient Maya people distributed themselves over a landscape absent the strong push–pull factors related to elevated settlement density—in human behavioral ecology, such a distribution is called an Ideal Free Distribution (Jazwa and Jazwa 2017; Prufer et al. 2017; Weitzel and Codding 2020). In this case, it is preserved on the surface over an area roughly half the size of Rhode Island, thus providing a useful sample for re-engaging the issue of macro-settlement patterns.

3.3. *Macro-settlement patterns and landforms in the Corona-Achiotal region*

Considering the favorable conditions presented by the settlement of the Corona-Achiotal survey block, we set out to determine some basic principles of settlement patterning via visual analysis. We concluded that: 1) settlement favors well-drained elevated levelled areas; 2) the largest clusters of contiguous settlement groups are located along the elevated edges of *civales* (pluvial marshes) or escarpments; 3) the low-lying, poorly-drained bajos are largely empty of settlement; and 4) settlement seems to favor proximity to locally abundant basins of pluvial water. This description closely matches Bullard's language from half a century ago, as well as other more recent summaries (Dunning and Beach 2011; Lucero et al. 2014). However, despite its accuracy, its utility for further analysis of any kind is limited. And it is here that a more systematic classification of the landscape becomes necessary.

3.4. *Topographic position Index*

The Topographic Position Index (TPI) is one of numerous means of classifying landforms from raw elevation models; in the simplest terms, it identifies areas of *locally* high and low ground. As discussed above, the literature on Lowland Maya settlement emphasizes the preference for: "comparatively level, well-drained, hill and ridge tops at medium elevations" (Bullard 1965:365). TPI makes it possible to classify a

Table 3
PRALC settlement typology distribution. Strs = Structures.

Site types		#	% of sites	strs	% of strs	strs/site	Platform (avg m^2)	Platform (median m^2)
VI	Monumental core	9	2.8	23	2.3	2.6	4,832	1,356
V	Formal plaza	10	3.1	115	11.6	11.5	1,347	207
IV	Patio cluster	16	5.0	127	12.8	7.9	320	81
III	Patio	78	24.5	299	30.1	3.8	325	78
II	Aggregate mound	102	32.0	325	32.7	3.2	121	66
I	Isolated mound	104	32.6	104	10.5	1.0	128	66
		319		**993**[*]				

[*] This total differs from the total of 942 verified structures reported above because not every multi-structure site was fully ground-truthed.

landscape in precisely those terms.

Importantly, TPI is also a good proxy for many of the factors that have been otherwise used to model the location of Maya settlement. For example, soil type has been recognized for decades as an important covariate of settlement location (Beach et al. 2006; Dunning and Beach 1994; Dunning et al. 2012; Dunning et al. 2015; Dunning et al. 2019; Fedick 1995; Fedick and Ford 1990; Ford and Nigh 2015; Griffin 2012; Murtha 2002; Sanders 1977). However, at local scales where variables such as rainfall and parent material tend to stay constant (at least, in a geologically monotonous region such as the Maya lowlands), soil type is largely a function of hillslope position—which is to say, topographic position. Vegetation communities, used since Ricketson's time to predict where settlement might occur, similarly covary with soil type and with topographic position, a fact that has been central to the scientific literature since the very first vegetation surveys in the Maya Lowlands (Lundell 1937) and which is reflected in common parlance, i.e. "*bajo* vegetation".

The correlation between local topographic position and vegetation communities is in fact so strong that ecologists have published straightforward conversion charts between the two (Schulze and Whitacre 1999: Table 1, Figure 11): "To a large degree, forest type [is] merely a condensation of topographic positions" (180). Since TPI neither relies on the existence of undisturbed natural vegetation as do optical classifications nor makes claims about the chemical or structural attributes of soils, it is better suited to macro-scale modeling than these other, dependent, variables.

TPI is computationally simple and logically straightforward: areas that are elevated vis-à-vis their surroundings have higher TPI values, while those that are lower than their surroundings have low TPI values[6]. Typically, TPI is calculated as the difference between any one pixel's elevation and the average elevation of its neighborhood divided by the standard deviation of the neighborhood. Since TPI is a neighborhood-based calculation, it is scale-dependent: small neighborhoods capture local variability but cannot distinguish a small knoll in the bottom of a valley from the summit of a mountain; similarly, large neighborhoods lose any distinction between the same small knoll and the valley that contains it. This scalar dependency works to the analyst's advantage, however, because large- and small-scale measures may be combined in a single classification. In this way, local elevation in valley bottoms (high TPI_{small}, low TPI_{large}) can be discriminated from mountain tops (high TPI_{small}, high TPI_{large}). Furthermore, TPI alone cannot discriminate between a flat plain and a steady 45° slope because it calculates the value of each pixel as the average value of its neighbors; consequently, our landform classification adapts Weiss's (2001) method which includes slope as a secondary variable to produce a ten-part landform classification (Table 4).

Table 4
Description of 10 TPI landform classes and their reclassification.

