Uncovering archaeological landscapes at Angkor using lidar

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Previous archaeological mapping work on the successive medieval capitals of the Khmer Empire located at Angkor, in northwest Cambodia (~9th to 15th centuries in the Common Era, C.E.), has identified it as the largest settlement complex of the preindustrial world, and yet crucial areas have remained unmapped, in particular the ceremonial centers and their surroundings, where dense forest obscures the traces of the civilization that typically remain in evidence in surface topography. Here we describe the use of airborne laser scanning (lidar) technology to create high-precision digital elevation models of the ground surface beneath the vegetation cover. We identify an entire, previously undocumented, formally planned urban landscape into which the major temples such as Angkor Wat were integrated. Beyond these newly identified urban landscapes, the lidar data reveal anthropogenic changes to the landscape on a vast scale and lend further weight to an emerging consensus that infrastructural complexity, unsustainable modes of subsistence, and climate variation were crucial factors in the decline of the classical Khmer civilization.

Southeast Asia | urbanism | sustainability | resilience | water management

The medieval temple complex at Angkor, in northwestern Cambodia, has been the focus of more than a century of intensive scholarly research. The principal focus of that work has traditionally been on the famous monumental remains of stone and brick and on the inscriptions and works of art that are found within them. Based on that body of research, archaeologists have arrived at a clear understanding of the developmental sequence of the public architecture of Angkor. Until recently, however, Angkor has remained very poorly understood as an inhabited space (1–3). In general, the use of masonry was limited to religious architecture, and most other components of the built environment—from the palaces of Angkor's kings to the vernacular architecture of the common people—were made of perishable materials such as wood and thatch and have not survived in the archaeological record. Nonetheless, subtle traces of these ephemeral cities remain inscribed into the surface of the Cambodian landscape even centuries later, in the form of topographic variations that indicate the former existence of roads, canals, ponds, field walls, occupation mounds, and other basic elements of the urban and agricultural networks (1). In the past 20 y, a series of archaeological mapping projects have used remote sensing techniques to map those traces at Angkor, with a view to elucidating the development of urban form and of hydraulic engineering over time and space (2, 4, 5).

Those studies have uncovered an engineered landscape on a scale perhaps without parallel in the preindustrial world (5). The macroscale structure of the settlement complex at Angkor bears a prima facie resemblance to many other low-density urban complexes of that era, such as the those of the Maya, and also to the low-density megacities that have emerged in the 20th century (6). Understanding the nature of human–environment interactions at Angkor, and the trajectory of its growth and decline, is therefore of value both for our understanding of contemporary human geography and for evaluating the historical sustainability of this specific mode of urban organization (6–9). Arriving at a detailed, accurate, and comprehensive understanding of the urban morphology of Angkor is a fundamentally important component of that research agenda.

Around the central monuments of Angkor, however, thousands of hectares of dense vegetation cover now obscure the remnant contours of the medieval cityscape from conventional remote sensing instruments, and ground-based surveys of the topography in the area have been fragmentary and incomplete (2). The problem that has thus arisen is that two quite different interpretations of habitat on the Angkor plain are possible from previous data (3): on the one hand, a view of urbanism as a succession of discrete, insular spaces that are functionally and morphologically distinct from an essentially "nonurban" hinterland (2, 10); and on the other hand, a view of Angkor as a vast, low-density urban complex with a high degree of operational and functional interdependency with a densely populated urban center (4, 5).

Elsewhere in the world, developments in airborne laser scanning (lidar) technology are revolutionizing the field of archaeological remote sensing in tropical environments (11). Lidar provides an unparalleled ability to penetrate dense vegetation cover and map archaeological remains on the forest floor. It can uncover and map microtopographic relief that otherwise cannot be discerned without very costly and labor-intensive programs of ground survey (12). Lidar technology has recently matured to the point where it has become cost effective for archaeologists to undertake bespoke data acquisitions at landscape scale, even while capturing topographic variation with sufficient accuracy and precision to identify archaeological features of only a few centimeters in size (13, 14). In Mesoamerica, programs of archaeological lidar have added important context to the monumental remains that form the core of low-density settlement complexes, revealing extensive and sophisticated urban and agricultural networks stretching between and far beyond the well-known temples (11, 13). Apparent similarities between early

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civilizations in the tropical forest environments such as Mesoamerica and Southeast Asia have long been noted by scholars (6, 7, 15, 16). However, archaeological lidar programs in such environments have so far been limited to Mesoamerica, and the unique potential of the method to produce detailed images of the archaeological landscape beneath forest cover has remained unrealized in Asia (17, 18).

