Journal of Anthropological Archaeology 63 (2021) 101323

Contents lists available at ScienceDirect

Journal of Anthropological Archaeology

journal homepage: www.elsevier.com/locate/jaa

The evolution of agro-urbanism: A case study from Angkor, Cambodia

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ARTICLE INFO

Keywords:
Urbanism
Agro-urbanism
Demography
Cambodia
Angkor
Southeast Asia

ABSTRACT

The vast agro-urban settlements that developed in the humid tropics of Mesoamerica and Asia contained both elite civic-ceremonial spaces and sprawling metropolitan areas. Recent studies have suggested that both local autonomy and elite policies facilitated the development of these settlements; however, studies have been limited by a lack of detail in considering how, when, and why these factors contributed to the evolution of these sites. In this paper, we use a fine-grained diachronic analysis of Angkor's landscape to identify both the state-level policies and infrastructure and bottom-up organization that spurred the growth of Angkor as the world's most extensive pre-industrial settlement complex. This degree of diachronic detail is unique for the ancient world. We observe that Angkor's low-density metropolitan area and higher-density civic-ceremonial center grew at different rates and independently of one another. While local historical factors contributed to these developments, we argue that future comparative studies might identify similar patterns.

1. Introduction

In recent years, comparative archaeological studies of urbanism have increasingly focused on agro-urban centers, which are sometimes called distributed urban network systems or garden cities (e.g., Chase and Chase, 2016; Fisher, 2014; Fletcher, 2009, 2012; Graham, 1996; Graham and Isendahl, 2018; Isendahl, 2012; Lucero et al., 2015; Scarborough and Isendahl, 2020). This type of low-density urbanism is not uncommon in the archaeological record of the tropical world, and is categorically different from the compact, high-density cities of Mesopotamia and other classical civilizations that have provided the archetypes for understanding urbanism (e.g., Coningham et al., 2007; Isendahl and Smith, 2013; Kusimba et al., 2006). Agro-urban spaces have relatively low population densities in the metropolitan zones that typically sprawl far beyond the higher-density regal-ritual or civic-ceremonial monumental centers. The boundary between these two spaces is frequently blurred (Fletcher, 2012). Civic-ceremonial centers often have extensive green spaces, such as household-level gardens and larger areas like parks (Stark, 2014a; Stark, 2014b). This integration of agricultural land within urban environments appears to have made agro-urban settlements flexible and sustainable (Isendahl and Smith, 2013; Scarborough and Isendahl, 2020).

While recent work has considered the decline of agro-urban centers (Lucero et al., 2015; Gilliland et al., 2013; Fletcher 2009: 15), there has been comparatively little effort devoted to understanding how these massive settlements formed and grew. In this paper, we draw on multiple datasets including lidar, archaeological excavation data, radiocarbon dates, and machine learning algorithms to map the development of one of the world's largest preindustrial agro-urban settlements: Angkor, in present-day Cambodia (Evans et al., 2007). Angkor was the preeminent regional power from the 9–15th centuries CE, controlling a large portion of mainland Southeast Asia. Our work suggests that Angkor's initial population in the 9th century likely was approximately 160,000–250,000 people and grew to between 688,000–900,000 people

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https://doi.org/10.1016/j.jaa.2021.101323
Received 20 February 2021; Received in revised form 8 June 2021;
Available online 20 June 2021

at its apogee in the 12-13th centuries CE (Klassen et al., 2021). We argue that Angkor's higher-density civic-ceremonial center (henceforth CCC), dispersed rural metropolitan area (henceforth AMA) and its embankments (henceforth BANKs) grew at different rates, and that this growth was facilitated by both top-down infrastructure development as well as bottom-up organization. In the following section we contextualize our work within broader studies of agro-urban settlements, before moving to provide a background on Angkor and our methods, and finally offering a detailed discussion of historical and demographic developments at Angkor over time.

2. Agro-urbanism in the archaeological record

Agro-urban settlement complexes are distinctive and important urban morphologies that are found in both the ancient and contemporary world. Despite the increased attention paid to agro-urban centers in recent scholarship, understanding the conditions and structures that allowed for the emergence and development of these settlements is still in the early stages (Fletcher 2019). Fletcher and others have proposed that extensive, low-density urban forms emerged from high-density cities that continued expanding (Fletcher, 1995; Chapman and Gaydarska, 2016a). Other recent work has identified different developmental trajectories based on the areal extent of the settlements (Fletcher and White, 2018); in this model, smaller (1–100 km^2) settlements tend to expand out of smaller villages. Several scholars have noted that these sites were egalitarian or heterarchical in their organization, with bottom-up or local organization as the driving force behind their trajectory of growth (Chapman and Gaydarska, 2016b; McIntosh, 1999; McIntosh and McIntosh, 2003; Moore, 2017).

In contrast, the vast agro-urban settlements (over 100 km^2) that developed in the humid tropics of Mesoamerica and Asia had a different type of organization. These settlements contained large communal ritual spaces, monumental architecture, and hydrological infrastructure that integrated rural spaces and civic-ceremonial centers (Fletcher and White 2018; Lucero et al. 2015). The socio-political organization of these cities was unequivocally hierarchical, yet we see variability in the role of elite power, state control, and centralized planning as drivers for the development of these sprawling settlement complexes. For example, at the Maya site of Caracol in Belize, it appears that the development of causeways connecting three distinct settlements catalyzed their growth and eventual coalescence into a single settlement. Over time, the epicenter at Caracol was rebuilt and expanded and continued to integrate administrative and market areas through transportation infrastructure. Agricultural fields and heterogeneous residences were also incorporated into this landscape (Chase and Chase, 2016). While this might suggest that elite planning and organization facilitated the growth of the city, recent work has identified that bottom-up construction and management of water reservoirs was also key to the successful expansion and agricultural productivity of this settlement (Chase, 2016). Similar studies at other Maya sites suggest households in those locations had even more autonomy in managing their infield agricultural systems, thereby shaping the organization of their settlement landscapes (Fisher, 2014).

The site of Anuradhapura, Sri Lanka, shows a different mix of centralized and decentralized autonomy in the formation of its extensive settlement complex. There the hinterland was integrated with the civic-ceremonial center by way of a network of Buddhist monasteries that held considerable economic power (Strickland et al., 2018). The growth of Anuradhapura and its extended hydraulic infrastructure began prior to the development of the monastic system, but expanded considerably as the monastic system grew. Anuradhapura's expansion seems to have been facilitated by both state-level construction of large water storage tanks and complex canal systems, as well as more localized hydraulic infrastructure overseen by the Buddhist monasteries (Gilliland et al. 2013; Strickland et al., 2018). The relationship between the secular rulership and powerful Buddhist communities in the hinterland shaped the formation of this urban center.

These studies raise intriguing questions about the conditions and structures that contribute to the development of extended settlement complexes; frequently, however, the absence of fine-grained detail impedes our ability to fully understand the complex processes at work across multiple scales of time and space, and this has certainly been true of Angkor itself. In this paper, therefore, our aim is to draw together several decades of multidisciplinary research results to model Angkor's spatio-temporal development in granular detail, in order to inform a discussion of the emergence and growth of the settlement complex over time (Fig. 1). Angkor is unusual in its archaeological coverage: over the last thirty years, more than 3000 km^2 of the Greater Angkor Region has been mapped by archaeologists, by hand, in exceptional detail and then followed up with comprehensive ground verification (Chevance et al., 2019; Evans, 2007, 2016; Evans et al., 2013; Gaucher, 2004; Pottier, 1999) (Fig. 1). Recent work combining geographic information systems analyses and machine learning algorithms has enabled temples and other features on the landscape to be dated (Klassen and Evans, 2020; Klassen et al., 2018) and has provided models of population growth and decline (Klassen et al., 2021). This extensive and unusual dataset allows us to begin creating finer-grained models for the development of the settlement complex of Angkor over time.

2.1. *Angkor's landscape and temples*

The empire's capital and heartland, the Greater Angkor Region, lies on a lowland plain on the eastern edge of the floodplain of the Tonle Sap Lake. As we define it for the current study, the Greater Angkor Region encompasses approximately 3000 km^2, reaching from the Tonle Sap into the Kulen hills (Fig. 1). This boundary is somewhat arbitrary and partially based on the watershed catchment boundaries of Angkor's rivers and the original Zoning and Environmental Management Plan for Angkor (ZEMP) established in the early 1990s as part of Angkor's UNESCO World Heritage listing (Evans, 2007; Wager, 1995). The extent of settlement beyond these boundaries is the subject of ongoing research, but it is clear that the low-density distribution of local temples extends in a wide arc across modern-day Cambodia. The monumental or CCC zone, containing the massive stone temples for which Angkor is famous, encompasses approximately 30 km^2 (Fig. 2)[1].

Conventionally, the Angkor period is considered to have begun with the ruler Jayavarman II (r. 770–830 CE), who established himself as universal monarch in 802 CE, and ended in 1431 CE with the supposed sacking of Angkor by the rival kingdom of Ayutthaya located in present-day Thailand (Briggs, 1951; Cœdès, 1968). These simplified narratives gloss over a great deal of historical complexity. Sedentary agricultural communities have been living on the eastern edge of the Tonle Sap floodplain since at least 1000 BCE (Pottier, 2006b; Pottier et al., 2004). Numerous inscriptions dating from the 6–8th centuries CE, along with the remains of brick temples, attest to the presence in this region of a significant population ruled by powerful elites throughout the Pre-Angkor period (6–8th centuries CE) (Pottier, 2017). Furthermore, there is no evidence for a sudden or violent downfall at the end of the Angkor period in the 15th century CE. On the contrary, recent archaeological and environmental studies have pointed towards a gradual demographic decline beginning in the late 13th century CE, driven in part by a series of climatic changes that heavily disrupted Angkor's water management system (Buckley et al., 2010; Buckley et al., 2014; Hall et al. 2021; Penny et al., 2019). Additionally, expanding trade opportunities, especially with China seems to have been an important "pull-factor" drawing people further south near the modern capital of Phnom Penh to take advantage of these economic opportunities (Polkinghorne, 2018; Vickery, 1977, 2010; Polkinghorne and Sato, 2021).