Landform	Landform Description (Weiss 2001)	Reclassification
1	V-shaped river valleys, deep narrow canyons	Bajo
2	Lateral midslope incised drainages, local valleys in plains	Bajo
3	Upland incised drainages, stream headwaters	Elevated Basin
4	U-shaped valleys	Bajo
5	Broad flat areas	Bajo
6	Broad open slopes	Islote
7	Flat ridge tops, mesa tops	Elevated Basin
8	Local ridge/hilltops within broad valleys	Islote
9	Lateral midslope drainage divides, local ridges in plains	Islote
10	Mountain tops, high narrow ridges	Upland ridge

Our application of TPI to the problem of Maya settlement patterns builds on Carlos Chiriboga's regional survey for PRALC, conducted between 2010 and 2012 (Chiriboga 2011, 2012, 2013), which to our knowledge was the first application of TPI within Mesoamerican archaeology (for another early example, see Balzotti et al. 2013). To identify those areas of highest likelihood of ancient settlement, Chiriboga applied TPI at two scales (2.7 kms and 900 m) on 90 m Shuttle Radar Topography Mission (SRTM) elevation data and set a relative elevation threshold at 5 m above the neighborhood average; this process identified roughly 6.6% of PRALC's research area (ca. 154 km^2) as highly likely to contain sites (Chiriboga 2011:26-28, 2012:30). Guided by this classification, Chiriboga's survey identified 34 previously undocumented sites, ranging from relatively modest clusters of residential buildings to monumental centers. The TPI classification presented here represents a logical next step to this approach, based on a dramatically expanded settlement dataset and much improved topographic data.

3.5. Landform classification methods

To undertake this analysis, we downsampled a 1 m per pixel resolution lidar-derived digital terrain model to 5 m (a 25-fold reduction in resolution). We did this for two reasons: first, to reduce the considerable processing time that large-scale TPI analysis requires; and second, to limit the effect of small terrain protrusions, such as individual ancient buildings and small bedrock knolls, on the overall classification (although the overwhelming majority of ancient structures are less than 1 m in height and therefore would have a negligible effect on TPI classification given the large neighborhood scales)(Ebert et al. 2016). All computations were performed in ArcMap 10.7 and ArcGIS Pro 2.6 using the Relief Analysis Toolbox (Miller 2015). We used circular neighborhoods with a radius of 300 m for TPI_{small} and 3000 m for TPI_{large}, a set of values that we determined to capture the smallest and the largest analytically-relevant landforms in the region and which could easily

[6] The method's primary drawback is that it cannot easily discriminate between landforms where the direction of elevation change is meaningful: for example, the base of an escarpment and the bottom of a narrow valley may have identical TPI values, since both positions are lower than their neighborhood average. In cases where directionality is important, other methods of classifying topography are better suited (such as the geomorphometric analysis implemented in GRASS GIS's r.geomorphon algorithm).

scale to moderate resolution topographic data[7].

This method produced a topographic classification with ten classes (Table 4)[8]. We aggregated these ten classes into four "super-classes" that reflect locally-meaningful landforms (Fig. 6): 1) well-drained areas in upland terrain (ridges), 2) low or flat areas within upland terrain ("elevated basins"), 3) low or flat areas in low-lying terrain (bajos), and 4) promontories within low-lying terrain (*islotes*). Three of these categories—bajos, ridges, and islotes—already figure to varying degrees in the lowland Maya settlement literature (Kunen et al. 2000; Sever and Irwin 2003). Less-prominent, generally slower-draining areas within uplands ("elevated basins"), however, have been elided by the recurring emphasis on an upland-bajo dichotomy—with the exception of "pocket bajos" (Dunning et al. 2015:96; Dunning et al. 1999) which form a subset of this superclass. The disambiguation of elevated basins from bajos and ridges plays a major role in defining a more precise *settlement suitability model*, elaborated below.

Our combination of landforms into our super-classes seeks to maximize their relevance to our analysis of settlement patterns within the interior central lowlands[9]. Because this area contains diverse ecological sub-regions (Dunning et al. 1998), a detailed analysis of landform correspondence with vegetation communities or soil types exceeds the scope of this paper. Nevertheless, we proffer some relevant observations about each super-class (Table 5). First, *ridges* universally support upland broadleaf forest (median canopy height: 17.1 m), with notable dominants including ramón (*Brosimum alicastrum*), sapodilla (*Manilkara zapota*), ceiba (*Ceiba pentaforma*), and cedar (*Cedrela oderata* spp.). Soils tend to be shallow but fertile, rocky, and well-drained.

Elevated basin soils are deeper and have higher clay content than ridge soils; forest species composition is similar but intermixed with more mesic-adapted species like laurel (*Nectandra sanguinea*) and mahogany (*Swietenia* spp.) and a variety of palms. Depending on the clay content of the soils, elevated basins may be highly desirable for agriculture, dedicated to specific mesic-tolerant cultivars, or reserved for dry-season and other "backup" plantings. The key feature of elevated basins is that they are ecologically productive upland environments, but their tendency to collect, channel, or retain moisture makes them less desirable habitation sites than ridges. Median lidar-derived canopy height for elevated basins in the Corona-Achiotal region is 15.4 m, lower than ridges and consistent with a mix of "upland/*montaña*" and "transitional" canopy heights reported elsewhere (Dunning et al. 2019:129-130; Reese-Taylor et al. 2016:333; Rice 1976:290-291).

Our *islote* superclass combines *meso*-scale topographic prominences (ridges and hilltops) located within low-lying regions and their surrounding slopes (Landforms 8 and 9) with broad open slopes (Landform 6). We did this because in the bajo zone, "open slopes" are so short due to the small scale of local elevation change as to not comprise a meaningful landform separate from the knolls, ridges, and shallow drainages with which they articulate. Like elevated basins, islotes support a mix of upland and mesic-adapted species with organic rich, very dark, silty, and unconsolidated soils. Because the elevation difference between islotes and the surrounding bajos varies widely, so does the degree to which islote forest diverges from bajo vegetation. Nevertheless, even the lowest islotes (less than5m relative rise) generally support a greater number and diversity of palms compared to their surroundings, along with emergent broadleaf trees. Forest on taller islotes (>10 m) is comparable in most respects to that found on ridges, and the median canopy height for the class in our study area, 16.0 m, reflects this.

