ARCHAEOLOGY

Diachronic modeling of the population within the medieval Greater Angkor Region settlement complex

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Angkor is one of the world's largest premodern settlement complexes (9th to 15th centuries CE), but to date, no comprehensive demographic study has been completed, and key aspects of its population and demographic history remain unknown. Here, we combine lidar, archaeological excavation data, radiocarbon dates, and machine learning algorithms to create maps that model the development of the city and its population growth through time. We conclude that the Greater Angkor Region was home to approximately 700,000 to 900,000 inhabitants at its apogee in the 13th century CE. This granular, diachronic, paleodemographic model of the Angkor complex can be applied to any ancient civilization.

INTRODUCTION

Studies of tropical urban societies have long acknowledged the importance of dispersed or agro-urban landscapes, sometimes referred to as low-density urbanism, in which agricultural or garden spaces are intertwined with urban infrastructure and activities (1–3). Angkor (Fig. 1) is anomalous in terms of its scale and structure, surpassing any other settlement complex in the premodern world in terms of its spatial extent (4). Angkor is one of the world's most visible ancient cities, as it has largely been left intact; this state of preservation allows us to produce a comprehensive archaeologically based demographic history. Archaeological mapping of the settlement complex in the 3000-km² Greater Angkor Region over the past 30 years has documented tens of thousands of features in the extensive hinterland zone or metropolitan area (4, 5), and recent lidar surveys have highlighted the higher density of features located in the civic-ceremonial center (CCC), which housed the royal residence and most of the large stone state temples (6, 7). Combined, these factors contribute to Angkor's place as a critical reference point for comparative studies of urbanism in the past and present (2).

The question of Angkor's demographic growth has been a source of persistent speculation and controversy since the beginnings of modern scholarship in the region. In the mid-19th century, the French naturalist Henri Mouhot, who provided one of the first detailed accounts of Angkor for European audiences, cites an oral tradition that the Khmer Empire "kept up an army of five or six million soldiers" (8). The first reasonably systematic attempt to calculate the population of Angkor was undertaken by archaeologist Bernard-Philippe Groslier, who cautiously suggested a total population of 1.9 million in a region around Angkor in the last half of the 12th century CE (9). More recent attempts based on the carrying capacity of the landscape estimate have estimated a population of approximately 750,000 people (10).

Estimating Angkor's population has been an enduring challenge, as conventional methods for estimating population size and density in urban areas (11, 12) are not easily applied at Angkor, where nonreligious architecture was composed almost entirely of organic materials that decayed centuries ago, leaving no structural remains (13). Since the 1990s, however, an interdisciplinary effort has brought new approaches and methods to bear on the problem of Angkor's population, focusing on the subtle, remnant traces of the nondurable urban environment, much of which had been previously obscured by dense vegetation (14). Here, we present the culmination of that 30-year effort, combining multiple lines of evidence at a landscape scale, including historical archives and maps (4), measurements from multiple airborne lidar acquisitions (6, 7), fine-grained archaeological excavation data (13, 15, 16), and machine learning algorithms (17) and present the first granular, diachronic, paleodemographic model of the Angkor complex. This modeling of the growth of an urban center can be used for diachronic paleodemographic modeling of premodern cities elsewhere. It also provides an opportunity for future fine-grained analyses in response to many of the grand challenges of archaeology (18), such as the emergence and decline of social complexity, and the implications of such analyses for understanding contemporary trajectories of human systems.

RESULTS

Figures 2 and 3 and Table 1 display our estimates for total population and population density in the Greater Angkor Region through time. Angkor's population took several centuries to reach its peak after its founding and grew at different rates in the CCCs, Angkor metropolitan area (AMA), and embankments (BANKs). During the earliest phases, the population growth rates within the three occupation zones were comparable. However, by the early 10th century CE, the population in the AMA had nearly quadrupled, additional