Here we begin to address that deficit by reporting the results of a 370 km^2 lidar survey undertaken in northwest Cambodia in 2012 (Fig. 1). We show that the dense forest surrounding the major temples of Angkor has previously obscured the remnant traces of a succession of formally planned urban spaces, which the lidar data now reveal with exceptional clarity. Previous studies identified a vast, low-density urban periphery stretching far beyond the major Angkorian temples (4, 5). We confirm that analysis, while further identifying a densely populated urban core and revealing that peripheral temples were also nodes in an extended, polynucleated settlement complex. We also identify previously undocumented urban landscapes in the region of Greater Angkor, and present a model of urban intensification and landscape engineering spanning several centuries, in which a very large and increasingly urbanized population was highly dependent on the delivery of consistent agricultural yields from an extended agro-urban landscape.

Results

The results of the lidar acquisition have profoundly transformed our understanding of urbanism in the region of Angkor, even while confirming various long-standing assumptions. The traditional model of the growth and decline of cities in the Khmer Empire (3) charts the development of urban form from "temple-cities" in the early first millennium in the Common Era (C.E.) to walled urban enclosures in the beginning of the second millennium C.E. (2). Within this conventional model, the assumption has always been that the enclosure walls or moats of the great monuments delimited densely populated urban environments. The lidar data provide unique material evidence of the existence of those "urban temples," in the form of formal spaces divided into regular "city blocks," with each block furnished with elevated occupation mounds and excavated ponds. This pattern is strikingly evident within the moated, early 12th century enclosure of Angkor Wat (Fig. 2).

We note that the presence of archaeological features is essentially ubiquitous across all of the acquisition area. Following a comparison with previously published maps (2, 4, 5, 19), we conclude that the lidar imagery reveals extensive and previously undocumented cityscapes in all three of the main acquisition blocks: Angkor (Fig. 3), Phnom Kulen (Fig. S1), and Koh Ker (Fig. S2). The lidar acquisition provides coverage over all of the main forested temple zones of the Greater Angkor area and their central "state temples" (Fig. S3). Combined with previous archaeological studies of the extended low-density urban hinterland (4, 5), our results provide a near-complete picture of archaeological topography throughout the settlement complex, irrespective of vegetation cover or other environmental conditions.

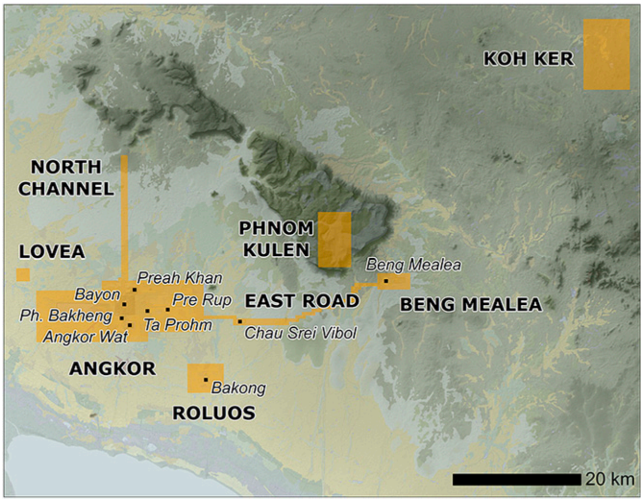

Fig. 1. An overview of the lidar acquisition areas in northwest Cambodia (background data courtesy of the Shuttle Radar Topography Mission).