Our *bajo* superclass subsumes the deep karst depressions (dolines) known locally as *rejolladas*; we justify this aggregation on the basis that both bajos and rejolladas are karst depressions distinguished by a gradient of concavity and subsurface drainage rather than a hard categorical break—and in any event, ancient settlement avoids both. Canopy height in bajos is variable, ranging from stunted scrub forest—especially palo de tinto (*Haematoxylon campechianum*)—to high palm forest to riparian environments. In our study area the median canopy height is 14.7 m, much higher than the ~ 6–10 m typically reported for bajos elsewhere in the region owing to the relative abundance of high-canopy riparian environments and palm-dominated bajos. Bajo soils are typically vertisols or histosols: potentially very fertile but requiring significant intervention to bring under cultivation.

Clearly, the four landform super-classes have strong ecological salience in the region. They correspond to topographically conditioned vegetation communities and soil catenas described for Tikal National Park and environs (Balzotti et al. 2013; Burnett et al. 2012; Lentz et al. 2015b; Luzzadder-Beach et al. 2016; Schulze and Whitacre 1999), the Calakmul Biosphere Reserve in southern Campeche (Brown 2005; Martínez et al. 2001; Reese-Taylor et al. 2016); and on either side of the Belize/Guatemala border (Dunning et al. 2003; Dunning et al. 1999). Perhaps more importantly for our study, this landform classification also proves strongly correlated to the distribution of the 3831 structures of the Corona-Achiotal region.

3.6. Settlement distribution

In the Corona-Achiotal region, the TPI classification resulted in a terrain map dominated by bajos (53%) and elevated basins (28%), while ridges and islotes combined to constitute less than 19% of the total land area (Figs. 7 and 8). There are two notable aspects of this terrain profile. First, our percentage for bajos is higher than published bajo coverage estimates for other Maya Lowland areas (e.g., Lentz et al. 2014; Puleston 1973, 1983; Rice and Culbert 1990:30-31; Ricketson 1937; Thomas 1981; Webster 2018:28) no doubt due to our study area's location straddling the central karstic uplands and low-lying western wetlands (i. e. the Laguna del Tigre Park) of the central Maya Lowlands[10]. Second, the "elevated basin" class is the second largest category in the region, representing more than a quarter of the region's surface area.

When these topographical categories are compared to the distribution of structures within the Corona-Achiotal region, a significantly imbalanced pattern manifests (Fig. 8). Consistent with previous research, only 5.5% of structures identified through visual analysis or field validation are located within bajos (209 strs over 230.0 km^2 for a density of 0.9 strs/km^2), with the vast majority of these occurring at the very edges. More surprising, only 5.4% of identified structures are located within "elevated basins" (208 strs over 120.5 km^2 for a density of 1.7 strs/km^2). Consequently, 89.1% of all identified buildings occupy either islotes (657 strs over 32.0 km^2 for a density of 20.5 strs/km^2) or ridges (2754 strs over 49.5 km^2 for a density of 55.6 strs/km^2), with the overwhelming majority occurring on the latter. Said another way, nearly 90% of the Corona-Achiotal settlement is located on less than 20% of the available terrain—a far more lopsided distribution than anything suggested by a simple upland/wetland dichotomy.

Given that the majority of the structure data under consideration have not been ground-truthed, we had to consider the possibility that the terrain of these different landforms, and their associated vegetation communities, could differentially impede the recognition of structures

[7] We tested other combinations of smaller (100-500m) and larger (2000–5000) radius values; the resulting terrain characterizations either varied negligibly from our 300/3000 combination or, in extreme cases, exhibited too great a loss of topographic detail to be useful for our analysis.

[8] See Miller 2015 for a detailed description of the calculations that underlie this tool's classification process and how they are associated to the ten topographic classes.

[9] Any analysis focused either on other aspects of the Maya landscape (agriculture, movement, etc.) or on topographically dissimilar parts of Maya Lowlands should consider amending these classifications.

[10] Our TPI calculations for areas located in the central karstic uplands result in bajo percentages consistent with published values, i.e. ca. 45% (Dunning et al. 2020a).