[1]Department of Anthropology, University of British Columbia, Vancouver, BC, Canada. [2]University of Oregon, 1585 E 13th Avenue, Eugene, OR 97403, USA. [3]Leiden University, Rapenburg 70, 2311 EZ Leiden, Netherlands. [4]Department of Anthropology, University of Oregon, 308 Condon 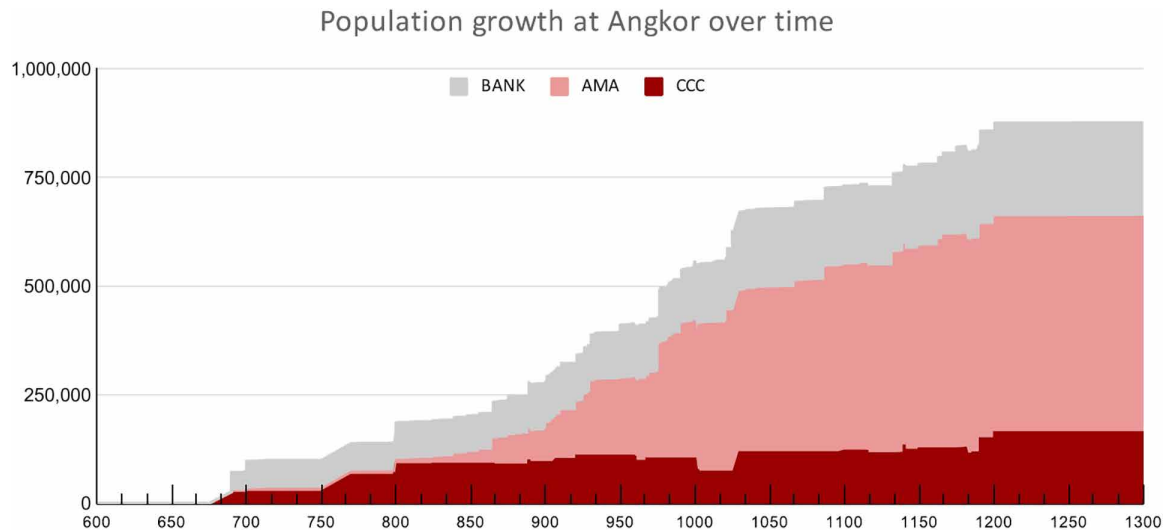Hall, 1321 Kincaid Street, Eugene, OR 97403 USA. [5]École française d'Extrême-Orient, 22 Avenue du Président Wilson, 75116 Paris, France. [6]Institute of Behavioral Science, University of Colorado, Boulder, CO 80309, USA. [7]Department of Anthropology, University of Hawai'i at Mānoa, Honolulu, HI, USA. [8]Department of Anthropology, Stanford University, Palo Alto, CA 94305, USA. [9]Archaeology, Flinders University, Adelaide, SA, Australia. [10]Center