[1] The 30km^2 area represents the main location of Yaśodharapura. If the earlier capital of Hariharālaya is included, the total area is closer to 75km^2.

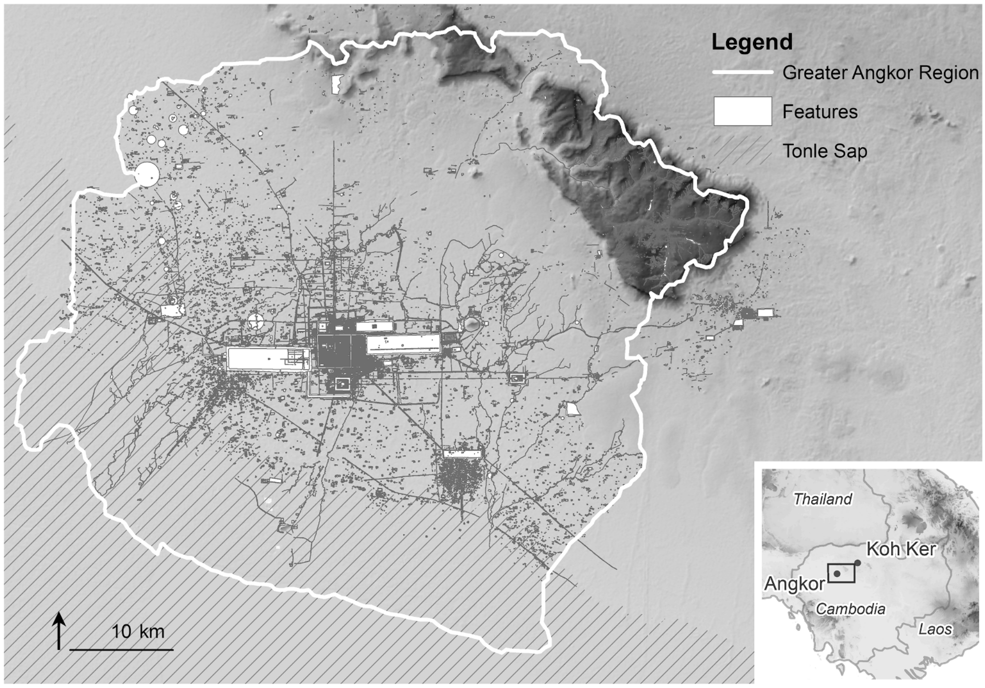

Fig. 1. The 3000 square kilometer area of Greater Angkor, including the upland region of Phnom Kulen, and the 10th century CE capital of Koh Ker.

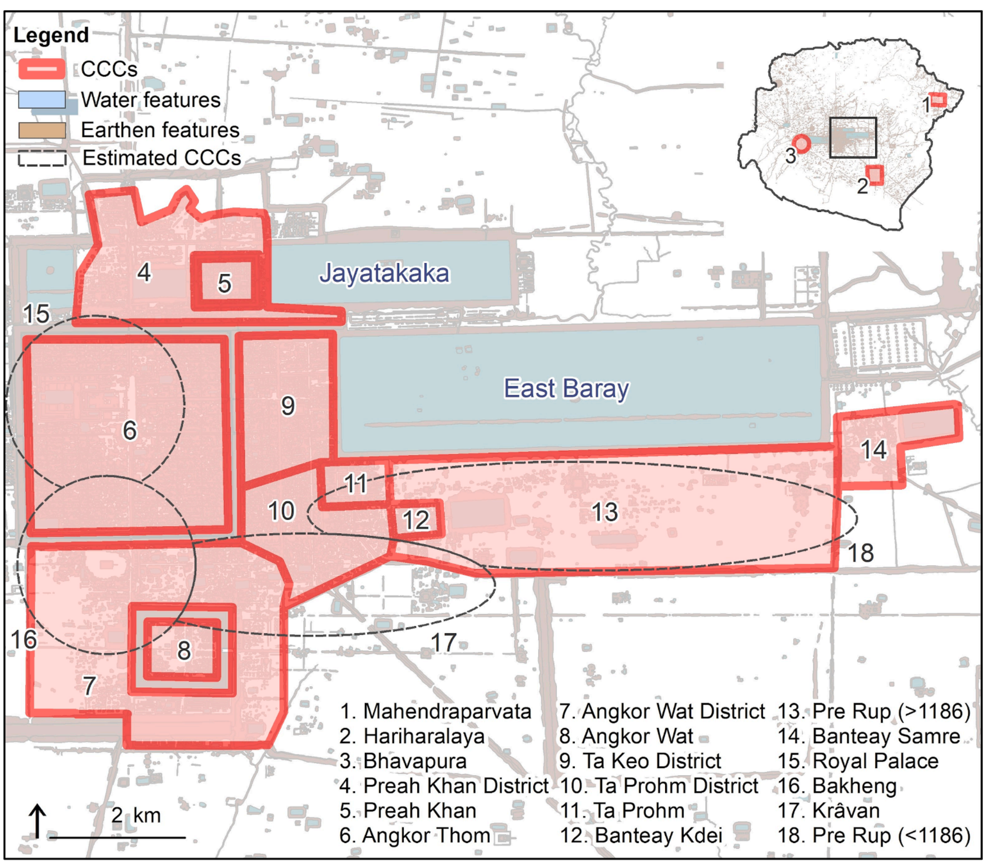

Fig. 2. Map of the 17 CCC zones. Adapted from Fig. 4 in Klassen et al. 2021 originally published in *Science Advances*.

Insights about Angkor's political organization can be gleaned somewhat from inscriptions, which describe a powerful king at the top of a hierarchy that included many bureaucrats, elite families and relatives, as well as religious specialists, craftsmen, servants, farmers and slaves (Lustig et al., 2021; Lustig and Lustig, 2013; Sedov, 1978). Kings would give or authorize the purchase of land, which in turn was frequently used to establish temples. In practice, the power of Angkorian kings has been described as cyclical; waxing and waning over time

(Lustig, 2011; Sahai, 1977; Stark, 2006a). Particular rulers seem to have been more effective at consolidating and expanding the empire than others with the power of regional elites shifting similarly (Lustig, 2011; Lustig and Lustig, 2019).

Angkor's agro-urban landscape grew incrementally over time, driven in part by the state construction projects of Angkorian kings who implemented major public works, including the construction of large water storage tanks or *baray* and the raising of massive stone temples (Table 1). These acts would transform the landscape and allocate (or reallocate) resources, since each temple would need many workers and associated support staff (Groslier, 1979; Pottier, 2000b). To track these developments over time and space, we divide Angkor's landscape into three categories—the civic-ceremonial center or CCC, the metropolitan area or AMA, and the embankments or BANKs—as well as five periods that represent developments in the CCC by some of Angkor's major kings (Table 1 and Fig. 2).

The AMA was an anthropogenic landscape (Chase and Chase 2016) dominated by rice fields (Hawken, 2013; Hawken and Castillo, 2021), earthen occupation mounds, and small community temples. This Angkorian settlement pattern is similar to those found throughout the Lower Mekong Basin, from the Khorat Plateau (Evans et al. 2016) to the Mekong Delta (Stark 2006b; Stark et al. 2015). In previous publications, we have referred to this zone as Angkor's hinterland (e.g., Carter et al., 2018; Evans et al., 2013; Klassen et al., 2018). However, in other archaeological studies around the world, the term hinterland has often referred to a remote zone outside the core's administrative control (e.g., Kepecs et al., 1994; Smith, 2014b). The area under consideration here was not peripheral but distinctly integrated into Angkor's CCC through hydraulic and transportation infrastructure (BANKs) as well as a ritual temple-economy (Fletcher et al., 2008a; Fletcher et al., 2008b; Hendrickson, 2010; Sedov, 1963). For this reason, we use the term metropolitan area to describe the almost 3000 km^2 zone surrounding the CCC as it is part of Angkor's urban form, not detached or separate from it as the term hinterland might imply.

AMA community temples have a particular configuration known as *prasat-trapeang* (temple-pond) (see discussion in Klassen and Evans 2020) (Fig. 3). AMA temples were frequently constructed of perishable materials, most have not been investigated archaeologically, and few have associated inscriptions. However, recent studies have combined multiple lines of evidence with statistical techniques to predict the construction dates of over 1000 of these temples in Angkor's AMA (Klassen and Evans, 2020; Klassen et al., 2018). In the Angkorian period, temples were the center of social and ritual life, and their affiliation with elites and royalty also made them an important part of the political economy (Lustig and Lustig, 2019; Sedov, 1963; Sedov, 1978). Although land ownership changed over time (see Lustig and Lustig, 2019, and discussion below), temples in the AMA frequently owned or controlled agricultural land and were central to the expansion of Angkorian agrarian economy (Sedov, 1963). Temples also marshalled many lower-status community members' labor. These individuals are frequently listed in large numbers in inscriptions (Lustig and Lustig, 2013; Lustig and Lustig, 2015), where they are often described as unfree or slaves (see further discussion below). In some cases, labor was provided by cyclical workgroups through a fortnight or seasonal calendar (Lustig and Lustig, 2015; Sahai, 2012; Stark et al., 2015).