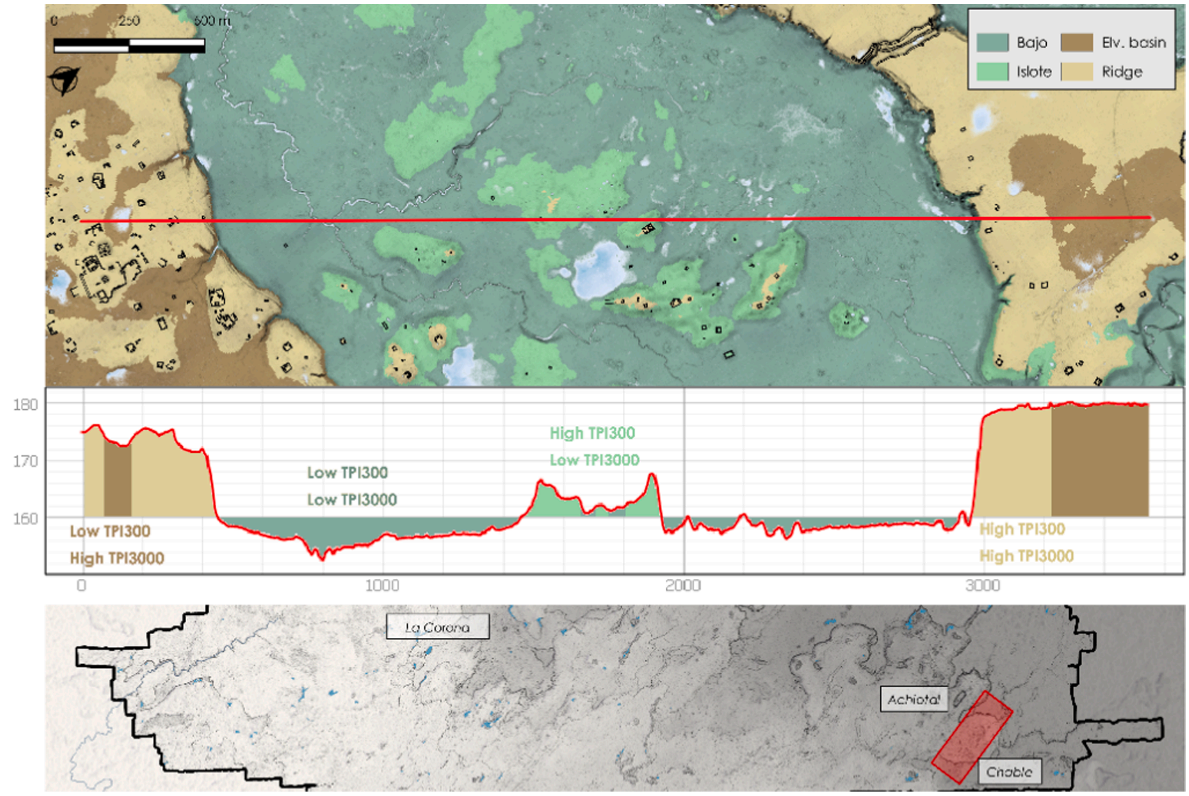

Fig. 6. Topographic profile of TPI classification. Architectural features (buildings, plazas, etc.) are drawn in black.

Table 5
Correspondences among landform super-classes, vegetation classes, and soil types.

Landform	Common Scientific Forest Classes (Dunning et al. 2003; Schulze and Whitacre 1999)	Common Folk Designations (vegetation, *soils*, landforms)	Typical soils (FAO, USDA) (Beach et al. 2006; Dunning 1992; Jensen et al. 2007)
Ridge	Dry upland forest, standard upland forest, montaña, climax forest, deciduous seasonal forest	ramonal, sapotal, cedral, ceibal, montaña, monte alto, ka'anal k'aax	rendzina, rendoll, alfisol, inceptisol
Elevated basin	Standard upland forest, mesic upland forest, sabal forest, transitional forest, hill base forest, escobal bajo, escobal transition forest, cohune palm forest	caobal, corozal, escobal, *Ya'ax jo'omal, k'ankabal, b'ox lu'um, ek' lu'um,* pocket bajo	eutric nitozol, chromic vertisol, vertic phaeozem, rendzina, usterindoll, argiustoll, paleustalf, rendoll, alfisol, inceptisol
Islote	Tall scrub swamp, transitional forest, hill base forest, escobal transition forest, mesic upland forest, sabal forest	escobal, botanal, caobal, ceibal, julubal, *pus lu'um, b'ox lu'um, ek' lu'um,* bajo island, isla, islote	rendzina, cumulic ustirendoll, rendoll, alfisol, inceptisol, vertisol
Bajo	Mesic bajo forest, tall scrub swamp, low scrub swamp, true swamp, tintal bajo, bajo forest, escobal bajo, cohune palm forest, riparian forest	tintal, pucteal, huechal, julubal, navajuelal, carrizal, chechenal, cival/ sibal, akalche, bajo, arroyo, uk'um	vertisol, histosol

during heads-up digitization, a phenomenon that has been documented in diverse parts of the lowlands (Inomata et al. 2018; Reese-Taylor et al. 2016). For this reason, we recorded the extent to which our ground-truthing modified the distribution of structures across the four terrain classes. As Table 6 shows, the differences in landform distribution of structures between ground-truthed and digitized data are statistically insignificant (χ^2 [3, N = 776] = 4.884, p = .181), lending further robusticity to this observed pattern.

Interestingly, there is a sharp distinction in architectural volume and quality between settlements on ridges and those on islotes (Fig. 9). Buildings on islotes tend to be isolated, smaller, and shoddier. Our excavated sample is too small at this point to make any strong functional claims, but we suspect on analogical grounds that the limited architectural investment across most islote settlements reflects a greater degree of short-term or seasonal occupation of these environments (Šprajc et al. 2021; Zetina Gutiérrez and Faust 2011)—which would, if true, add a further wrinkle to the already diverse category of (mostly resource-specialized) "bajo communities" (Kunen et al. 2000). Inversely, the largest site types in the region—monumental cores, plazas, and patio clusters—overwhelmingly occupy ridges. Considering the notion that long-occupied sites tend to grow in both volume and size (Haviland 1988; Tourtellot 1988a), the current landform distribution of settlement types suggests that ridges are host to the earliest sites within the region, consistent with the notion that ridges were the preferred settlement landform generally.