for Southeast Asian Studies and Department of Anthropology, Northern Illinois University, DeKalb, IL 60115, USA. [11]Independent Scholar, Portland, OR 97214, USA. [12]Courant Institute of Mathematical Sciences and Center for Data Science, New York University, New York, NY 10012, USA. [13]Casey & Lowe Archaeology and Heritage, Sydney, NSW 2040, Australia. [14]Department of Archaeology, University of Sydney, NSW 2006, Australia.
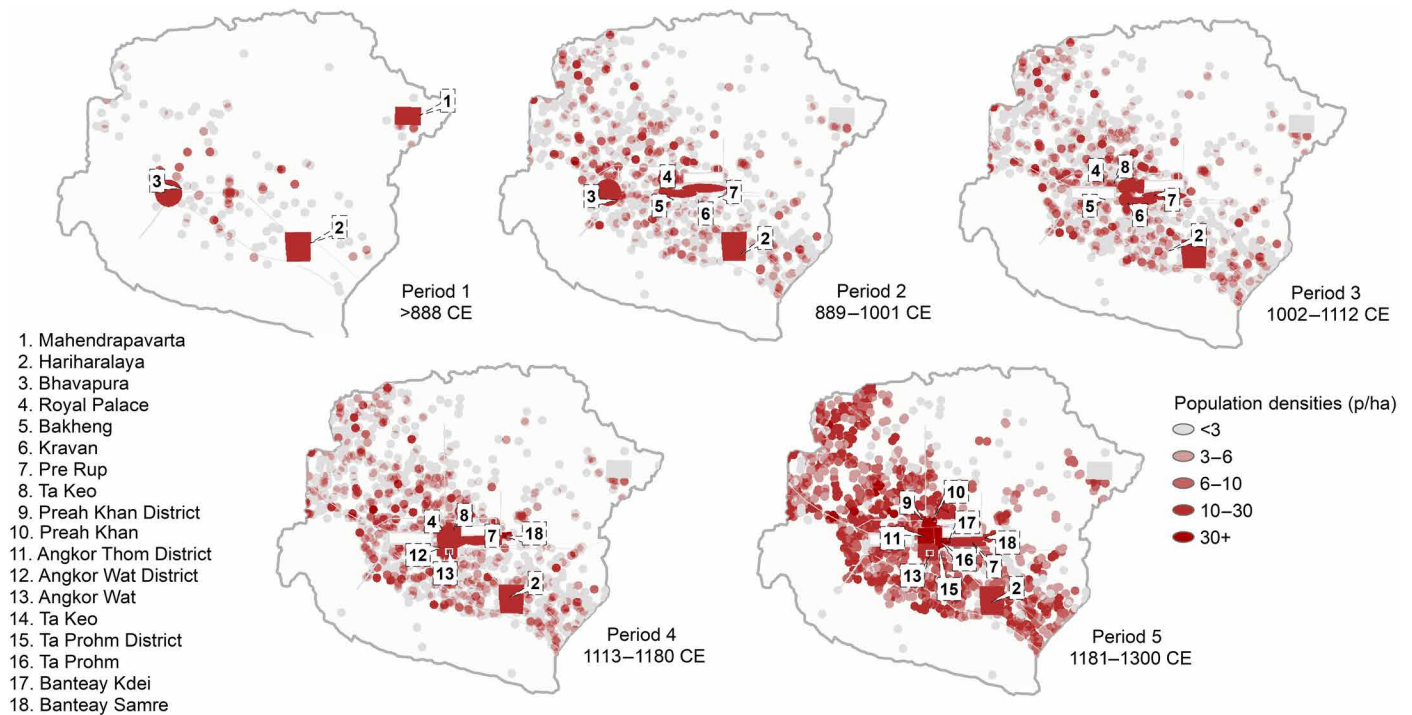*Corresponding author. Email: sarah.e.klassen@gmail.com
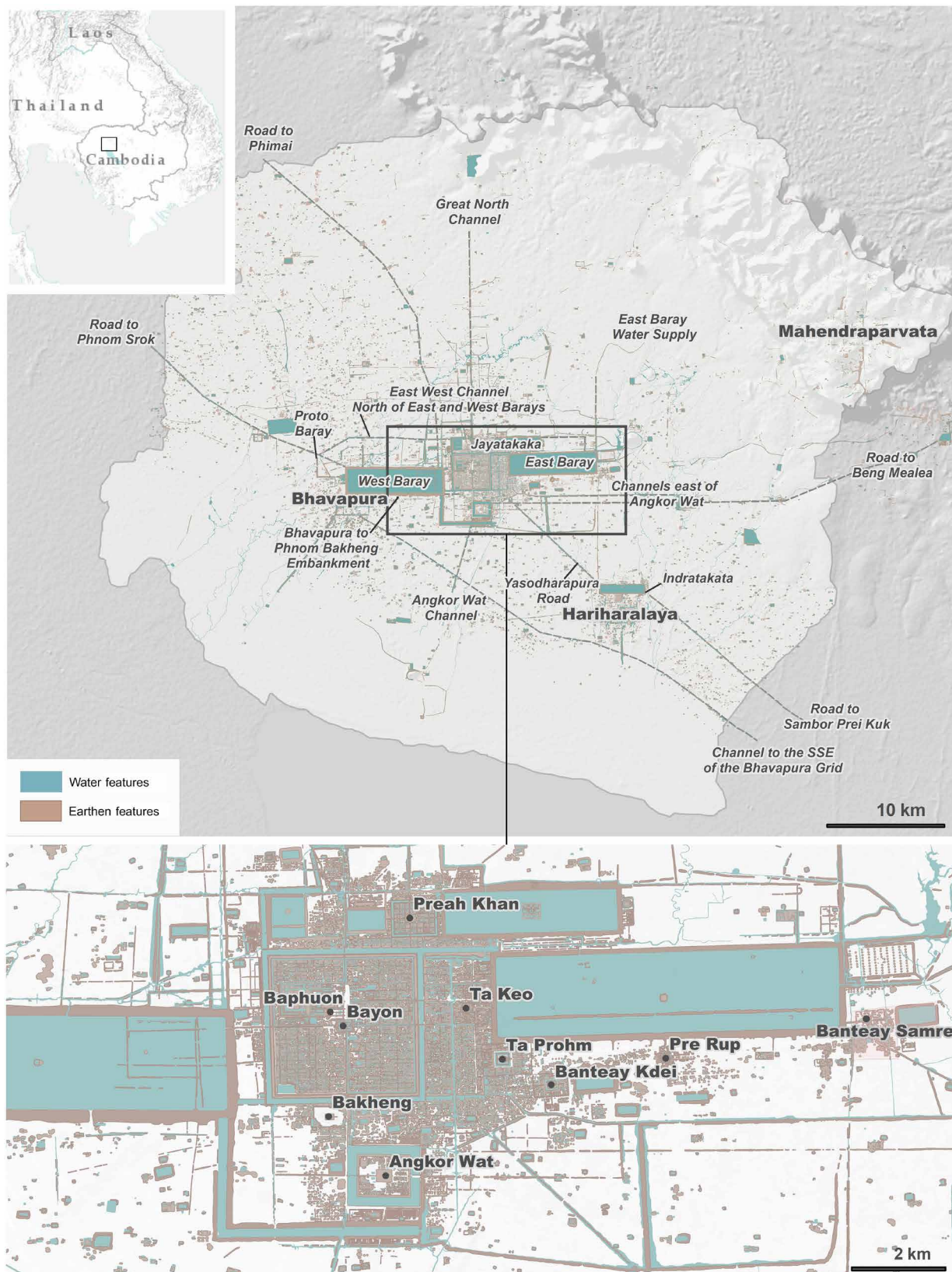
Fig. 1. Archaeological map of the Greater Angkor Region by C.P., D.E., J.-B. Chevance, P.W., and S.K. The top portion shows the entire 3000-km² Greater Angkor Region, and the bottom shows the details of the CCCs.