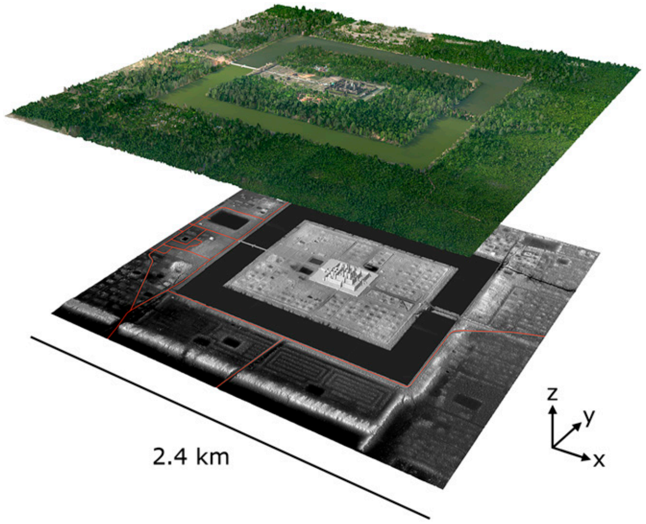

Fig. 2. An oblique view of Angkor Wat and its immediate environs. *Upper* layer: Digital orthophoto mosaic, with elevation derived from the lidar digital surface model at 1-m resolution. *Lower* layer: extruded lidar digital terrain model, with 0.5-m resolution and 2× vertical exaggeration. Red lines indicate modern linear features including roads and canals.

The lidar data also confirm the existence of basic elements of a schematic rendering of orthogonal divisions in the enclosure of Angkor Thom, previously identified by Gaucher (2). What is striking, however, is the extent to which the rigorously conceived geometric spaces of urban landscapes extend far beyond the ostensibly "enclosed" areas (Fig. 3). This is true not only of the so-called 'walled city' of Angkor Thom, but essentially of all of the temples in the central area, including Angkor Wat itself, which shows clear evidence of coherent and highly formalized space continuing in the extramural zone on at least three sides (east, west, and south). In fact, the lidar reveals clearly that the formalized, urban center of the city of Angkor extends over at least 35 km^2, rather than simply the 9 km^2 conventionally recognized within the walls of Angkor Thom (2).

Most of that urban 35-km^2 urban core conforms to an orthogonal, cardinally aligned grid pattern of linear features (either canals or city streets) defining city blocks containing occupation mounds and ponds. There are significant exceptions: adjoining the southern side of the moat of Angkor Wat, for example, we have identified a series of rectilinear coil-shaped embankments of indeterminate function (Figs. 2 and 3) and with a form never before documented in Angkorian archaeology or iconography. Based on their spatial and morphological characteristics, these features, which cover several hectares, are certainly contemporaneous with Angkor Wat. However, ground verification and preliminary analyses reveal no apparent function relating to agriculture, occupation, or water management. Although the reason for the construction of these features remains unexplained, they represent a substantial and significant addition to the known repertoire of Angkorian urban elements.