Villages in the AMA were also tied to larger "central temples" in the AMA to which they provided goods and labor (Sedov, 1963). The inscriptions of Ta Prohm and Preah Khan, both state temples of Jayavarman VII (r. 1181/1183 – c.1220 CE), describe in detail the large number of villages tasked with providing rice, goods, and labor to these institutions (Cœdès, 1941; Cœdès, 1906; Maxwell, 2007). For example, at Ta Prohm, inscriptions indicate that there were 12,000 people associated with the functions of this single temple and 66,625 people from 3,140 villages that provided goods and labor (Cœdès, 1906). However, state temples also owned agricultural lands and temple workforces (Sedov, 1963; Sedov, 1978).

The AMA was not just an agricultural zone but a "theocratic" landscape (sensu Coningham et al., 2007), in which temple communities organized the agricultural land, labor, rice surplus, socio-political, and religious life of its members. Epigraphic data suggest that the rulers, state officials, and other elites were actively engaged in the temple economy, particularly in reassignments of land and labor (e.g., Lustig and Lustig, 2015; Moffat et al., 2020; Ricklefs, 1967). While private land ownership was common, the King appeared to have had final authority regarding land claims, which facilitated an elite patronage system (Mabbett, 1978). Although not organized in a formal hierarchy, the AMA temples were connected to the CCC through these temple-related economic networks. Additionally, the AMA included state-sponsored infrastructure in the form of transportation networks (Hendrickson, 2010), water management features, and embankments (below) (Fletcher et al., 2008a; Fletcher et al, 2008b Klassen and Evans, 2020), which tied this space into the CCC.

The CCC was the location of most of Angkor's massive, state-sponsored stone temples and contained the city's highest population densities at different points in its sequence, although densities fluctuated through time. Like the AMA landscape, the CCC also had extensive hydraulic features. Limited excavations within CCC temple enclosures suggest the presence of garden spaces around residential areas (Castillo et al., 2020). In the CCC, temples are constructed of stone or brick and surrounded by occupation mounds (Fig. 3). Temple enclosures themselves may have served as urban neighborhoods and likely included the temple staff's habitation areas (Carter et al., 2018; Stark et al., 2015).

The CCC grew over time as various kings built new temples and transformed the landscape. Our model identifies 17 diachronic zones of temples and their associated occupation mounds (Fig. 2). The areas of some of these zones are estimated, as later temples and occupation mounds expanded over earlier ones. For example, our portions of the Pre Rup zone (or district, see Heng et al., 2021) were taken over later by the construction of Ta Prohm and Preah Khan temples. Similarly, the initial Royal Palace zone was subsumed by the later walled city of Angkor Thom (Fig. 2). In such cases, we drew from studies on the chronology of the urban core to delimit the extent of the CCC zones at different points in time (see Table S1 in Klassen et al., 2021 for a detailed discussion).

3. Methods

Angkor's landscape is a palimpsest, in the sense that the patterns we see on the surface today are the end product of multiple periods of human occupation and transformation spanning millennia, with newer developments often at least partially erasing the traces of previous urban and agricultural networks. Since the 19th century, one of the key challenges at Angkor has been to make sense of the complex, overlapping patterns that we see on the landscape, particularly when we look at it from above, and to organize the traces into some kind of chronological sequence. Although a limited number of archaeological excavations have provided radiocarbon dates and many of the major temple sites in the CCC include inscriptions with consecration dates, the vast majority of features on Angkor's landscape remain undated by absolute dating techniques, and increasingly we have come to rely on establishing webs of relative chronological information that are anchored, in places, to absolute dates from inscriptions or excavations, or to periods derived from art historical or achitectural studies. Earlier publications discuss in detail our methods for dating AMA features at Angkor (Klassen et al.,

Table 1
Major developments and rulers at Angkor with associated population estimates in the Civic Ceremonial Center (CCC) Angkor Metropolitan Area (AMA) and embankments (BANKs).

Period	Ruler	Dates of Reign	Major developments	Population			
				CCC	AMA	BANKs	Total
Period 1: 770–888 CE Pre-Angkor Period and the early cities of Mahendraparvata and Hariharālaya	Jayavarman II	802–835 CE	Jayavarman II declared universal monarch. Dominion includes city of Hariharālaya	89,137	70,668	88,891	248,696
	Indravarman I	877–889 CE	Construction of the Indratatāka *baray*, Preah Kô Temple, and possibly the Prei Monti royal palace and Bakong Temple at Hariharālaya				
Period 2: 889–1001 CE Initial foundation of Yaśodharapura	Yaśovarman I	889–900 CE	Declared construction of the Lolei temple in Hariharālaya, moved the capital northwest centered on Phnom Bakheng and constructed the East Baray.	76,796	318,439	139,191	525,313
Capital at Koh Ker (Chok Gargyar)	Jayavarman IV	928–941 CE	Moved capital to Koh Ker				
Return of capital near Pre Rup	Rājendravarman II	944–968 CE	Returned capital to Angkor and established the state temple of Pre Rup in 961 CE.				
Period 3:1002–1112 CE Reign of Sūryavarman I	Sūryavarman I	1002/ 1003–1050 CE	Modified the Phimeanakas temple in the area near the Royal Palace as well as the Baphuon temple and West Baray.	117,288	431,181	183,399	761,663
Period 4:1113–1180 CE Reign of Sūryavarman II and construction of Angkor Wat	Sūryavarman II	1113–1149 CE	Expanded the territory of the Angkorian kingdom and built Angkor Wat	122,534	491,322	203,949	847,600
Period 5: 1181–1300 CE Reign of Jayavarman VII	Jayavarman VII	1181/1183-c.1220 CE	Reclaimed Angkor from Cham rulers, established Angkor Thom, the Bayon, Ta Prohm, Preah Khan, Banteay Kdei, and the Jayataṭāka *baray*.	159,852	497,949	216,215	903,811

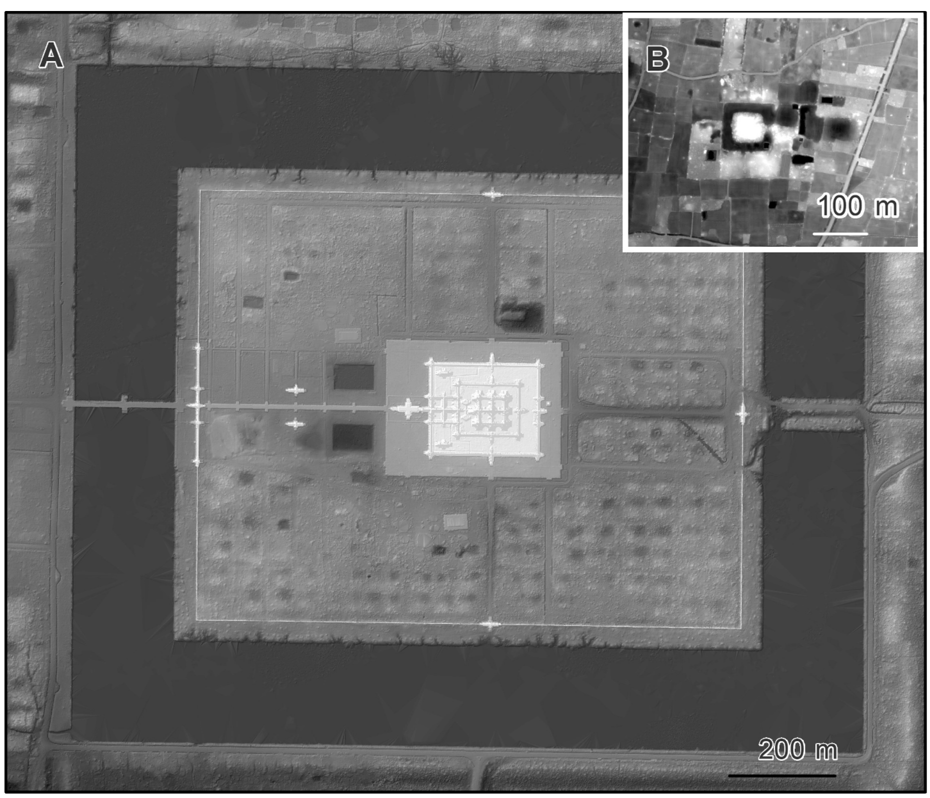

Fig. 3. Lidar imagery of (A) Angkor Wat and (B) a temple community with a classical *prasat-trapeang* formation in the AMA. The two areas are shown at the same scale to emphasize the much larger size of the state temples in the CCC compared to the smaller size of the temples in the AMA.

2018) and estimating Angkor's population (Klassen et al, 2021). We summarize these approaches below.

3.1. Dating and population estimates in the CCC

Temple spaces were our primary analytic unit. Temples in the CCC are often associated with art historical data and inscriptions that provide their date of construction or consecration (Klassen et al., 2018, 2021;

Lustig, 2009; Polkinghorne, 2007).[2] However, dating the CCC is not always as straightforward, as parts of this landscape were used and reused over time, obscuring previous habitation and use. Some scholars have suggested that the builders of Angkor's temples followed particular ritual practices in which temples were to be constructed on "pure soil," which required that meters of existing soil be removed and replaced by beds of sand (Dumarçay et al., 2001: 34). In many cases, this soil replacement obscures any previous habitation in the area, although excavations at Angkor Wat and Ta Prohm suggest some light prior habitation/use of these landscapes (Carter et al., 2018; Carter et al. 2019; Sonnemann et al., 2015). At Angkor Thom, the orthogonally arranged city was developed in three phases beginning in the late 9th century CE, which continued until it was seemingly formalized with the construction of an enclosure wall by Jayavarman VII in the 12th century CE (Gaucher, 2017; Gaucher and Husi, 2013). These transformations complicate our understanding of the landscape's evolution; however, we attempt to incorporate all such factors into our model (see additional discussion in Klassen et al., 2021).