Population growth at Angkor over time

Fig. 2. Total population of the Greater Angkor Region in the CCCs, BANKs, and AMA.

1. Mahendraparvata
2. Hariharalaya
3. Bhavapura
4. Royal Palace
5. Bakheng
6. Kravan
7. Pre Rup
8. Ta Keo
9. Preah Khan District
10. Preah Khan
11. Angkor Thom District
12. Angkor Wat District
13. Angkor Wat
14. Ta Keo
15. Ta Prohm District
16. Ta Prohm
17. Banteay Kdei
18. Banteay Samre

Population densities (p/ha)
- <3
- 3–6
- 6–10
- 10–30
- 30+

Fig. 3. Densities of people per hectare in the Greater Angkor Region over time. For information on the density analysis see the Supplementary Materials.

investments in infrastructure could have led to increased populations on the BANKs, and Angkor's overall population had doubled in less than a century. The AMA continued expanding until period 4, when population growth began to slow. Conversely, the CCC population did not begin its major expansion until the 11th century CE (period 3). Population density markedly increased in period 5, which we associate with the establishment of the walled civic-ceremonial enclosure of Angkor Thom [~50 persons per hectare (p/ha)] (Fig. 1 and table S4). There are multiple historical reasons for these

developments, such as policies toward land ownership and tax policies on temples (19, 20).

At its 12th to13th century CE height, our model predicts that between 700,000 and 900,000 people inhabited the 3000-km² Greater Angkor Region (Table 1). This range is due to uncertainty regarding variations in the density of occupation on the BANKs; it is likely that population density decreased farther from the CCCs. The lower end of this estimate is in line with a previous population estimate of 750,000 people based on the amount of rice that could have been

Table 1. Population estimates, growth rate, and densities in the CCCs, BANKs, and AMA over time.

Period	Date	Population				Growth rate*				Density†			
		CCCs	AMA	BANKs‡	Total	CCCs	AMA	BANKs	TOTAL	CCC area	AMA area (ha)	CCC (p/ha)	AMA (p/ha)
1	770–888	89,137	70,668	88,891	248,696	–	–	–	–	5847	294,153	15.2	0.2
2	889–1001	76,796	318,439	139,191	525,313	−0.001	0.013	0.004	0.007	8498	291,502	13.8	1.1
3	1002–1112	117,288	431,181	183,399	761,663	0.004	0.003	0.003	0.003	3200	296,800	36.7	1.5
4	1113–1180	122,534	491,322	203,949	847,600	0.001	0.002	0.002	0.002	3868	296,132	31.7	1.7
5	1181–1300	159,852	497,949	216,215	903,811	0.002	0.000	0.000	0.001	4207	295,793	38.0	1.7

*Growth rate = (Natural log(Population 2) − Natural log(Population 1))/Number of years. †Average density for the entire study area (3000 km^2), divided between the CCCs and AMA (AMA includes BANKs). ‡The population of the embankment ranges from 0 to the numbers shown here.

produced in the region without irrigation (*10*). The economic catchment of the Greater Angkor Region is not clear, and inscriptions do not clearly state that provincial regions were provisioning the capital with additional food as populations increased (*10*). In the future, our model would benefit from research designed to quantify the economic linkages between the Greater Angkor Region and outlying provincial areas.