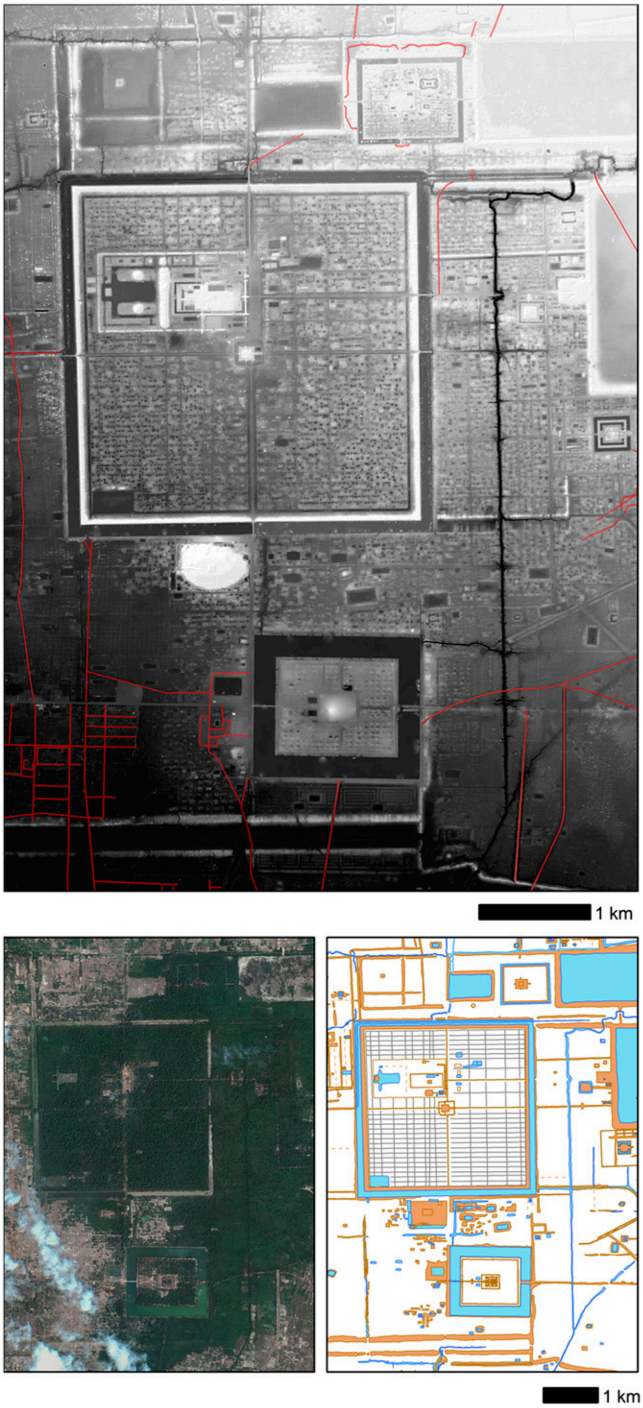

Fig. 3. The central area of Angkor, showing the "walled city" of Angkor Thom above Angkor Wat. *Upper*: lidar digital terrain model, with 1-m resolution. Red lines indicate postmedieval linear features including roads and canals; other features are Angkor era. *Lower Left*: conventional high-resolution satellite imagery of the central area, showing archaeological topography obscured by forest. *Lower Right*: previously documented (prelidar) archaeological features in the central area (2, 4).

To the northeast of central Angkor, in the Koh Ker acquisition block, anthropogenic modifications cover essentially the entire 67-km^2 area. In the Phnom Kulen acquisition block to the north of central Angkor, the lidar data have revealed an entire, previously undocumented cityscape etched into the surface of the mountain beneath the forest, including highways, undocumented temples, and other elements of urban form (Fig. S1). This newly mapped urban landscape corresponds to the 8th- to 9th-century city named Mahendraparvata, one of the first capitals of the Khmer Empire, which was previously known primarily from written inscriptions (10, 20). As with the 9th- to 10th-century cities located on the Angkor plain and centered around the temples of Bakong, Pre Rup, and Phnom Bakheng (3, 21), both Koh Ker and Phnom Kulen are "open cities" unconstrained by a clearly defined enclosure or city wall. Furthermore, both Koh Ker and Phnom Kulen show evidence of Angkor-era hydraulic engineering on a scale comparable to that of Angkor itself, indicating that a dependence on water management systems to ameliorate annual-scale variation in monsoon rains and ensure food security was not unique to the low-lying floodplains of Angkor, but a common feature of early Khmer settlements across mainland Southeast Asia (22), including upland sites.

Chronology. Evidence from inscriptions, architecture, and art historical styles has traditionally provided an extremely solid foundation for the chronology of Khmer temples. The last significant revision to the developmental sequence of the major religious foundations at Angkor was in the 1920s (23–25). At this point, our analysis of the lidar data offers no major new insights into the chronology of the temples, and we accept the standard model of the development of sacred architecture at Angkor.