Archaeologists have used numerous methods for estimating population size and density in urban areas (Chamberlain, 2006; Hassan, 1978). Early studies estimated population by counting residential structures and estimating the number of people per structure (Nelson, 1909) or making similar calculations by considering floor area (Narroll, 1962; Wiessner, 1974). Ethnographic data about household size has been valuable for estimating the number of people per household (David, 1971; Kolb, 1985). Communities with robust mortuary data have used skeletal remains to model populations (see Milner et al., 2019 for a review of this method and its challenges). Other studies have taken a broader approach by considering available natural resources and the landscape's carrying capacity (Zorn, 1994). Scholars working in time periods with historical documents have used these resources to complement archaeological data (e.g., Jones and DeWitte, 2012; Kowalewski, 2003). More recent studies have used innovative methods to better estimate population, including the study of fecal stanols as a means of measuring population increases and decreases on a landscape (White et al., 2019), lidar data (Inomata et al., 2018), and agent-based modeling (Kohler et al., 2012) to identify residential structures more accurately.

These methods are difficult to apply at Angkor. Only a handful of skeletal remains have been uncovered as the dead were largely cremated in the Angkor period (Pottier and Chhem, 2008). Identifying dwelling spaces has been challenging due to the ephemeral nature of Angkorian habitation structures (Carter et al., 2021; see also Graham, 1996). Early scholars were aware of occupation mounds around Angkor and attempted to map them, but were hampered by the dense forest (Stark et al., 2015). Despite this, numerous estimates for Angkor's population have been proposed, evolving as conceptions of Angkor's urban form have shifted over time (see Table 2). Several of these methods have looked at the carrying capacity of the landscape and the population that could be supported based on the hydraulic network's development. The most recent and comprehensive estimate by Lustig (2001) argues for a total population of 750,000 people at Angkor's height, based on a 1500 km^2 area and assuming both of the largest water storage tanks (the East and West Baray) were in use but were not irrigating rice fields to the south. Despite usage in the comparative literature (e.g., Chase and Chase, 2016; Diamond, 2011: 539; Fletcher and White, 2018; Stone, 2009), this number was never meant to be definitive. Instead, it was an

[2] To date features such as embankments, mounds, and ponds in the CCC, which typically do not have inscriptions, we used several methods. In many cases we could use a relative system of grouping features with other features that either date to the same time period or date to an earlier time period. For example, if a mound was built over an embankment it is assumed that the mound was built after the embankment (see Klassen et al., 2021 for further discussion).

Table 2
Summary of previous population and density estimates proposed for Angkor.

Source	Estimated population	Estimated population Density persons (p)/km^2	Source and notes
Civic-Ceremonial Center "The Hydraulic City"	600,000[a]	526 p/km^2	(Groslier, 1979)
"Hydraulic Suburbs" the less densely populated area of 10,000 km^2 surrounding the civic-ceremonial center that included 5 *srok* of Siem Reap province: Siemreap, Chikreng, Kralanh, Puok, Sautnikom.	429,000 [a]	464 p/km^2	(Groslier, 1979)
Hinterland area of dryland cultivation to the north and east of the hydraulic city	872,000[a]	101 p/km^2	(Groslier, 1979 - see Carte 7)
Core Area 1000 km^2 area Includes major temple zone	150,000–400,000 people[b]	150–400 p/km^2	(Lustig, 2001)
Inner Area 1500 km$_2$ area that includes Core Area as well as southern area near Tonle Sap	350,000–750,000 people[b]	233 p/km^2 500 p/km^2	(Fletcher et al., 2017; Lustig, 2001)
Extended Area 2500 km2Core and Inner Area as well as expanding to Damdek Canal to the East, westward to rivers, and north/northeast to foothills of Phnom Kulen.	650,000–1,000,000 people[b]	260 p/km^2 400 p/km^2	(Lustig, 2001)
Angkor's "Hydraulic Zone" (area between the East and West *baray* and the Tonle Sap lake) similar to Groslier's "Hydraulic City" above	288,000[c]		(Acker, 1998 drawing on Groslier 1979)
Angkor Thom enclosure	16,000 (1651 ponds*/2 families per pond)[d]	1778 p/km^2	(Hanus and Evans, 2016) *The pond algorithm noted in the article identified 1651 ponds.
	30,000 (2219 ponds**/3 families per pond)[d]		**Based on a count from a map by Gaucher, 2004
	40,500 (2700 ponds***/3 families per pond)[d]		***2219 were mapped in the revised count of ponds within Angkor Thom

(continued on next page)

Table 2 (*continued*)

Source	Estimated population	Estimated population Density persons (p)/km^2	Source and notes
			based on lidar data (Hanus and Evans, 2016)
Angkor Wat Enclosure	2500–4500[d]		(Evans and Fletcher, 2015)
Ta Prohm Enclosure	1800–2000[d]		(Evans and Fletcher, 2015)
Ta Prohm Enclosure	1400–2000 people[e]	882–1260 p/km^2	(Carter et al., 2018)

[a] Based on available cultivable (irrigated) land.
[b] Population that could be supported by rice produced using various water management strategies.
[c] Estimated amount of people fed by dry season and wet season rice.
[d] Based on number of ponds within enclosure and 13th century visitor Zhou Daguan's account.
[e] Based on available mound space.

estimate of rice productivity and the carrying capacity of the Angkor region (Lustig, 2001). More recently, several scholars have provided population estimates for some of the enclosure areas within the CCC based on archaeological excavations and recently acquired lidar data (Table 2).

With lidar data, the mounded residential areas across the Greater Angkor Region have become more visible, even where they are covered by dense vegetation, allowing for more precise identification of residential spaces (Evans et al., 2013). Nevertheless, we are still unable to see individual house structures. To remedy this, we drew on recent archaeological work at Angkor Wat (Klassen et al., 2021; Stark et al., 2015). A horizontal excavation on a single mound in the Angkor Wat enclosure in 2015, as well as numerous smaller excavations on discrete occupation mounds, indicated only one household per mound, with each mound measuring approximately 600 m^2 in size. Although Cambodian households can include nuclear and extended families with varying numbers of children, ethnographic data suggests a preference for nuclear families with ethnographic surveys noting approximately five people per household (Delvert, 1961: 319; Ebihara, 2018: 51-68, 266; Ebihara, 1977: 52; Heuveline, 2017; Kalab, 1968: 525). Worldwide ethnographic studies also suggest that approximately five people are typical for most households (Hassan, 1978: 58).

To estimate the CCC population, we used a method we call the "mound method" in which the total square meters of mounded occupation features, including occupation mounds, pond embankments, and linear embankments were calculated. We then assumed that each household of five required approximately 600 m^2 (see also discussion in Klassen et al., 2021). For example, at Angkor Wat, we extrapolated the mound-depression pattern seen in the eastern portion of the Angkor Wat enclosure across the entire enclosure to estimate a total of 271–278 mounds and a population of 1355–1390 persons.

We view this 600 m^2 per household measurement as merely a beginning point based on the best currently available evidence for estimating the number of potential households, and by extension the total population at Angkor. A recent ethnoarchaeological study of household space around the ancient site of Bagan, Myanmar estimated the average household compound area to be 760 m^2, close to our estimate at Angkor (Talving-Loza, 2020). We acknowledge that there was likely variation in household space in the past. Historical data has suggested that Angkorian households varied by size and status (Zhou, 2007: 49-50), and ethnographic studies also suggest that household size and density varied in village settings (Delvert, 1961: 180-198, 204; Ebihara, 2018: 41; Kalab, 1968; Prak, 2006). Rural households may have encompassed more space for gardens or tending animals than those in the CCC (Bâty et al., 2014). We also expect that further excavations will refine our estimate for household size in different contexts. At Ta Prohm, for example, not all mounds within the enclosure seem to have been as intensively inhabited (Carter et al., 2018).

It is worth noting that the 13th century Chinese visitor to Angkor, Zhou Daguan, described slaves associated with households in Angkor, observing that "most families have a hundred or more of them; a few have ten or twenty; only the poorest have none at all" (Zhou 2007: 58-59). These slaves are described as ethnic minorities who had little status within Angkor's society (Mabbett, 1983) and only allowed to "sit or sleep under the house" (Zhou, 2007: 59). It is unclear how to interpret this evidence when calculating household size at Angkor. Excavations within the CCC have not uncovered evidence for people such as slaves living underneath houses (Carter et al., 2018; Heng et al., 2021; Stark et al., 2015). It is unlikely that even ten slaves could easily live underneath an average-sized house and would therefore require additional living quarters. Zhou (2007: 59) also implies that some of these slaves may have lived outside the city. In both cases then, we believe we have accounted for this population in our model. Overall it is likely that a large portion of Angkor's population was not free and would fall under some category of slave (Lustig and Lustig, 2013; Mabbett, 1983).

3.2. Dating and population estimates in the AMA

Most temples in the AMA do not have accessible datable material culture or inscriptions and the "mound method" is difficult to apply in this zone; therefore, we used different methods to calculate dates and population estimates. In the AMA, over 1,100 *prasat-trapeang* (temple-pond) configurations have been identified and mapped (Klassen and Evans 2020; Klassen et al.2018). The AMA temple dates were estimated using an algorithm that used a combination of multiple linear regression and graph-based semi-supervised machine learning to predict temple dates with a 49–66-year average absolute error (see full discussion in Klassen et al., 2018).