DISCUSSION

It is the integration of the AMA with the CCCs through water management infrastructure (BANKs) and transportation networks that makes Angkor a massive agro-urban complex (*19*, *21*). Our models demonstrate, however, that population density varied across the site. Contrasting our models with other comparable preindustrial urban traditions in the tropics and subtropics suggests, for example, that while the range of AMA population densities (1.5 p/ha) are much lower than the estimated overall population densities of the agro-urban landscape at the Classic Maya city of Caracol at its 7th century CE peak (ca. 6 p/ha), approximately half of the space included in our analysis was not cultivated and may not have been occupied. Meanwhile, the CCCs have densities (~13 to 75 p/ha) that are consistent with Teotihuacan or Anyang (50 p/ha) (table S4) (see table S3 for further details and citations).

Distinguishing between CCC and AMA population density is vital for producing accurate population estimates that limit the impact of sampling bias. For example, CCC areas are often favored over metropolitan areas for intensive investigation when resources are limited (e.g., the high cost of acquiring lidar data or undertaking extensive surface surveys). This is true in the Greater Angkor Region, where the lidar surveys focused on the CCCs in more heavily vegetated terrain than the AMA, and has been true of many other archaeological lidar surveys of ancient cities and epicenters [e.g., (*22*)]. Hence, it is not appropriate to extrapolate the densities calculated in these areas across the entire sites. By considering different occupation zones, we provide a more nuanced approach to demographic analyses that accounts for variation in density across sites.

Combining multiple lines of data, we have been able to show the logistic growth of one of the world's largest agro-urban center. Over several centuries, elites in the CCC zones developed a sprawling water

management and transportation infrastructure that integrated much of the landscape, facilitating the growth of the population to perhaps up to 900,000 people in the 13th century. However, note that Angkor began its gradual decline shortly after reaching its apogee (*23*). Scholars have noted the fragility of such expensive urban systems (*24*); however, ongoing work suggests that the Angkor region was not completely depopulated (*15*, *25*).

This study has demonstrated the dynamic nature of agro-urban settlements and provides a model for future comparative analyses. For example, we note that the CCC and AMA zones evolved at different times and independently of one another. Are such dynamics found in other low-density cities? The role of bottom-up land management within AMA communities may speak to the heterarchical social organization of these communities, as seen in other agro-urban settlements (*19*, *26*). Future work could also further consider the role of migration, especially during period 5 when density in Angkor's CCC was at its most intense [e.g., (*27*)]. We look forward to future studies that add further nuance to the rise of this urban form.

MATERIALS AND METHODS
Areas of occupation
We identify three primary areas of occupation at Angkor: the CCCs, the AMA, and the BANKs (fig. S10). In all zones, communities were established on earthen mounds and BANKs, which elevated residential areas from annual floodwater levels.