The fact that these temples were directly associated with urban spaces is well attested in the epigraphic record, even if, until now, it has seldom been clear from the archaeological record what the "cities" mentioned in those inscriptions actually consisted of (3). The Ta Prohm and Preah Khan inscriptions, for example, describe populations on the order of 10,000–15,000 people that were directly associated with each temple, and the assumption has always been that those people resided within the enclosing walls of the temples (25). Importantly, we also know from the inscriptions that a fundamental aspect of Angkorian kingship was to implement projects of urban development, including the construction of new temple foundations and related infrastructure, and the expansion of Angkor's urban space (26). The inscriptions therefore provide a basis for understanding the association of well-dated temples with the remnant traces of urban features that are visible in the lidar. Furthermore, analyzing the orientation, morphology, and relative spatial relationships of surface archaeological traces at Angkor can provide crucial insight into the chronology of the built environment (21, 27). Thus, we have a sound logical and methodological basis for using lidar data to elucidate the spatiotemporal development of urban form at Angkor. We present a general model of that development here.

Urban form in the early medieval period in the 9th to 10th centuries was characterized by a central temple precinct organized around a central state temple, both in the Angkor area and in other cities of the period at Phnom Kulen and Koh Ker. This central temple precinct frequently contains moated temples, but the archaeological topography inside the moated areas is relatively unstructured. In fact, in most cases this bounded space is completely unstructured, aside from the temple itself. A relatively unstructured low-density distribution of urban elements such as ponds, village shrines, and irregularly shaped mounds stretches between and far beyond the central temple zone. Typically, this low-density urban environment is interspersed with gardens and fields, with no enclosing wall or moat delimiting or defining any significant subset of the urban space.

In the 11th to 12th centuries, we discern a marked shift in the patterning of urban space. Linear elements such as roadways and canals begin to appear within the moated precincts of temples and eventually form symmetrical rectilinear grids that define city blocks. These city blocks themselves are highly structured spaces, with each of them generally containing occupation mounds and ponds of consistent size and consistent placement within the rectilinear city block. All of the occupation mounds within the moat of Angkor Wat, for instance, are near identical in size, and each occupation mound has a pond immediately to its northeast, with all of these ponds also being near identical in size. This pattern can be clearly discerned throughout the area defined by the moat of Angkor Wat, except for two areas in the western half where the archaeological topography is obscured by the presence of postmedieval Buddhist pagodas. Throughout the 11th and 12th centuries a low-density urban network continues to stretch between and far beyond the moated precincts of the temples; the major temples of this period can therefore be characterized as high-density nodes in a polynuclear urban landscape. Furthermore, by the mid-12th century the highly structured urban space also occurs to a certain extent outside of temple moats, as we can see clearly in the case of Angkor Wat. These urban temples are not isolated; rather, they are nodes in an increasingly concentrated medieval cityscape.

In the late 12th to early 13th centuries this "overflow" of the rectilinear grid into areas far beyond the space delimited by temple enclosures becomes well established. With the construction of Angkor Thom in this period, we see unambiguous evidence of the construction of a "city wall" as distinct from a temple enclosure; however, it is once again clear that the rectilinear grid encompasses both intramural and extramural areas, and transitions almost seamlessly in extramural areas into the surrounding low-density urban landscape. The organization of space within each of the city blocks has undergone a significant transformation by the 13th century, however, as the highly formalized spaces of the 11th to 12th centuries give way to a less rigid pattern, with ponds and mounds showing a significant degree of variability in placement, size, and morphology. This heterogeneity is partly a function of the extension of the rectilinear urban grid beyond the sacred geography of the temple precincts and is indicative of increasing complexity and population density in the urban core of Angkor, which by the 13th century encompassed ~35 km^2 at the center of an extensive, low-density urban complex stretching over ~1,000 km^2. In terms of medieval urbanism, this is the end point of a trajectory that begins with the essentially open cities of the 9th to 10th centuries, progresses through a period of increasing urbanization and the formation of high-density nodes in the 11th and 12th centuries, and culminates in the 12th to 13th centuries when the high-density nodes in the central area of the settlement complex have expanded and coalesced.