As noted earlier, these temples are thought to be the center of Angkorian-period communities. Occupation mounds within the AMA are not as visible in the CCC, and Angkorian inscriptions are of limited utility. While many describe the numbers of temple personnel and even the names of villages and lands donated (Lustig and Lustig 2013, 2019; Lustig and Lustig 2015), they are non-specific regarding the size and the demographic make-up of villages. However, some temple communities do have surviving occupation mounds. With these temple communities, we applied an algorithm originally devised by Hanson and Ortman (2017) to provide spatial resolution to our population estimates. This algorithm assumes that density increases with the size of the occupation mounds. Ethnographic data suggests that approximately 100 families of five people were associated with each temple community (Delvert 1961 see also Kalab 1968). Based on this understanding, we adjusted the Hanson and Ortman algorithm, so the outputs have a mean population of 497. For temples without surviving occupation mounds, we assigned a population of 497 people (see further discussion in Klassen et al., 2021).

As in the CCC, the AMA landscape was dynamic. Over time, land belonging to lower-status families or corporate groups appears to have been sold to higher-ranking elites (Lustig and Lustig, 2019). Archaeological evidence suggests that smaller temples may have been replaced by or superseded by larger temples. For example, excavations at the site of Trapeang Thlok show the site was in use only from the end of the 10th century to the mid-11th century CE when it was seemingly abandoned, with the population possibly shifting to the larger nearby temple sites of Prasat Trapeang Ropou or Prasat Prei (Bâty, 2010). Determining the longevity of occupation at many sites will require similar careful archaeological excavation. However, in our model, we argue that populations of smaller temple communities would have been aggregated into those of large temples after the land was acquired. Therefore, once founded, the associated temple populations remain on the landscape, even if their affiliations, labor, and agricultural products were moved to a larger temple (see further discussion in Klassen et al., 2021).

3.3. Dating and population on the BANKs

The final form of occupation was on embankments (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 (Fletcher et al., 2003: 109-111). These spaces may have been occupied by recent migrants to the city, as they offered land for housing that was not controlled by existing AMA communities, but this hypothesis requires further testing (Fletcher et al., 2003: 110-112; Klassen et al. 2021).

Angkor's hydraulic network has been reconstructed with a reasonable degree of confidence (Fletcher and Pottier, 2021; Fletcher et al., 2008b). While some hydraulic network elements (e.g., the massive East Baray) can be dated from inscriptions, other BANKs were indirectly dated by their spatial and functional relationship with well-dated temples or based on the superpositioning of features on a landscape. Features with unknown dates used 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 these methods in Klassen et al., 2021).

The BANKs population was calculated assuming that the widest surviving part of the embankment represented the width of the embankment at the time of construction. We used our "mound method" described above to estimate household size on the embankments and with the same household composition. Preliminary surveys suggest that population density on the BANKs decreased farther from Angkor's CCC (Roland Fletcher, personal communication). Until further research can be done to determine variable population density along the BANKs, we report the maximum population on these features and note that the actual population likely fell within a range between zero and the population maximum (see Klassen et al., 2021).

To be sure, these population estimates are models that require further testing. Additional data from residential areas in both the CCC and AMA are needed to determine if the average household size, calculated here based on mounds within Angkor Wat, was typical or if this varied over time and space. Similarly, ethnographic data demonstrates that household composition was diverse and frequently changed over time (e.g., Ebihara 1977). As many house mounds in the AMA are missing, it is also difficult to determine exactly how many households were affiliated with a particular temple and ethnographic data suggest some flexibility in how households could support various pagodas (e.g., Kalab 1968). Excavations to identify datable material, would also help refine the timing of sites whose dates were estimated based on machine-learning algorithms. Additionally, habitation on embankments has not been thoroughly examined and so our population estimates for these locations are the most speculative. We are curious if habitation was as intense on these features and if material culture might tell us more about who was living on these mounds and their occupations.

Our reliance on ethnographic data to estimate household and community sizes is both a boon and a limitation. The exact composition of an Angkorian household may be difficult to determine, especially given a lack of skeletal remains that might facilitate understandings of biological family reliationships or clear outlines of dwelling size and rooms within a dwelling space. Non-kin members of households, such as slaves or servants, are also difficult to account for. Nevertheless, we feel that the ethnographic data, provides the most informed option for estimating population given that other source of data for estimating household size are absent.

4. Discussion

Table 1 lists the total number of people in the CCC, AMA, and BANKs during each period (see also Fig. 4). We note that at its height in the 12-13th centuries CE, Angkor's population could have been as high as 900,000 people if the BANKs were fully inhabited. We also observe different rates of growth in these three occupation zones, with major population growth in the AMA in Period 2. However, in subsequent periods, we observe slower growth in the AMA with increasing population density in the CCC (Fig. 5 and Tables 3 and 4). This culminates in the highest population density in the CCC associated with Period 5 and the reign of Jayavaraman VII, who intensified and formalized Angkorian space. These developments were short-lived, however, as Angkor began its slow decline in the 13th and 14th centuries CE. In the sections below, we discuss each period in detail and the historical developments that were shaping Angkor's agro-urban landscape.

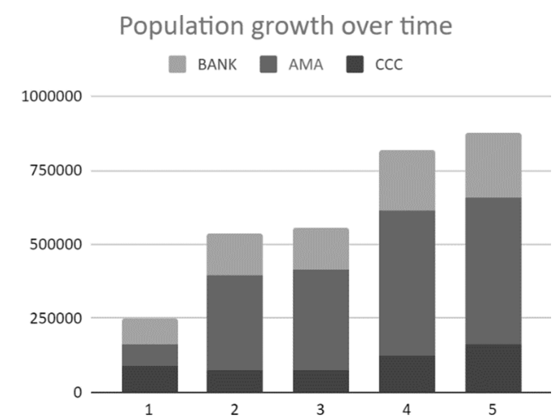

Fig. 4. Population growth over time.

4.1. Period 1-770-888 CE: Pre-Angkor period and the early cities of Mahendraparvata and Hariharālaya

We begin our Period 1 in 770 CE with the habitation of two early Angkorian capital cities (Mahendraparvata and Hariharālaya) and a third likely population center near what would become the West Baray (Bhavapura) (Fig. 2).[3] We estimate the total population of Angkor in this period to be approximately 250,000 people (Fig. 4 and Table 1). The two capitals of Hariharālaya and Mahendraparvata have the highest population densities of approximately 16 persons per hectare (henceforth p/ha) and monumental construction and infrastructure development we

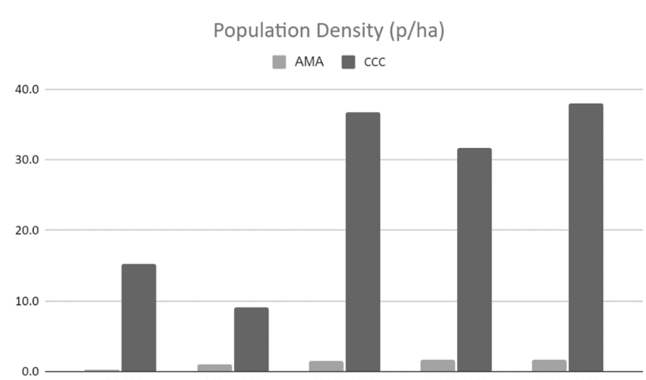

Fig. 5. Population density in the AMA and CCC zones over time.

[3] Our start date for Period 1 is based on a radiocarbon date from excavations within Hariharālaya and reflects evidence for this earlier population (Pottier et al., 2005: 15; Penny et al., 2006). This date is somewhat arbitrary; as our focus is on developments from the 9th century CE period, we use the 770 CE date to partially capture the earlier phase at Hariharālaya.

Table 3
Amount of km^2 with densities less than 5, 5–10, and greater than 10 people/ha.

Period				Total (km^2)
	>5	5–10	10>	
1-770-888	201.2	21.1	62.8	285.0
2-889-1001	687.5	101.3	111.6	900.3
3-1002-1112	748.3	136.0	116.4	1,000.8
4-1113-1180	777.3	158.6	136.3	1,072.1
5-1181-1300	380.0	353.5	349.5	1,083.0

consider to be typical of CCC zones. The third population center, Bhavapura (discussed below), has a slightly lower population density of approximately 13p/ha (Table 4). The presence of temple communities in the AMA is sparse; just over 200 km^2 of Angkor's AMA contains less than 5p/ha (Table 3) with approximately 70,000 people. However, if the embankments were fully inhabited at this time, this would add about 89,000 people to the AMA landscape.

Mahendraparvata, located on Phnom Kulen (Fig. 1), contains the massive Rong Chen pyramid temple, where Jayavarman II was supposedly declared a universal monarch establishing the start of the Angkor kingdom (Cœdès, 1968; Cœdès, 1943; Coedès and Dupont, 1943). Recent studies have demonstrated that this was a large, planned city of approximately 40–50 km^2, organized on a grid with occupation areas, temples, linear causeways, hydraulic features including a large reservoir (Chevance et al., 2019). The construction of these hydraulic features would have likely required a large labor force during the early phases of urban development on the mountain (Chevance et al., 2019; Penny et al., 2014). The city appears to date to the late 8th-early 9th centuries CE, although the presence of at least two Pre-Angkorian temples points towards this location's importance during the Pre-Angkor period (Chevance et al., 2019). Calculating population at Mahendraparvata is challenging as there are not clear occupation mounds as seen in the lowland floodplains. For this reason, we estimated the population density to be similar to that at Hariharālaya (see Klassen et al., 2021).