The CCCs encompass an overall area of 30 km^2, including many of the massive stone temples for which Angkor is famous. Adding the older capitals of Mahendraparvata and Hariharālaya expands the CCCs to 75 km^2 (Fig. 4). This urban core of Angkor included large populations associated with the royal court and the major religious institutions; traders; and specialized workforces of craftsmen, bureaucrats, and officials (*28*). The landscape of the CCCs is a complicated palimpsest representing many centuries of accumulated development. We have subdivided this landscape into 17 diachronic districts, named after their most prominent temple (Fig. 4 and figs. S1 to S8). For areas that were built over in subsequent periods, we drew from studies on the chronology of the urban core [e.g., (*29*)] to delimit the extent of the CCCs at different points in time.
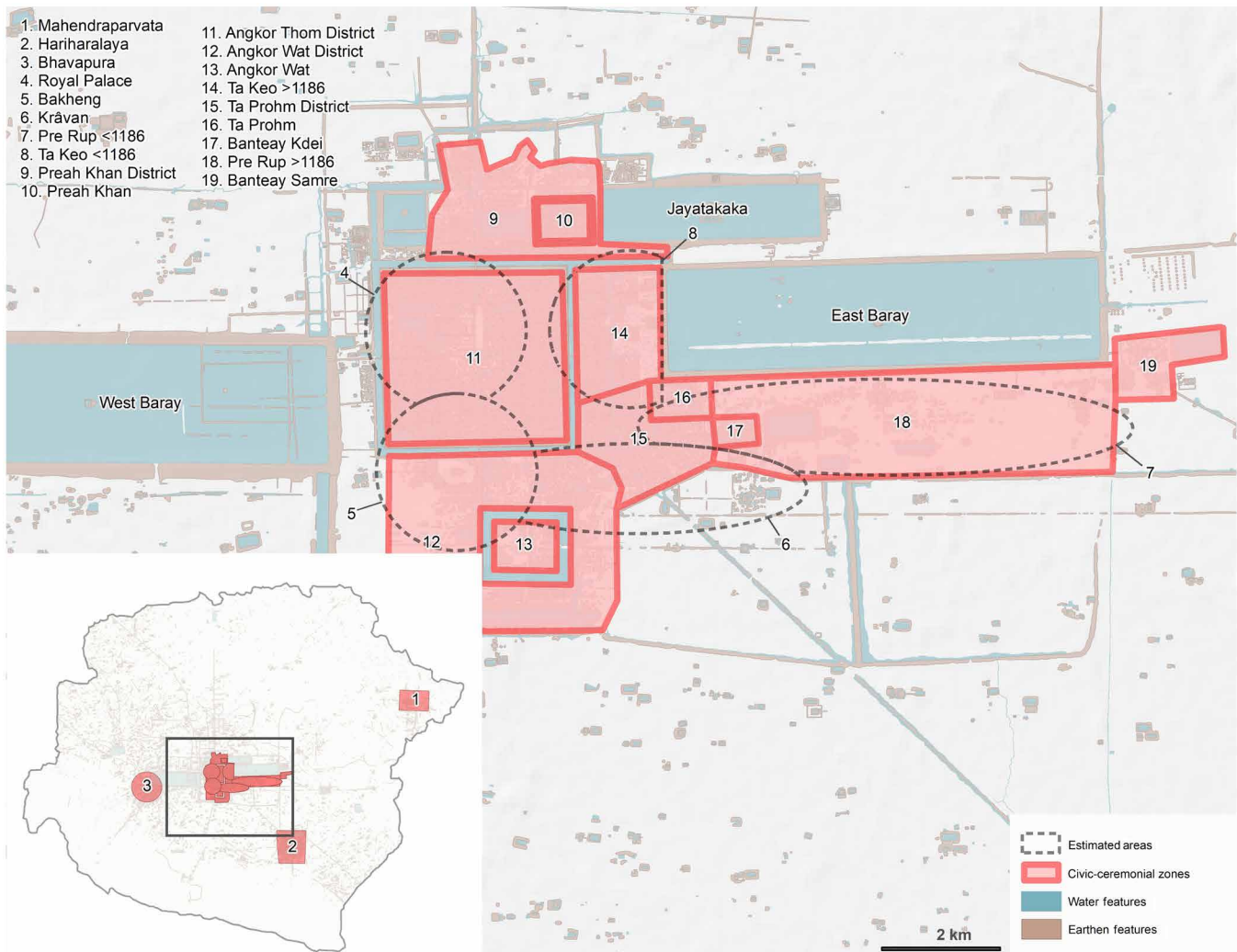
Fig. 4. The sequential CCCs within the Greater Angkor Region. There are 17 CCC zones within the Greater Angkor Region. Each zone is shown here, either as a polygon encompassing the features associated with each CCC (red) or an estimated area of CCCs that were built over in later time periods (black dotted).

In contrast to the CCCs, AMA temples do not have a high density of occupation mounds and are instead identified by a particular configuration known as *prasat-trapeang* (temple-reservoir) (*19*). These temples are known to be the center of Angkor period communities that were located on associated occupation mounds and whose inhabitants were engaged primarily in farming activities (*30*). More than 1100 of these configurations have been identified and mapped in the Greater Angkor Region (*17*).

A third form of occupation was on the BANKs of large water management features and roads. Evidence for occupation on the BANKs includes scatters of domestic debris such as ceramics on the surface and similar debris in the channels along with dark organic deposits (*31*). The communities that occupied these BANKs had access to trade opportunities along the roadways and were also able to access adjacent rice fields. As this state-sponsored infrastructural network of BANKs expanded across the Greater Angkor Region from the 9th to 13th centuries CE, it offered elevated land for housing that was not controlled by the long-established residential clusters associated with temple communities in the rice fields.

The initial occupants on the BANKs may therefore have been people migrating into the city (*31*).