Broadly speaking, the lidar data indicate that highly structured, orthogonal urban spaces within temple enclosures were an 11th-century innovation that later became ubiquitous within Khmer temples in the Angkor region. The lidar data thus provide a key insight into the changing nature of urban space, in which the open cities of the early Angkor period (3) had developed high-density urban nuclei by the early 12th century, with heavy reliance on an extended agricultural catchment (6) and continued on a trajectory of further urban intensification from the late 12th century onwards.

Discussion

The most significant outcome of the lidar mission is the discovery of the magnitude of anthropogenic modifications to the regional landscape. Evidence for Angkor-era construction and engineering, either for urban or agricultural space or some combination of the two, is ubiquitous across the entire acquisition area, even in relatively unvegetated areas of Angkor that have been intensively studied for decades (Fig. 3). We conclude from these data that not only dense forest but even modest amounts of vegetation coverage have previously obscured traces of important archaeological remains, and that the intensity of land use and the extent of urban and agricultural space have both been dramatically underestimated in the Angkor region until now.

This in turn has a series of significant implications for our understanding of interactions between humans and their environment in tropical forest landscapes. As has been argued for at least 30 y (6, 7, 28, 29), resolving questions relating to the scale, structure, and population density of Angkor is critically important not only for evaluating the sustainability of settlement growth there, but also for explaining the collapse of classical Angkorian civilization and for understanding the nature of early urbanism in tropical forest environments in general.

As with the Maya, the sharp seasonality of water availability and unpredictable levels of annual rainfall presented significant challenges to the sustainability of inland agrarian populations in Southeast Asia (9, 29, 30). The success of those communities often revolved around their ability to develop and implement solutions to the problem of water scarcity. At Angkor, the transition from basic subsistence-level agricultural communities to a complex state-level society was catalyzed by advances in hydraulic engineering (29). Over several centuries, increasingly sophisticated technologies of water management helped to guarantee a baseline water supply and afforded a measure of resilience against the uncertainties of the tropical climate. Even if the "hydraulic city" of Angkor may never have been capable of producing the vast increases in rice yields that scholars once believed were possible (31), the system nonetheless stabilized food production. In years of average or above-average rainfall, surplus rice could be converted into projects of temple construction, warfare, and empire building (27). What is now clear from the lidar data is that the food security provided by the water management system would also have played a crucial role in supporting an increasingly highly urbanized population, consisting of people who were relatively unproductive in terms of rice agriculture.

Paradoxically, however, even as they gave rise to the Khmer Empire, these same technologies of water management also created systemic vulnerabilities at Angkor, as Groslier noted several decades ago (29). The archaeological record shows that episodes of failure were commonplace within the hydraulic infrastructure within the medieval period (5, 32–35), and this partly explains the sequence of construction of ever-larger reservoirs on the Angkor plain over many centuries. The lidar data lend further weight to an emerging consensus that this development of a vast engineered landscape of Angkor over several centuries was fundamentally unsustainable (7, 32, 34–37). Based on the data presented here and in other recent studies (38), it is now clear that urban extensification, deforestation, and dependence on fragile and problematic hydraulic infrastructure were not unique features of Angkor, but were in fact characteristic of almost all medieval Khmer cities. For several centuries at Angkor, episodic renovation of the water management system offered a series of provisional solutions that were adequate for mitigating the risk of low rainfall on an annual scale. Eventually, however, the civilization was confronted with decadal-scale megadroughts in the 14th and 15th centuries (36, 37). The engineers of this period inherited a degraded natural landscape, along with five centuries' worth of legacy infrastructure in the heartland of Angkor, including a system of dysfunctional canals and reservoirs, and high-density urban landscapes that severely constrained the possibilities for large-scale hydraulic engineering projects. By the 15th century, the inland agrarian civilization of Angkor had entered a long and irreversible period of depopulation and decline, as new urban centers emerged and flourished along riverine trading routes closer to Cambodia's coast (25).