The expansion of Hariharālaya as a capital is also associated with Jayavarman II, in the early 9th century CE, although many of the major constructions at Hariharālaya, including aspects of the brick towers of Preah Kô, the Indratatāka reservoir, and the Bakong temple are affiliated with the ruler Indravarman I (877–889 CE). Archaeological and epigraphic data suggest long-term habitation in the Hariharālaya area prior to the Angkor period. A recently identified inscription from the Bakong temple might be one of the oldest in the region, dating to the 6-7th centuries CE (Pottier and Soutif, 2014). Excavations around the site of Trapeang Phong also indicate habitation from the 7th century CE (Pottier, 2017; Pottier and Bolle, 2009). Recent archaeological and palynological data suggest the construction of the Bakong began in the late 8th century CE, prior to Indravarman I's reign (Penny et al., 2006; Pottier, 2012). By the 9th century CE, the population at Hariharālaya expanded, especially around the royal palace, Prei Monti (Pottier, 2012; Pottier et al., 2008; Pottier et al., 2009; Pottier et al., 2007). Using the mound method, we estimate the population of this city to be approximately 39,000 people.

The area around the future site of the West Baray and the Ak Yum, believed to have been known as Bhavapura, presents a unique challenge (Pottier 2017). This region has a long history of habitation. Burials dating from the Bronze Age (approx. 1000 BCE) were identified in the West Baray (Pottier, 2006b; Pottier et al., 2004), and Iron Age or Protohistoric burials from the early-mid first millennium CE were uncovered during excavations at the nearby temple site of Prei Khmeng (O'Reilly et al., 2020; Pottier, 2001). Several inscriptions and large temples were located in this region, including Prei Khmeng, Ak Yum, and Wat Khnat, testifying to the significant population in this area in the 7th and 8th centuries CE (Pottier, 2006a; Pottier 2017; Pottier et al., 2001a; Pottier et al., 2001b). The Bhavapura settlement contained powerful rulers and may have included a "proto-*baray*" and associated rice fields (Fletcher et al., 2017: 277; Hawken, 2013: 360; Klassen and Evans, 2020: 5; Pottier, 2017; Soutif, 2009). Unfortunately, much of the habitation in this area was destroyed by the construction of the West Baray in the 11th century CE. In our model, we gave this area the same density as Pre Rup, whose mounds are visible and have been mapped. The surviving remains in this zone suggest a lower density than Hariharalaya. Fletcher and Pottier (2021) suggest that Bhavapura may have been approximately 35 km^2. We estimate the total population at approximately 26,000 people; however, these estimates will need to be refined with further archaeological investigation.

4.2. Period 2-889-1001 CE: Initial foundation of Yaśodharapura, Jayavarman IV's capital at Koh Ker (Chok Gargyar), and return to Yaśodharapura

In 889 CE, the ruler Yaśovarman I came to power and established a new capital, Yaśodharapura, centered around the natural hill of Phnom Bakheng where he also built a temple (Gaucher, 2010; Pottier, 2000a) (Fig. 1). Inscriptions (K. 464 and K. 558) date the consecration of gods at Phnom Bakheng temple to 907 CE (Jacques, 2005; Jacques, 1970). During this period, we observe two major population centers within the CCC (Fig. 2). The first is around the temple of Phnom Bakheng extending to the north to the area around the Royal Palace and Phimeanakas and to the east around the Krâvan temple (Fig. 2 zones 15–17). Although heavily disturbed by later modifications and more intensive habitation during the reign of Jayavarman VII, excavations within Angkor Thom suggest habitation in this area dating at least to the 9th century CE and the period of Yaśovarman I (Gaucher, 2017; Gaucher and Husi, 2013). Inscriptions K. 291 and K. 576 also imply that Yaśodharapura reached this palace area (Coedès, 1937: 199; Finot, 1925: 307) and ceramics dating to the 9th century CE have been identified in excavations within

Table 4
Population estimates and densities of sites mentioned in the text.

Temple and districts	Date	Area of Mounds (ha)	Total Area (ha)	Houses	Population	Density (Ppl/ha)
Bhavapura (Ak Yum)	690	–	1900	–	26,296	13.84
Mahendraparvata	800	–	1545.00	–	24,982	16.17
Hariharālaya	770	466.3	2402.64	7,772	38,859	16.17
Bakheng (temple and district)	889	–	994.01	–	13,757	13.84
Krâvan (Pr.) (district)	921	–	575.4	–	7,963	13.84
Royal Palace (temple and district)	889	–	527.4	–	7,299	13.84
Pre Rup (Eastern District) (district)	961	165	994.0	2,751	13,757	13.84
Angkor Wat (temple)	1140	–	83.4	275	1,375	16.48
Angkor Wat (district)	1140	242.3	846.3	4,037	20,189	23.86
Ta Prohm (temple)	1186	28.4	66.7	473	2,366	35.49
Ta Prohm (district)	1186	176.5	275.8	2,941	14,708	53.33
Preah Khan (temple)	1191	32.3	56.6	539	2,695	47.58
Preah Khan (district)	1200	363.1	408.3	6,051	30,256	74.10
Angkor Thom	1200	497.7	833.5	8,296	41,478	49.76

Angkor Thom (Gaucher and Husi, 2013; Polkinghorne et al., 2014). The population of these three zones totals nearly 30,000 people. A second population center was around the temple of Pre Rup and the area of the Eastern Baray, also called the Eastern District (Heng et al., under review) (Fig. 2, zone 13). The mounds in the Eastern District are less disturbed; therefore, we are able to use the "mound method" to estimate population within this region and assume that similar densities were in place in the Yaśodharapura area with a population of almost 14,000 people.

It is unclear why Yaśovarman I decided to shift the location of the capital from Hariharālaya. As noted above, there had been a population living in this area during Period 1 and likely earlier (Groslier, 1979: 165-166). Groslier notes that Yaśovarman had a "predilection" for hilltop temple sites (Groslier, 1979: 172). Hydrological studies also demonstrate that this area had a higher and less variable water table than Hariharālaya, which may have facilitated rice agriculture with groundwater access during the dry season (Acker, 2012). Increased water management certainly seems to have been an important focus during this period. Inscriptions (K. 280–283) describe the East Baray's construction in association with King Yaśovarman I in the late 9th century CE (Bergaigne, 1893: 407-408; Coedès, 1932: 108-109). During this period, the creation of the channel known as the Siem Reap River brought water closer to the newly established capital (Acker, 2012; Groslier, 1979; Lustig et al., 2008). The aim of the increased investment in water management is believed to have been to facilitate agricultural production (Fletcher and Evans 2012; Fletcher et al. 2008a; Fletcher et al. 2008b; Groslier 1979). The labor of a large number of people would have been required for the construction of the East Baray and related channel features. Pottier (2000b: 105) has estimated that a workforce of 148,000 people could have taken three months to construct the larger West Baray. It is likely that such a workforce would have been drawn from these surrounding AMA populations.

Despite the infrastructure development at Yaśodharapura during Period 2, our model estimates a population decrease to approximately 77,000 people in the CCC during this period. Part of this may be due to the estimates used in our model that was based on the visible occupation mounds at Pre Rup, which are lower density than those at Hariharālaya. However, there were additional changes taking place in Angkor's landscape. During this period, King Jayavarman IV (r. 928–941 CE) ruled from an alternative capital site at Koh Ker (called Chok Gargyar) approximately 80 km northeast of Angkor in what is now Preah Vihear province (Fig. 1). Although well-located for access to stone, recent work has identified serious problems with the city's water management system that likely affected its viability as a long-term capital (Evans, 2010; Lustig et al., 2018; Moffat et al., 2020). The establishment of this alternative capital may have drawn some population away from the CCC at Yaśodharapura (Hall et al., 2018). However, this period also saw the foundations of numerous temples in the AMA by non-royal officials (discussed below and Lustig and Lustig, 2019).

In the mid-10th century CE, King Rājendravarman II (r. 944–968 CE) returned the capital to Yaśodharapura from Koh Ker, where it remained the location of Angkor's capital for several centuries, growing and expanding with subsequent kings. Rājendravarman II constructed the large state temple of Pre Rup near the East Baray, inaugurating it in 961 CE (Cœdès, 1909). Additional modifications were made to the East Baray during this period, including the construction of the East Mebon temple on a man-made island in the middle of the *baray* (Dumarçay et al., 2001: 64–65; Fletcher et al., 2008b; Groslier, 1979).

Archaeological evidence suggests continued habitation at Bhavapura until the construction of the West Baray in the 11th century CE (Pottier et al., 2001a; Pottier et al., 2001b). For these reasons, we have left these population estimates unchanged until that time. Archaeological and palynological data suggest some depopulation at Hariharālaya with the establishment of Yaśodharapura (Penny, 2006). However, archaeological excavations at Trapeang Phong show evidence for continued habitation in this area until the 15th century CE, and the central tower of Bakong was renovated in first half of the 12th century CE (Boisselier, 1952: 223; Pottier and Bolle, 2009). Our model leaves a population of approximately 37,000 people, moving only a small elite population of approximately 2,000 people to Yaśodharapura. In contrast, Mahendraparvata appears to have been depopulated during this period, although later features indicate the area was not completely abandoned (Chevance et al., 2019). For this reason, we have reduced the population at Mahendraparvata to 1000 people. This number is merely an estimate and will need to be refined with further archaeological investigation.