Dating the landscape

Intensive mapping projects over the past 30 years have led to a comprehensive map of the Greater Angkor Region (*4–7, 32*). The study area for this work encompasses an area of approximately 3000 km^2, a somewhat arbitrary boundary that is based on the watershed catchment boundaries of Angkor's rivers (*4*). The extent and density of settlement beyond this area is the subject of ongoing research, although it is clear that the low-density distribution of local temples extends in a wide arc across modern-day Cambodia, spanning many thousands of square kilometers beyond the Greater Angkor Region (*4*). To visualize diachronic change, we divided Angkor's growth into five periods on the basis of major historical and infrastructural developments (see summary table S2).

Dating the CCC landscape

In the CCCs, temples are constructed of stone and brick and are often associated with inscriptions that give their consecration dates.

Most temples without inscriptions have distinctive diagnostic architectural features that have been dated through reliable art historical stylistic analyses refined since the beginnings of scholarship on Angkor (*33*, *34*). The chronological information that we used for this study can be found in data S1, including recalibrated ^{14}C dates (see data S16 and S17 dates and the Supplementary Materials for methodology). Temples in the CCCs often have clear spatial, functional, and chronological relationships with grids of occupation mounds that surround them (*6*, *7*, *13*, *16*). In our analyses, we gave these occupation mounds the same dates as the temples with which they were associated.

Dating the AMA landscape

Less than 10% of the temples in the AMA have been dated from inscriptions and art historical analyses. Using these dates and known attributes for the remaining temples (see data S1), dates for 1177 temples were predicted using multiple linear regression and a graph-based semisupervised machine learning algorithm with a 49- to 66-year average absolute error [see full discussion in (*17*)]. The dating method for each temple is listed in the "Notes" column of data S1.

In addition to more than 1100 temples and tens of thousands of occupation mounds that are scattered across the Greater Angkor Region, more than 3000 reservoirs are located in proximity (~1.5 km) to individual temples. Previous studies have used quantitative and qualitative assessments to establish spatial and functional relationships between these elements and to link collections of mounds, reservoirs, and local temples into groups. These groups are the fundamental building blocks of premodern settlement across much of Cambodia's Lower Mekong basin (*35*, *36*), including Angkor's dispersed agro-urban landscape (*9*, *37*–*39*). Using a dissimilarity formula incorporating proximity and orientation (see the Supplementary Materials for full discussion), we were able to group 2437 reservoirs with temples and assign dates accordingly (data S15; see also figs. S1 to S8).

Dating the BANKs

The BANKs and channels of the Greater Angkor Region were developed over time as elements in a series of networks that gathered, stored, and distributed water. Using the simple logic of the flow of water through the system, from higher areas to lower, we can reconstruct functional hydraulic networks with a reasonable degree of confidence, including systems to aggregate and disperse water from the vast moats and reservoirs of Angkor's urban core. In addition to the lateral coherence of the network, changes were made to it over time, which produced superpositioning, from which we can identify relative chronological relationships and model the spatiotemporal development of the landscape. Some elements of the hydraulic network (e.g., the massive East Baray) can be dated from inscriptions, while other elements can be indirectly dated by their spatial and functional relationship with well-dated temples, providing chronological anchor points for major components of the network (see data S1) (*40*).

Last, for the CCCs, AMA, and BANKs, we assigned dates to features with unknown dates using a relative system of grouping features with other features that either date to the same time period or date to an earlier time period (see further discussion of the sorting algorithm in the Supplementary Materials). This allowed us to systematically associate otherwise undated features to features with dates, such as the BANKs of a channel with the date of the channel. It also allowed for inferential assessments of features based on relative spatial relationships. For example, if a mound was built over an embankment, then it is assumed that the mound was built after the embankment. In total, we recorded more than 30,000 of such relationships (Fig. 4 and data S3). There are over 30,000 mapped features in the Greater Angkor Region (data S2), and with the methods described above, we were able to determine dates for approximately 21,000 of these features (figs. S1 to S7).