This trajectory of urban growth and decline in the region of Angkor offers a series of apparent parallels with the 9th century C.E. collapse and abandonment in the Central Maya Lowlands in the Yucatán region (9, 25) and may therefore have a series of broader implications for our understanding of tropical urbanism. As Turner and Sabloff have argued in relation to the Maya, it will not suffice to simply present long-term climatic variation and aridity as an overarching explanation for the decline of the civilization of Angkor. The collapse of Angkor as the capital of the Khmer Empire needs to be considered as the product of a complex interaction between factors operating at multiple different scales of time and space (8). At the largest scale there are global currents such as climate variation and perhaps also the resurgence in maritime trade in the middle of the second millennium C.E. (37). As with the Maya (9), the impact of these exogenous forces was amplified at Angkor by the specific social, environmental, and material conditions that had developed over several centuries: urban intensification and extensification, the scale and inertia of the vast material infrastructure, and dramatic changes within the society and the ecology of the region (8). In the face of these varied and complex challenges, the prospect of relocating the Khmer royal court to better take advantage of flourishing maritime trade must have seemed appealing to local elites in the 15th and 16th centuries. The implications of that shift in the center of gravity of power away from the Angkor region were profound: the remote sensing data reveal an episode of abandonment and depopulation from which the region has never entirely recovered. As Fletcher has argued (6), such episodes of collapse are one of the defining features of low-density urbanism, and the evidence presented here supports the assertion that "the great agrarian low-density cities such as Angkor were also enmeshed in a massive and intractable infrastructure whose scale and inertia resonates into the modern world. If the infrastructure of low-density cities is inherently liable to be or to become a constraint on the viability of a city's daily life then this is an issue of some serious consequence for our engagement with a future of giant, low-density cities" (39).

Conclusions

The lidar data indicate that a comprehensive reevaluation of the nature of urban space is required in the study of Southeast Asian settlement patterns. Using this technology, we have shown that the conventional view of Angkor (3)—in which a temporal progression of physical barriers neatly define a "genuine urban area" whose rigorously conceived geometrical model is distinctly different from the less-structured, nonurban space that stretches beyond (2)—is deeply problematic. Firstly, formal geometrical patterns of the "civic-ceremonial centers" extend well into extramural areas and frequently have very poor edge definition. Secondly, numerous temples located beyond the urban core and disconnected from the "central grid" show evidence of the same formally patterned space both inside and outside of their moats and enclosures, indicating that greater Angkor was a polynuclear urban landscape, with a dense urban core and an extended agro-urban periphery containing numerous secondary, highly urbanized centers. The lidar data lend further support to the definition of much of that landscape as part of an extended, low-density urban complex (4–6), a periurban fringe consisting of a complex mosaic of residential and infrastructural features and open agricultural spaces.

These data highlight the need to challenge traditional dichotomies between "bounded" and "nonbounded" urban environments and to move toward a more sophisticated typology of urban space that includes due consideration of transitional and liminal spaces, as well as extended, low-density agro-urban peripheries such as those characterized in studies of Mesoamerican urbanism (40, 41). It is now clear that, some 50 y after the suggestion was first tabled by Coe (16), lidar provides a truly unique and highly effective method of pursuing comparative studies of early urbanism in tropical forest civilizations such as the Khmer and the Maya. It does so by acquiring high-precision data on archaeological topography over wide areas and by delivering consistent and comparable datasets that can elucidate similarities and differences in human–environment interactions and in trajectories of growth, decline, and collapse (6, 9, 11, 18).

Methods

The lidar acquisition area consisted of one contiguous block covering the majority of the Angkor World Heritage site, including all of its forested area; four other noncontiguous blocks; and two corridors for total data coverage of 370 km^2 (Fig. 1). Our aim was to map decimeter-scale variations in surface topography in both the horizontal and vertical planes throughout this area, including in densely canopied dipterocarp forests with a dense fern understory (20). All mission parameters were calibrated to achieve this objective, including the timing of flight operations in April to coincide with the period of least vegetation cover. Before flight operations, lidar technicians undertook a field survey to evaluate the morphology of archaeological topography, assess the nature of vegetation cover in different zones, and develop mission parameters accordingly.