The implications of this severely lopsided settlement distribution go far beyond previous observations regarding the relative emptiness of bajos. First, the manifest avoidance of our "elevated basin" category suggests that there exists an extensive terrain class that the Lowland Maya deemed almost equally unsuitable for settlement as the bajo and which, by extension, they presumably reserved for other uses. Given that much of the "elevated basin" terrain in the Corona-Achiotal region supports upland forest, the landform is clearly not hostile to biomass and would thus be well-suited to either agriculture or forestry. Second, and

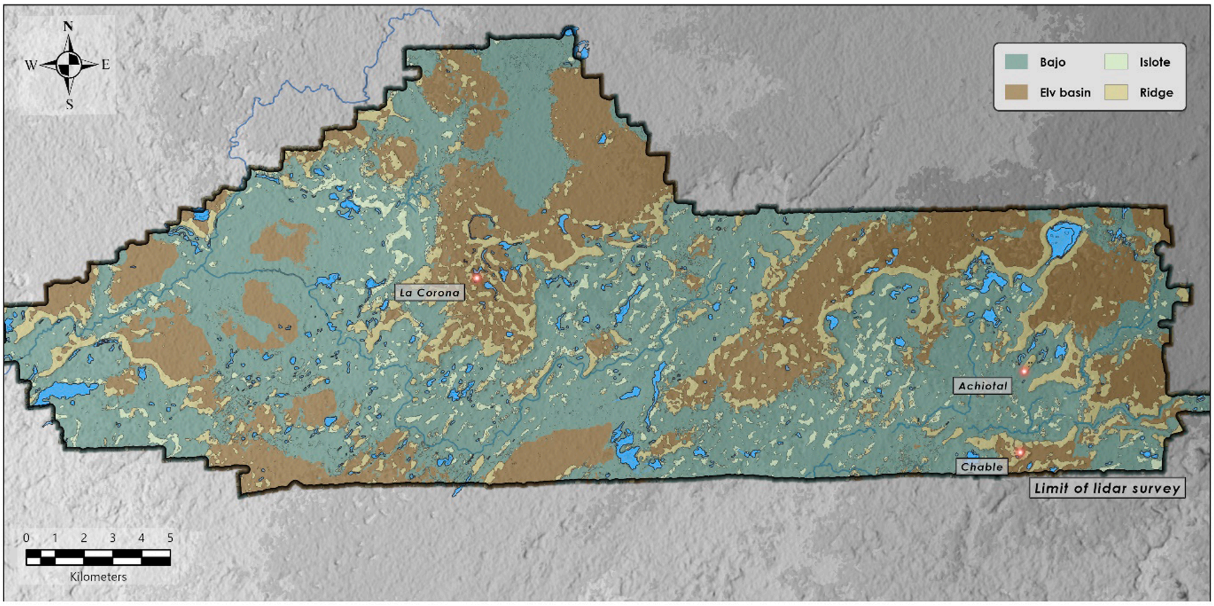

Fig. 7. Landform “super-classes” in the Corona - Achiotal region.

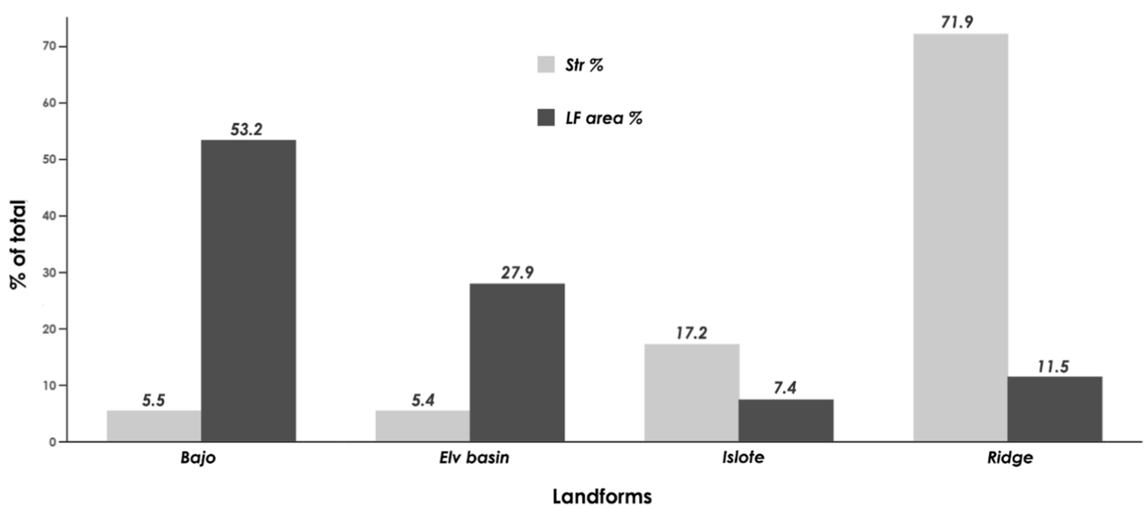

Fig. 8. Distribution of structure and landform class percentages throughout the Corona-Achiotal region.

Table 6
Landform distribution of lidar based (n = 776) vs. ground-truthed (n = 942) structures.