Estimating population growth over time

Estimating population in the CCCs

To estimate the population of the CCCs over time, we first calculated the total area in square meters of mounded occupation features mapped on the modern ground surface in each CCC for each period including discrete mounds, pond BANKs, and linear BANKs (hereafter referred to as the "mound method"). Evidence suggests that Angkorians built dwellings on all such features (*31*). Houses in the Angkorian period, similar to those today, were raised on piles or stilts above the ground surface. In some cases, such as at Angkor Wat, mounds are discrete and of the same general size with a pond immediately next to it (*13*). On the basis of our 2015 excavations, A.K.C. believes that they likely contained a single household. In other cases, occupation mound spaces were larger and may have contained numerous households. In our mound method, we use Angkor Wat's mounds, each approximately 20 m by 30 m (600 m^2), as a proxy for the approximate size of a household in the Greater Angkor Region, with the 600-m^2 surface area encompassing both a house structure and the surrounding living space. To estimate the number of households within the CCCs, we calculated the total square meters of mound and embankment features mapped on the modern ground surface in each CCC zone for each period and then divided this number by 600 m^2 to approximate the total number of houses. We acknowledge that house size likely varied and that further excavations will refine our estimate for household size in different contexts (*13*). This method does not preclude the ability to conduct density analyses because earlier urban landscapes have more agricultural space among archaeological features than later urban landscapes (table S4 and fig. S3).

Population estimates were made using the household size of 600 m^2 and ethnographic assumptions that each household consisted of five members (*12*, *41*, *42*). Zhou Daguan, a Chinese visitor to Angkor in 1296–1297, reported that from 10 to 100 slaves served many Angkorian households and lived under the houses or perhaps outside the city (*43*). No evidence of occupation under houses has yet been identified in excavations. If slaves had separate living quarters inside or outside the city, then this would be accounted for in our model.

Estimating population in the AMA

Mid-20th century AMA communities in Cambodia, similar to those of the Angkor period, were engaged in subsistence rice agriculture in seasonally inundated fields, in a period before the arrival of mechanization. They were typically organized in village-level units called *phum*, built on elevated earthen mounds, and have temple and reservoir (*prasat-trapeang*) configurations analogous to those of the Angkor period (*16*, *35*, *42*). Ethnographic reports indicate that these village-level temples serviced approximately 100 families (*41*).

Unfortunately, approximately half the occupation mounds surrounding AMA temples are missing or disturbed, likely because of their destruction for agricultural purposes. Because of the lack of preservation, we are unable to use the mound method to accurately estimate population as in the CCCs. In addition, archaeological

studies indicate that rural community household spaces were larger than those in the CCCs (*37*), with occupation density increasing with proximity to the center of communities (*41*).

To provide spatial resolution to the temples with surviving occupation mounds, we adapted the method developed by Hanson and Ortman (*44*) to the 7216 occupation mounds that we can associate with AMA temple communities. This method builds on theoretical and cross-cultural empirical work, which suggests that, on average, the resident population of small and spatially unorganized settlements varies with area according to $A = aN^{2/3}$, where A is the settlement area, N is the resident population, and a is a baseline area per person in the smallest settlements in a system (*44*). This relation can be rearranged to solve for population in terms of area, $N = (1/a)^{3/2}A^{3/2}$, to provide a means of estimating the population of an occupational mound based on its area and the baseline area per person in the smallest settlements.

Absent direct evidence for the value of a, we set this value so that the resulting mean population of temple communities across the dataset would match that of ethnohistoric Khmer communities (100 families with five people). We found that setting $a = 0.05$ led to a mean (497) at 623 temple communities, so we used this value to estimate the resident population of each occupational mound. With this method, the largest temple communities have fewer than 5000 people. We then estimated the total temple community populations by summing the resident populations of all mounds associated spatially with its central temple (see further explanation in the "Estimating AMA population" section in the Supplementary Materials). For temples without surviving occupation mounds, we assigned the mean population of 497 people.

These estimates are based on the terminus post quem (earliest potential date) of the temple. Without fine-grained analyses at each site, it is difficult to determine the length of occupation. Archaeological evidence suggests that smaller temples may have been replaced by or superseded by larger temples (*37*), which suggests that prime land held by small communities and non-elite families were frequently taken over by elites (*20*). Our model assumes that once founded, the associated temple populations remain on the landscape, even if their population was subsumed into that of a larger temple over time.

Estimating population on the BANKs
To calculate the population on the BANKs, we first measured the length of features. Our model assumes that the widest surviving part of the embankment is likely similar to the width of the embankment at the time of construction and that families were likely to be living on the BANKs at the same density as they were in the CCCs, with each household occupying approximately 600 m^2 (See table S5 and data S4 to S14 for results). Preliminary surveys suggest that population density on the BANKs decreased with distance to the nearest CCCs. Consequently, we present the results of this analysis as a range until further research can be done to determine variable population density along the BANKs.

SUPPLEMENTARY MATERIALS
Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/7/19/eabf8441/DC1

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