While the CCC population was seemingly shrinking, Angkor's AMA population saw a dramatic jump, from 70,000 to approximately 318,000 people. The total area of land with a density of <5 people per hectare expands from 201 km^2 to 687.5 km^2 (Tables 1 and 3). Inscriptional evidence suggests that non-royal officials established many new temple communities in the AMA during this period (Klassen et al., 2018; Lustig and Lustig, 2019). Additionally, the water management system and road and transportation networks expanded, especially in the northeastern portion of Angkor's territory (Hendrickson, 2010). Many of these new temple communities in the 10th and 11th centuries CE (our Periods 2 and 3) specifically tend to cluster around the state-sponsored hydraulic infrastructure, including the construction of *baray* (Klassen and Evans, 2020). Combined with inscriptional evidence, Klassen and Evans (2020: 6) hypothesize that these newly established temple communities practiced a form of bottom-up organization where they had some degree of local autonomy over their associated land. These combined factors seem to have allowed for the expansion of Angkor's AMA into a massive agro-urban center (Klassen and Evans, 2020).

4.3. Period 3-1002-1112 CE: Reign of Sūryavarman I

In the early 11th century CE, there was an internal struggle for power between two rival kings, with Sūryavarman I (1002/1003-1050 CE) ultimately claiming the throne, which begins our Period 3 (Vickery, 1985). Sūryavarman I continued habitation within Yaśodharapura and modified some of the Royal Palace area and the temple of Phimeanakas, while also constructing numerous temples outside of the capital (Jacques and Lafond, 2007). As part of these expansions, Sūryavarman I also seems to have formalized some of Angkor's road networks (Hendrickson, 2010).

During this period, the dramatic increase in the AMA population begins to slow, with only about 112,000 new people during this more than 100 year period. In contrast, the CCC expands to approximately 117,000 people. The CCC's growth is likely due to the formalization of the Royal Palace compound, including the nearby temples of the Baphuon (Leroy et al., 2015) and Phimeanakas in the area that would later become incorporated into Angkor Thom (Gaucher, 2017). King Sūryavarman I is also associated with the construction of the West Baray in the western part of the capital (Pottier, 2000b). The construction of this feature would have required a large labor force, likely drawn from AMA populations and disrupted much of the earlier settlement of Bhavapura.

While one might expect continued expansion of AMA populations due to the West Baray's construction, our model predicts only modest growth. Klassen et al. (2018) have noted a decline in new AMA temple constructions from the 11th century CE onward. Inscriptions also indicate a shift in the titles of individuals buying and selling land during the 10th century CE, prior to Sūryavarman I's reign. Inscriptions demonstrate changing land ownership, where high-ranking elites appeared to have monopolized landholding at the expense of the lower status individuals and communal/corporate groups (Lustig and Lustig, 2019; cf. Vickery, 1985). Additionally, the number of tax immunities granted to new temple foundations appears to decline in the 11th century CE, which would have discouraged the formation of new temples (Lustig and Lustig, 2019). Taken together, it appears that during the 11th century CE, there was a shift from the establishment of new temples on undeveloped land to elite consolidation of land-ownership (Klassen and Evans, 2020; Lustig and Lustig, 2019). These top-down controls appear to have slowed Angkor's AMA population growth.

4.4. Period 4-1113-1180 CE: Reign of Sūryavarman II and construction of Angkor Wat

Our Period 4 begins with the next major king of Angkor, Sūryavarman II (1113–1149 CE), who came to power in the early 12th century CE and is responsible for Angkor's most famous temple, Angkor Wat. Like his namesake, he also expanded the Empire's borders. While we primarily associate this period with Suryavarman II, a newly discovered inscription also describes a subsequent ruler, King Tribhuvanadityavarman, who took power after Sūryavarman II and ruled from 1149 to 1180 CE (Sharrock, 2018). The inscription also recounts that he built "eight Buddhist sanctuaries" and was then killed during a Cham attack on Angkor in 1180 CE (Sharrock, 2018: 112). This new inscription suggests that Tribhuvanadityavarman was a more important ruler than previously supposed, and future research is needed to determine his impact on Angkor's history.

Our model predicts a continued slow population growth in both the CCC and AMA during this period. The CCC saw a population increase of only approximately 5,000 people. However, Angkor Wat's construction had major impacts on Angkor's socio-political landscape and may have inspired reorganization of habitation within the CCC. The construction of the temple itself would have required an immense number of laborers. Additionally, lidar images reveal a large series of square spirals south of Angkor Wat, whose function is not yet clear, but may have acted as large gardens (Evans, 2016). During his reign, Sūryavaraman II invaded the neighboring kingdom of Champa in Vietnam and moved the Angkorian Empire farther into Thailand and the northern Malay Peninsula (Coe and Evans, 2018; Cœdès, 1968). One must wonder if this expansion and focus outside the Greater Angkor Region contributed to the slower growth of the AMA during this period (Table 1).

4.5. Period 5–1181/1183–1300 CE: Reign of Jayavarman VII

The ruler many consider to be Angkor's most celebrated king, Jayavarman VII, came to power at the end of the 12th century, which marks the beginning of Period 5. With Jayavarman VII's reign (1181/1183-c.1220 CE) came a period of dynamism. He was responsible for the greatest expansion of the Empire, massive building campaigns within the capital, and additions to the water management network (Cœdès, 1943). Jayavarman VII is associated with the construction of five major temples in Angkor's CCC: the state temple of the Bayon, Banteay Kdei, Ta Prohm, Preah Khan, and Neak Pean on a small island within the Jayataṭāka *baray* (Cœdès, 1968; Stern 1965). Additionally, Jayavarman VII built large temples, such as Banteay Chhmar outside the Greater Angkor Region (Sharrock, 2015), contributed to Angkor's expanding road networks (Hendrickson, 2010), and constructed small hospital chapels inside and outside the CCC (Pottier and Chhem, 2008; Sharrock and Jacques, 2017).

We see another demographic increase during this period, with the population across Angkor reaching its peak—perhaps up to 900,000 people—and approximately 1000 km^2 of the 3000 km^2 study having been occupied (Tables 1 and 3). This population growth is largely due to an increase in population in the CCC, from approximately 122,000 to 160,000 people, as the AMA and BANKs populations grew only slightly. In portions of the CCC, population density increased dramatically. For example, habitation around Preah Khan temple may have had a density as high as 75p/ha (Table 4). However, we note that excavations at the nearby Ta Prohm temple, also constructed by Jayavarman VII, suggest not all the mounds within the enclosure were equally or as intensively inhabited (Carter et al., 2018) and based on these data have revised the population estimates down from that predicted by the mound-method. Confirming that these enclosures were densely inhabited will require more fine-grained archaeological investigation.

Most scholars agree that late-12th – early-13th-century CE Angkor contrasted markedly with its preceding urban forms both in structure and worldview (Cœdès, 1943; Cœdès, 1968; Gaucher, 2004; Groslier, 1973; Hawixbrock, 1998; Mus, 1961; Sharrock, 2009), such changes likely explain its steep increase in population density. Jayavarman VII was a remarkably effective consolidator of previous state infrastructure: roads, bridges, and even some provincial capitals (Hendrickson, 2008, 2010; Hendrickson and Leroy, 2020). Angkor's urban core also reflects this pattern in, for example, the formalization and walling of the Angkor Thom area (Gaucher, 2017). Labor requirements to undertake such massive state projects would have placed demands on both AMA and core populations and likely brought more residents to the city center (Klassen and Evans, 2020).

While there would have been an increased demand for agricultural production to support this large population of non-producers living in the CCC, recent work by Klassen et al. (2021) suggests that the heightened demand for surplus may not have led to the immiseration of farmers. Using settlement scaling theory, the authors argue that supra-household scale organization of agriculturalists facilitated through temple communities (whether owned on a local level or by elites) likely allowed for increasing returns to farming labor that did not necessitate decreased fallowing, more hours of work, or increased technological inputs. Further, the patterning of agricultural temple communities is consistent with the Alonso-Mulls-Mills model (Alonso, 1964; Brueckner, 1987), where land is valued based on the commuting cost to the CCCs. This indicates that the urban development and form of medieval Angkor was beholden to the same processes that structure the urban form of contemporary cities (Klassen et al., 2021).

A population of 900,000 people would have exceeded the previously estimated landscape capacity of 750,000 people without irrigation from the *baray* (Lustig 2001). Therefore one must wonder if Angkor's provincial zones were sending other food or staple finance to the capital (D`Altroy and Earle, 1985; Isendahl and Barthel, 2018). For example, an inscription from one of Jaryavarman VII's large state temples in the CCC, Ta Prohm, notes that 66,625 people from 3,140 villages supplied the temple with goods and labor (Cœdès, 1906). Our model predicts only 2000 people living within Ta Prohm's temple enclosure, with an additional 14,000 in the temple district; far below the numbers mentioned in the inscription. Therefore, there must have been additional villages outside the temple district, likely in the AMA and beyond, that would have provisioned Ta Prohm. Inscriptions note that small AMA temples would collect goods and products from their agricultural lands, a small portion of which were sent as tax to larger centralized temples (Sedov, 1963). However, no inscriptions suggest staple finance was sent from AMA or provincial temples to the capital (Lustig, 2001, 2009). Instead, it appears that many temples would convert their staple finance to wealth finance or "high-value goods" that would be sent as tax to the capital (Lustig and Lustig, 2019). Several provincial zones, notably the province of Battambang were well-known in the 19th and 20th centuries CE for their fertile agricultural soils and rice productivity (Nesbitt, 1997). It is plausible these regions were sending rice to the capital; however, no such material or epigraphic evidence yet exists for this practice.