	Lidar-based (%)	Ground-truthed (%)
Bajo	0.4	0.5
Islote	3.5	4.7
Elv basin	9.3	10.7
Ridge	86.9	84.1

relatedly, it is now possible to specify the degree of preference—that is, the suitability rank—the ancient Lowland Maya conferred to each class: ridges, then islotes, with elevated basins and bajos following far behind. Third, the close alignment of our super-classes and the distribution of settlement thereupon with the qualitative descriptions offered by Bullard and others indicates that our classification has succeeded in capturing the signal of what Mayanists have long understood about settlement in the bajo zone of the central Maya Lowlands—this time in spatially-explicit, quantifiable, and generalizable terms. In as many words, our identification of ranked landform preference converts existing knowledge of ancient Maya settlement patterning into an explicit settlement suitability model.

4. Variation of macro-scale settlement patterns and Maya urbanism

We extended our analysis to other survey blocks in the PLI sample to determine how closely other more densely inhabited parts of the interior central lowlands adhere to the pattern established for the Corona-Achiotal area. Since the published PLI settlement data derive from lidar data subject to ongoing analyses by PLI member projects, we applied the landform classification to freely available, moderate-resolution terrain data from the Advanced Land Observing Satellite (ALOS) mission of the Japanese Aerospace Exploration Agency (JAXA). Despite some salient deviations, we found a strong adherence to the same pattern.

First, a technical note: ALOS DEMs are 1 arc-second (~30 m) *surface* models, representing a mix of tree crowns, modern roof tops, and bare ground; therefore, the DEM lacks the topographic precision of a lidar-derived *terrain* model. This, together with the reduced spatial

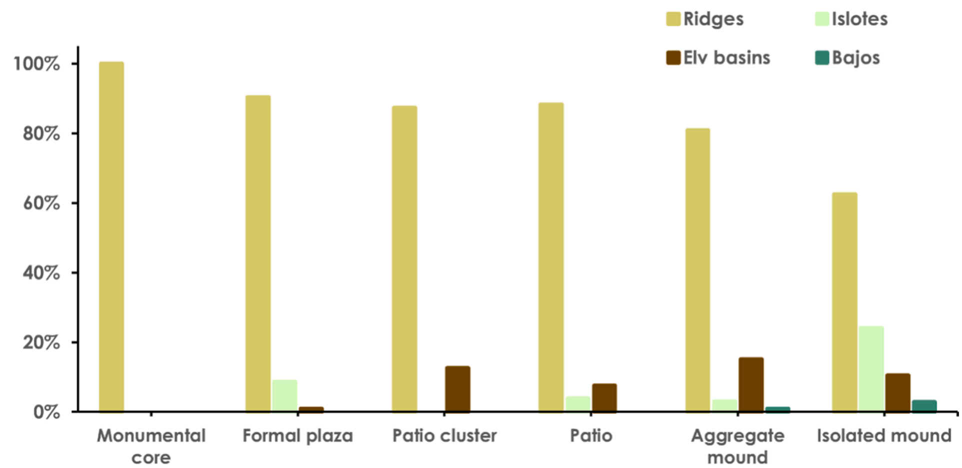

Fig. 9. Percent of site types by super-class landforms.

Table 7
Distribution of structures (2018 PLI dataset) across landforms (ALOS 30 m DEM).

	Peru	Naachtun	Tikal	Holmul	Xultun	Zotz	Uaxactun	Env2	Env1	Corona	Yala	Total
Islotes/Ridges strs	3226	9151	9271	5749	4108	4743	4112	201	242	2992	593	44,388
Islotes/Ridges str %	79	76	75	80	75	76	81	68	79	82	81	77
Islote/Ridges area %	39	38	40	36	37	37	38	29	32	39	34	36

resolution, means that the ALOS-based landform classification is less precise as well as prone to noise. For example, in ALOS, a larger percentage of the PRALC study area is classified as islote compared with lidar (12.5% vs 7.4%). This is because 1) some small but sharp hills are smoothed into larger, gradual rises in the coarser-resolution data and 2) variability in canopy height leads surface model-based classifications to identify some areas as ridges or islotes when the underlying topography may be level (and the opposite problem applies to gaps in the canopy caused by tree falls and anthropogenic clearing). Noisy classifications are simply the cost of doing business with surface models.

These issues notwithstanding, the same patterns in landform ranking are clear in the ALOS classification. Using the 2018 PLI structure dataset (Canuto et al. 2018a; Canuto et al. 2018b) and applying the same procedure we used for the lidar-based analysis of the PRALC survey block, our results showed the same striking pattern seen in the Corona-Achiotal region: settlement overwhelmingly favors ridges and islotes across 10 PLI survey blocks, such that an average of 77% (68–82%) of structures occupied favored landforms even though these only constituted an average of 36% (29–40%) of the terrain within the PLI dataset (Table 7). Both bajos and elevated basins were preferentially avoided across all blocks.

These results indicate that the patterns starkly visible in the Corona-Achiotal region are in fact a phenomenon of the interior central lowlands *in general* (see Fig. 1). Consequently, tracking the distribution and extent of these landforms can provide an important baseline for understanding the disposition of settlement within any particular subregion. A review of the PLI data set shows some interesting variations that prove relevant here. Regions with low overall settlement density have the higher percentages of ancient buildings occupying preferred landforms: Corona-Achiotal is at 82%. Inversely, where overall settlement density is higher, the total proportion of buildings on favored landforms decreases: Tikal is at 75%. Is this 7% difference a meaningless bit of statistical noise or does it reflect a salient difference in the way settlement was disposed in those two areas?