We installed a Leica ALS60 laser system and a 40 megapixel Leica RCD105 medium-format camera within an external pod mounted to the left skid of a Eurocopter AS350 B2 helicopter. The 200-MHz aerial lidar system is capable of emitting 200,000 laser pulses per second with up to four returns per pulse. Each of the first three returns per pulse had intensity values assigned with the returns. The instrumentation included a Honeywell CUS6 inertial measurement unit, which registered aircraft orientation at 200 Hz. Absolute positional information was acquired by a Novatel L1/L2 global positioning system (GPS) antenna attached to the tail rotor assembly and logging positions at 2 Hz.

Twenty hours of flight time were undertaken with this configuration of equipment between April 11 and April 22, 2012. The flight plan was designed so that a cross-hatch pattern would be flown over moderate to heavily vegetated areas to maximize ground returns; flights over open areas were in a single direction (either E-W or N-S). Flight lines were flown in opposing directions to ensure that overlapping data could be analyzed for laser alignment. A flying height of 800 m above ground level and speed of 80 kn were chosen to give the optimal point densities, providing a field of view of 45° for the laser scanner and a default of 46° for the camera equipped with a 60-mm lens. The ALS60 was set at a pulse rate of 120 kHz, with full waveform acquired. Single-pass lidar point densities averaged 4–5 points per square meter and raw photo images were collected at 8-cm resolution. The single-pass lidar swath width averaged 650 m.

Position measurements from the aircraft-mounted GPS were postprocessed using differential correction data from Trimble R8 global navigation satellite system base station receivers over surveyed benchmarks at a distance of no more than 40 km from any acquisition point. Before the mission, test points were established at two sites for calibration using an RTK GPS with ∼100 points per site; at least one test site was overflown on each aircraft sortie. Our specifications for accuracy were a mean root-mean-square error of <15 cm compared with surveyed ground control points. All survey measurements were based on the master benchmark for the area (42), and all data were collected and processed in the WGS84 datum using ellipsoid heights. The raw laser data were postprocessed against ground survey data to ensure data quality and conformance with project tolerances for spatial accuracy and precision.

The raw data points were imported into the Terrascan software environment, subdivided into 25 ha tiles and passed through a data processing chain developed specifically for archaeological applications of lidar in forest environments (12). The workflow was designed to minimize the errors caused by close canopy and dense understory and maximize the definition of microtopographic relief. It consisted of several stages of filtration, culminating in a surface-based ground classification routine using an iterative triangulation approach (43, 44). For this final stage, operators visually cross-referenced unclassified point data against georeferenced aerial photographs, performed a subjective assessment of local land use/land cover, and assigned appropriate threshold values for progressive densification of triangulated irregular networks. Editors performed quality control on the output data and calibrated threshold values and reclassified the dataset where necessary. The end product was a point cloud divided into two separate classes consisting of "ground" and "nonground" returns.

The ground returns averaged exactly two points per meter squared across the acquisition area. These were processed into digital terrain models, hillshade models, and local relief models (45) in an ArcGIS software environment, manually analyzed, and interpreted by landscape archaeologists, and loaded into portable GPS units for field verification. Field verification consisted of two stages. Stage one was to confirm that archaeological features previously mapped using high-precision ground survey methods could be seen in the lidar data. Ground survey data in the densely forested area of Angkor Thom (2) had previously identified some of the smallest topographic features of archaeological interest ever documented at Angkor, including remnant ponds as small as ~100 m^2 in area and linear features of ~10 m in width, defined by topographic relief at submeter scale. We concluded that the archaeological topography visible in the lidar data accorded precisely with the previously published results from ground surveys, and that the resolution and accuracy of the lidar data were therefore adequate for mapping even the smallest elements of Angkorian urban form. For the second stage of field verification, we created an inventory of previously unknown features across the lidar acquisition area according to well-established typologies (2, 4, 5). From July 2012 to March 2013, we undertook a systematic pedestrian survey to confirm and document those sites.

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