4.6. Angkor's decline (after 1301 CE)

Following a population high in Period 5, Angkor's population began to fall. Accumulated archaeological evidence suggests that Angkor's decline started in the late 13th through 14th centuries CE, before the supposed sacking of Angkor by the Kingdom of Ayutthaya in 1431 CE (Buckley et al., 2010; Carter et al., 2019; Fletcher et al., 2017; Hall et al. 2021; Penny et al., 2019; Penny et al., 2018). The last Sanskrit inscription dates to 1327 CE, with the last major stone temple (Maṅgalārtha) constructed in 1295 CE (Briggs, 1951: 243, 251; Finot, 1925: 393-406). The growing influence of Theravāda Buddhism, which had emerged with a new fervour in the late 13th century CE, appears to have appropriated pre-existing power structures (Thompson, 1997), though its relationship with the decline of Angkor as capital is unclear

(Polkinghorne, 2021).

Additionally, recent environmental studies have suggested that people were likely leaving the walled precinct of Angkor Thom in the early 14th century CE (Hall et al., 2021; Penny et al., 2019). As noted above, some portion of this population may have been moving further south, as Early Modern capitals were located closer to present-day Phnom Penh, where China's trading potential was growing (Polkinghorne, 2018; Vickery, 1977, 2010; Polkinghorne and Sato, 2021). On top of this, a series of decades-long droughts and heavy monsoons severely impacted Angkor's water management network in the 14th and 15th centuries CE, which must have also impacted Angkor's agricultural productivity (Buckley et al., 2010). If people were already leaving the CCC, one might wonder if the water network's maintenance was necessary as communities in the AMA could produce enough for themselves with their existing infrastructure (Fletcher et al., 2017: 283; Polkinghorne, 2018: 260). This is a question worthy of further investigation.

Accurately determining which portions of Angkor's landscape were still inhabited during this period is challenging. Recent archaeological studies have highlighted the dynamic and complex life histories of some of Angkor's temples and their populations. At Angkor Wat, there appears to be a break or decline in occupation mounds surrounding the temple, followed by a lighter re-occupation in the Early Modern period (Carter et al., 2019; Stark et al., 2015). Conversely, at Ta Prohm, archaeological evidence suggests no habitation or use of the temple following the 14th century CE (Carter et al., 2018). Some temples, such as the Bapuon, were heavily modified in the 15th century CE, indicating a significant population's presence to undertake these changes (Leroy et al., 2015). Other archaeological and art historical studies have demonstrated continued habitation around Angkor (Brotherson, 2019; Castillo et al., 2018; Polkinghorne et al., 2018). Recently, Fletcher et al. (2017) have proposed a population of approximately 300,000 adults at Angkor by the early 14th century CE. We are currently unable to model population decline in Greater Angkor more accurately, as this will require careful archaeological excavation. Although there was a significant depopulation, this region was not abandoned or forgotten.

5. Conclusions

To summarize, several salient trends characterize the Angkor case study. The first involves initial nucleation in the urban core (Period 1) with three major population centers and a population density of 13–16p/ha. This was followed by a rapid AMA expansion in Period 2, which quadrupled the population in this zone. Angkor's total population during this period was approaching half a million people, depending on the density of habitation on the BANKs. Angkor's AMA always housed more people than its urban civic-ceremonial core. Such demographic imbalance coincided with the construction of new temple-based communities in the capital and the expansion of the city's water management network to include more of the metropolitan region. The AMA temple communities took advantage of this top-down state-sponsored infrastructure and relied on their own bottom-up management strategies (Klassen and Evans, 2020). Interestingly, social constraints regarding land sales and a reduction of tax immunities on temple foundations (especially 10th through early 12th century CE taxation) seems to have slowed the growth of the AMA beginning in the 11th century CE, as land in these regions was increasingly consolidated into the hands of elites. It is also likely that environmental factors and the landscape's carrying capacity limited settlement expansion (Hawken, 2013; Lustig, 2001; Pottier, 2000b).

Overall population growth in both the AMA and CCC was slow during the 12th century CE, but our model supports conventional Angkorian scholarship in placing Angkor's apogee (sensu Feinman and Carballo, 2019) during Period 5 in the late 12th to early 14th centuries CE when at least 688,0000 and perhaps as many as 900,000 lived in the Greater Angkor Region. Jayavarman VII's reign seems to have spurred a significant increase in population density in the CCC. Major works in the polity's capital included a series of state temples and the walled enclosure of Angkor Thom under Jayavarman VII. However, in the period after Jayavarman VII's death, elites likely began to abandon the CCC, prompting socio-political, religious, and environmental changes that reduced population across much of the Greater Angkor region, although the exact scale of this is currently unknown.

This study makes several contributions to our understandings to the growth of agro-urban centers and urbanism more broadly. Firstly, the Angkorian case study suggests centralized state control is not a necessary determinant for urban expansion. On the one hand, the development and increased density of Angkor's civic-ceremonial zone were shaped by Angkorian rulers and their entourages, both through intentional acts like state projects and unintended consequences like the growth of an elite "middle class" (Fletcher, 2019; Smith, 2018). Developments in the AMA, in contrast, involved local decision-making and governance and did not simply reflect exploitation by capital elites (e.g., Abrams, 1995; Klassen and Evans 2020; Hirth, 2013; Small, 2006; Steinkeller, 2007; Taylor, 2013). Aspects of Angkor's political economy are similarly heterogeneous. The production of stoneware ceramics was reatively decentralized and use of these ceramics was widespread across the Angkor empire (Grave et al., 2021; Grave et al., 2017). However, the production and use of objects associated with temples such as decorative lintels, bronze statues, and even the iron used in the construction of temples, was more centralized and under state control (Hendrickson and Leroy, 2020; Polkinghorne, 2013; Polkinghorne et al., 2014; Polkinghorne et al., 2015).

Secondly our work shows that both agrarian potential and individual ruler policies may limit urban size and configuration. Until the late 12th century, Angkor's growth stayed within the carrying capacity of the landscape. Even then, the upper range of our population estimate during this period (approx. 900,000 people) is based on intensive habitation on the embankments, which is thus far untested. However, the growth of Angkor over time was "pushed" by the activities of particular rulers who expanded Angkor's borders and infrastructure. This resulted in variable growth in the CCC and AMA over time. The relationship between the CCC and AMA communities was likely a critical factor in Angkor's urban longevity. As has been noted for other agro-urban settlements, the CCC's integration with the AMA and BANKs zones could have allowed for access to diverse ecological resources leading to urban sustainability; recent work has pointed out that "the Khmer did not live on rice alone" (Castillo et al. 2020; see also Castillo et al. 2018; Scarborough and Isendahl 2020). A ritual economy linking the AMA temple communities with those in the core may have also facilitated Angkor's long-term sustainability. Work at Teotihuacan, for example, has suggested that public rituals were key to maintaining long-term unity within the multicultural population (Filini, 2015). We expect that people in AMA communities likely came into the CCC to participate in ritual festivals and royal performances (Stark, 2015). Migration was an important component of ancient urbanism (Smith, 2014a; Smith, 2014b; Storey, 2006). As noted earlier, temple inscriptions suggest that some smaller temples had cyclical labor forces. Could similar workgroups be moving into and out of the state temples within Angkor's CCC? Future studies could estimate, for example, the labor needed to expand Jayavarman VII's CCC (see Kim, 2013; Smailes, 2011). Such work might also shed light on how Angkorians crafted their shared identity and how AMA communities may have been integrated into or resisted the Angkorian state (e.g., Buell, 2014; Smith, 2003; Yaeger, 2000).

Angkor's massive settlement complex was neither an accident nor entirely planned, but it was certainly created (Cowgill, 2004: 535). That Angkor was able to maintain its dominance for hundreds of years also testifies to the sustainability and stability of this urban form (Klassen and Evans, 2020; Scarborough and Isendahl, 2020; Stark, 2019). As discussed above, multiple factors influence the development of agro-urban settlements. This fine-grained analysis allows us to see more clearly how and when these factors facilitated the development of the

Greater Angkor region. While many of these took place within a local historical context, we argue that future comparative studies might observe similar patterns.

CRediT authorship contribution statement

Alison Kyra Carter: Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing. **Sarah Klassen:** Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing, Visualization. **Miriam T. Stark:** Investigation, Writing - review & editing. **Martin Polkinghorne:** Investigation, Writing - review & editing. **Piphal Heng:** Investigation, Writing - review & editing. **Damian Evans:** Investigation, Writing - review & editing. **Rachna Chhay:** Investigation, Writing - review & editing.

Declaration of Competing Interest

None

Acknowledgements

The Authors thank the APSARA National Authority for their permission to conduct remote sensing and field investigations. Thanks also to Roland Fletcher for his support. Thank you to Terry and Eileen Lustig for their comments and suggestions on aspects of economic geography and Michael E. Smith for reading and offering comments on an earlier draft of this paper. Thanks to Malay So and Maryne Dana for administrative support.

Funding

Research, planning, and writing of this manuscript was undertaken with the support of the University of Oregon Global Oregon Faculty Collaboration Fund supported by the Global Studies Institute in the UO Office of International Affairs. Data collection for parts of the research in this study have been funded by: the National Geographic Society Committee for Research and Exploration under Grant 9602-14; Dumbarton Oaks under a Project Grant in Garden and Landscape Studies; the Social Sciences and Humanities Research Council of Canada Postdoctoral Fellowship; the National Science Foundation Doctoral Dissertation Research Improvement Awards (#1638137); Australian Research Council Discovery Early Career Researcher Award (DE150100756) and Council Discovery Grant (DP170102574); and the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreements 639828 and 866454).

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