To answer this question, we look to "elevated basins". Though these are ecologically productive upland environments, they were largely avoided by settlement. It follows that these parts of the landscape were host to the lion's share of the region's outfield agriculture, forestry, and wild-food harvesting—all of which favor upland forest environments and ecotones (Balzotti et al. 2013; Dunning et al. 2020a; Fedick 1996; Ford and Nigh 2009, 2015; Griffin 2012). However, in the most heavily settled regions, elevated basins demonstrate higher-than-average settlement density rates: in Naachtun elevated basins are 4.9% more densely settled than the regional average, while in Corona-Achiotal, they are 36% less (Fig. 10)[11].

Parsimony would suggest that as the landscape became populated, people were pushed to build in less favorable areas. A closer look, however, reveals that this explanation does not account for 1) the unexpectedly high settlement density of elevated basins found in only moderately dense regions, such as El Perú, or 2) the existence of uninhabited ridges and islotes within all regions. Consequently, the notion of a "full" landscape compelling settlement of marginal lands does not adequately explain the distribution of settlement across landforms. Why, then, would people crowd into marginal terrain even when preferred landforms remained unsettled a few kilometers away?

The data suggest that the above-average use of marginal landforms was (at least, in part) a function of their proximity to densely urbanized areas rather than overall population size at the *meso*-scale (>100 km^2). Where the largest, densest centers existed in the PLI data set, the centripetal force of these urban centers was sufficiently compelling to crowd elevated basin terrain in their immediate vicinities—regardless of how densely settled the broader landscape was. Settlement preference was therefore not just determined by topography but also impacted by local socio-economic and politico-historical factors.

This finding is consistent with a detailed and chronologically-controlled case study of settlement patterns at the site of Uxbenka in

[11] Although settlement percentages across landform classes using higher resolution lidar data will likely differ from those derived from ALOS data, we are confident that *the manner in which* settlement distribution varies between distinct regions will not change significantly. Future research comparing lidar data analyzed using our TPI method from multiple areas in the Maya Lowlands would permit a more precise analysis of these patterns.

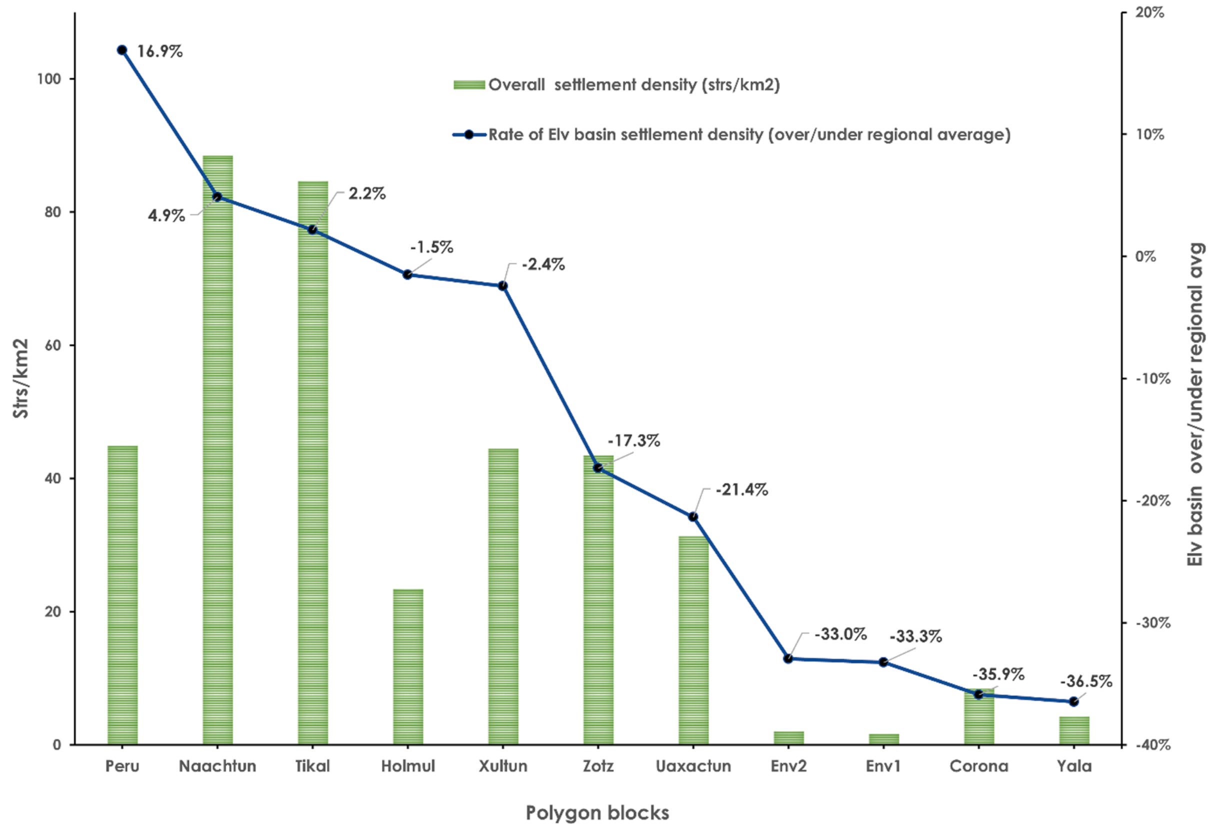

Fig. 10. Settlement density (PLI 2018 dataset) and rate of Elevated basin usage.

Belize (Prufer et al. 2017; Thompson and Prufer 2021), and demonstrates that those authors' broadest conclusion applies to Lowland Maya settlement patterns generally: as specific places on the landscape took on political, religious, and economic importance, people elected to live near them even though it meant settling on less desirable land. This settlement pattern is all the more significant considering that expansion of settlement into these landforms would have unavoidably strained a carefully-managed land-use/land-cover balance among woodlands (as a source of fuel, wild foods, and building material), farms, and built space (Dussol 2020; Emery and Thornton 2008; Fedick 2010)—a process detected in charcoal assemblages from Tikal (Lentz et al. 2015a; Lentz et al. 2014) and Naachtun (Dussol et al. 2020), perhaps not coincidentally the two largest cities in the PLI sample (Canuto et al. 2018a; Canuto et al. 2018b).

These observations run counter to arguments claiming that agriculturally-motivated settlement dispersal impeded the development of genuine urbanism in the Maya lowlands (Drennan 1988; Griffin 2012; Murtha 2015:94-95; Sanders 1962, 1963, 1973, 1977; Sanders and Webster 1988; Webster and Murtha 2015; Webster 1997, 2018). Instead, these data suggest that the gravitational pull toward urbanization counteracted the centrifugal imperative of subsistence agriculture (Smith et al. 2021) even in landscapes that were not yet "full". That is, Lowland Maya could and did forego colonization of higher-ranked areas in favor of proximity to urban amenities and other people, leading to "densification" and what Kostof (1991; see also Smith 2019; Smith and Lobo 2019) called the "energized crowding" of their urban centers. While Lowland Maya cities were indeed generally lower-density than cities in temperate Eurasia (Fletcher 1995; Isendahl and Smith 2013; Smith et al. 2021), our analysis shows that socio-economic and politico-historical factors played a key role in the development of urban landscapes. It bears noting, at the risk of tedious repetition, that the above analysis derives from *recognizing variation within generalized settlement patterns*—teasing local nuance from regional pattern is precisely the benefit of robust macro-settlement analysis.

5. Conclusion

Settlement archaeology's foundational goal was to describe, and then explain, "the way in which man disposed himself over the landscape on which he lived" (Willey 1953:1). As Willey and other pioneering surveyors recognized, a convincing analysis of settlement patterns had to grapple with and ultimately reconcile environmental and cultural forces. And while Mayanists can claim some major successes in this regard at the community scale (e.g., Hammond 1991; Lentz et al. 2015b; McAnany 2004; Murtha 2002; Pyburn 1989; Robin 2012), bridging from local case studies to a robust and testable regional model for macro-settlement patterns remained limited.

To achieve this fuller accounting of the ancient Lowland Maya settlement landscape, we must leverage the insights from lidar data to understand the full suite of variables—geomorphologic, floristic, climatic, etc.—that enabled, constrained, and indeed even *reflect* the patterning of settlement, and then model the implications of those variables across space. In spirit, this analysis represents the kind of local-to-regional scale modeling previously undertaken by Puleston (1973), Rice (1976, 2006), Fedick (1994, 1995), Garrison (2007, 2010), Griffin (2012), and Ford and Nigh (2015) but with the clear advantage of lidar-based data that enable exhaustive community-scale analysis while also bridging to macro-scale, quantitative analysis of settlement data and its ecological covariates.

Our topographic *settlement suitability model* represents a step in that direction. It suggests that for a large swath of the Maya Lowlands, topographic position (as modeled by the Topographic Position Index) is a powerful proxy for the factors that ancient Lowland Maya people considered when deciding where to build. Furthermore, it demonstrates that the high degree of local-scale environmental variability together with the strong preference conferred to certain landforms as building sites means that lowland Maya settlement is best understood as *patchy*, rather than *dispersed* or *low-density*. This term, borrowed from behavioral ecology, better represents the relationship of settlement to landscape at both the micro- and macro-scale.

The suitability model presented here applies to the interior central Maya Lowlands, an area whose boundaries remain unspecified. Determining where this macro-settlement pattern gives way to a different kind of settlement distribution, tuned to a different physiographic landscape, is an area for future research, though on the basis of physical geography and descriptive treatments of settlement patterning, we expect that the same ranked landform preference will indeed hold true for some areas beyond the limits of what we preliminary propose here. We hope that colleagues working in those areas are inspired to develop such models.

Finally, our proposed model for the *potential* distribution of ancient settlement should also encourage use of the same robust, lidar-derived settlement datasets to explain regional variation. Our analysis of variability in the rates of "spillover" into marginal landforms suggests that topographic preferences were continuously revalued by social, economic, and political factors that had a measurable impact on patterns of settlement concentration or dispersal. Thus, far from being deterministic, our settlement suitability model provides a quantitative basis for considering the specific impact of non-environmental factors on the character and morphology of individual communities. As this and other spatially explicit suitability models are applied throughout the Maya lowlands, we will gain a clear view of where and how and why specific cultural and environmental forces articulated to create the ancient Maya settlement landscape.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The authors will make available the lidar-derived data (LDD) from the Corona-Achiotal region pursuant to the guidelines established by the Guatemalan Institute of Anthropology and History regarding access to archaeological data. By the end of 2021, the data embargo on the Corona-Achiotal LDD will be lifted and the data will be provided a unique DOI and made available through Tulane University's LabArchives platform.

Author statement

All authors have seen and approved the revision of the manuscript being submitted. We warrant the article is our original work and has not received prior publication and is not under consideration for publication elsewhere.

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